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EXPLORING BUILDING OCCUPANTS’ BEHAVIOUR USING EMERGING BUILDING INFORMATION MODELLING

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Abstract: According to the recent the Intergovernmental Panel on Climate Change (IPCC), Fifth Assessment Report (AR5) globally, buildings were responsible for about 32% of energy consumption and emission of 19% of energy-related greenhouse gases in 2010. These shares impact negatively on the environment and communities. Many studies reveal that emerging Building Information Modelling (BIM) has a great potential to contribute to improving sustainable design practices that can lead to the mitigation of climate change impacts. Despite the wide use of BIM in performing sustainable building analysis, building occupants’ behaviour is hardly considered. Recent studies including the IPCC AR5 reveal that occupants’ behaviour contributes significantly to household energy consumption. The use of emerging BIM in modelling human behaviour and influences on energy efficiency of buildings is still very sketchy. This study aims to investigate the use of BIM in modelling household occupants’ behaviour and impacts on energy consumption. The research methods to be adopted are three-fold. First, in order to understand the nexus between occupants’ behaviour and energy simulation, a review of behavioural practices in homes and current BIM-energy simulation software packages is undertaken. Secondly, based on the first, suitable BIM-energy simulation software systems are identified and used for simulating occupants’ behaviour vis-à-vis energy consumption. Thirdly, a building with well-known and established characteristics is employed as a case study to investigate different behaviour options and impacts and results discussed.

1 BACKGROUND STUDY

The major factors that influence energy consumption in a building are its physical characteristics, the equipment installed to provide comfort (the heating, ventilation and air-conditioning system, auxiliary production of electricity and hot water), household and portable devices, the outdoor environment and the behaviour of occupants. While advances in technologies supported by research have facilitated the assessment of impacts of the first four factors on energy consumption, studies about the latter are still very scanty. Research have revealed that occupants influenced the final energy consumption of buildings (Gram-Hanssen 2014; Steemers and Yun 2009; Makashini et al. 2014). Buildings are often designed
based on scientific assumptions on how it will be used. However, when the building is erected it may be used differently by occupants in some cases deviating significantly from the designer’s assumed intentions and underlying scientific assumptions (Fabi et al. 2011). While early collaboration of project team members to capture client’s requirements is common today, occupant’s daily behaviour is hardly considered. This may be partly due to the fact that clients may not necessarily be the future occupants of the buildings. Even if clients were to be, in most cases occupants generally behave unconsciously and in a very unpredictable manner making it difficult for these requirements to be properly captured at the early design stages. Furthermore, even when these requirements have been captured, modelling them for predictive purposes is often a daunting task. This partly explains why statistical and probabilistic algorithms have often been used in modelling human’s behaviour in buildings (Baetens and Saelens 2011; Page et al. 2007). Also, to automate computation, simulation software packages are widely being used in modelling the same (Gram-Hanssen 2014; Ben and Steemers 2014). Simulation tools have been great in modelling physical characteristics, the equipment installed to provide comfort (the heating, ventilation and air-conditioning system, auxiliary production of electricity and hot water), household and portable devices, the outdoor environment and the behaviour of its occupants. With regards to occupants’ behaviour, simulation tools have generally relied on fixed profiles of typical occupant presence and associated implications of their presence (Page et al. 2007).

Emerging BIM has been hailed as one of the solutions to enhanced sustainability in the built environment. The strength of BIM lies in the fact that a building can be virtually modelled and then embedded with rich data that can be manipulated to explore alternative options even before construction on a site. This quality of BIM makes it quite suitable for modelling data that can be used in evaluating building energy efficiency. Thus, the current trend in research and practice is to integrate BIM with specialist building energy simulation software to optimise performance with regards to sustainability building assessment. Despite this, current integrated BIM-energy simulation software systems are great in modelling building physical characteristics, the equipment installed to provide comfort (the heating, ventilation and air-conditioning system, auxiliary production of electricity and hot water), household and portable devices with very little emphasis on the modelling of behaviour of occupants. The proposed study aims to explore the use of BIM in modelling household occupants’ behaviour and impacts on energy efficiency. The key research questions are: What are the different human behaviour factors to be considered in building energy assessments? What is the connection between BIM/energy simulation systems? How do human behaviour factors fit with the BIM/energy simulation system connection? What is the whole assessment procedure and challenges? To answer these questions, appropriate research methods (see Figure 1) will be pursued.

2 RESEARCH METHODS

The first step consists of undertaking an extensive literature review about the different domain relevant to this study. Specifically, behaviour of building occupants, BIM and energy analysis software are reviewed. This led to the understanding of nexus between occupants’ behaviour and household energy consumption.
consumption. Furthermore, BIM and energy analysis software from vendors’ websites and peer-reviewed publications (Abanda and Tah 2014; Kurul et al. 2013; Nguyen et al. 2014; Bambardekar and Poerschke 2009; Attia et al. 2009; 2011; 2012; Sharma and Prouhit 2014; US Department of Energy 2014; Crawley et al. 2008) and their suitability established. Secondly, based on the different software identified in the previous step, their uses in modelling of building and energy simulation are investigated. The details of the simulation will be presented in Figure 2. Thirdly, based on the preceding step, the simulation processes are implemented on a chosen case study building with well-known information. Choosing a building with well-known and established characteristics is important as it allows authors to easily analyse and interpret findings from iterating the different modelling of occupants’ behaviour. This allowed for an in-depth analysis of the potential in modelling household occupants’ behaviour.

3 AN OVERVIEW OF BEHAVIOURAL PRACTICES IN HOMES

The aim of this section is to establish what drives behaviour, how occupants react to external/internal stimuli to meet their needs and which systems are available in facilitating their desire to meet the needs. Recent studies have revealed that climate and building characteristics are insufficient in determining energy demand. Occupants’ behaviour and socio-economic factors are also important factors that have recently gained importance (Steemers and Yun 2009; Lucon et al. 2014). Lucon et al. (2014) reported behavioural changes coupled with recent technological advances, design practices and know-how can achieve a two to ten-fold reduction in energy requirements of individual new buildings and a two to four-fold reduction for individual existing buildings largely cost-effectively or sometimes even at net negative costs. Providing feedback about energy consumption is crucial and can influence the behaviour and lifestyle of building occupants. Although the impact or effectiveness of feedback to household occupants is quite a highly contested issue (Vine et al. 2013), Darby (2006) argued that feedback can reduce electricity consumption in homes by 5 to 20%. Integrating feedback information into BIM energy simulation software can help drive changes in occupants’ behaviour that can potentially lead to efficient energy management. What are the occupants’ behavioural actions? Presently, there is an abundance of literature on occupants’ behaviour, however, there are hardly structured. This weakness is currently being investigated by an ongoing research project (Turner and Hong 2013) with the aim to develop a technical framework that describes human-related behaviour in buildings. The framework proposes four main components — drivers, needs, actions and systems (Turner and Hong 2013):

- **Drivers** represent the stimulating factors that provoke an occupant into performing an energy-related behaviour or an interaction with a system;
- **Needs** represent the physical and non-physical requirements of an occupant that must be met in order to ensure the satisfaction of the occupant with their environment;
- **Actions** are interactions with systems or activities that an occupant can conduct in order to achieve environmental comfort (e.g. window opening/closing);
- **Systems** refer to the equipment or mechanisms within a building with which an occupant may interact to restore or maintain the environmental comfort of the occupant(s).

To facilitate understanding, a scenario will be described to illustrate the drivers, needs, actions and systems concept in relation to occupants’ behaviour in a domestic home in Section 5.

4 BIM AND BUILDING PERFORMANCE SIMULATION TOOLS: RELATED STUDIES

In this section, the software required for building energy simulation will be identified. The identified software will be used in modelling and performing energy simulation of a case study building. BIM software packages have been reviewed in the literature (Abanda and Tah 2014; Kurul et al. 2013). These studies generally tend to focus on technical and market features of the software (e.g. cost of software and file management facilities), with very little emphasis on their different uses. Thus the application of these software packages in performing building energy analysis is hardly discussed and unclear; talk less of considering occupants’ behaviour in the analysis. This study will build on past efforts (Abanda and Tah 2014; Kurul et al. 2013) with focus on energy modelling and analysis. Furthermore, how occupants’
behaviour can be modelled in these systems will be investigated. To avoid duplicating the works of others (e.g. Abanda and Tah 2014; Kurul et al. 2013; Bahar et al. 2013), this study considered only criteria relevant to household occupants’ behaviour, excluding others already investigated in the preceding studies. One important criterion to note that was considered is interoperability. This defines standards that allow files to be shared over different BIM software packages. It facilitates the integration of accurate information from a variety of disciplines into common data formats such as Industry Foundation Classes (IFC), IFCXML (IFC Extensible Markup Language) and COBie (Construction Operations Building Information Exchange). Other schemes that have emerged with focus on the extraction of environmental data include gbXML (green building Extensible Markup Language), ecoXML and obXML (occupants behaviour XML) (Turner and Hong 2013). Although, these interoperability formats are still under-development, Gupta et al. (2014) argues that they can still facilitate the exchange of rich and useful information between project partners without loss of accuracy or design intent. Other parameters considered are whether the software packages are commercial or open source and whether different systems such as windows and doors have been incorporated in the software packages. A summary of the comparison of the different software systems is presented in Table 1.

Table 1: Comparison of building energy simulation software

<table>
<thead>
<tr>
<th>Data exchange formats</th>
<th>Ecotect</th>
<th>IES</th>
<th>Green Building Studio (GBS)</th>
<th>eQuest</th>
<th>Design Builder</th>
<th>EnergyPlus</th>
<th>Ruiska</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFC</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>gbXML</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, via GBS</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Plug-ins</td>
<td>SketcUp</td>
<td>Revit</td>
<td>OpenStudi o plug-in in Sketch-Up</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completely open</td>
</tr>
<tr>
<td>Commercial</td>
</tr>
<tr>
<td>Behaviour</td>
</tr>
<tr>
<td>Opening/opening of windows</td>
</tr>
<tr>
<td>Opening/opening of doors</td>
</tr>
<tr>
<td>Appliances</td>
</tr>
<tr>
<td>Blinds</td>
</tr>
</tbody>
</table>

Based on Table 1, IES-VE –Pro will be used. IES-VE-Pro incorporate tools for analysing different climatic and energy related scenarios. Furthermore, it is widely used by commercial as well as research communities. Despite this, it is quite a complicated software and requires a stiff learning curve to understanding its potential. Consequently, it is important to provide clarity about some terminologies about the software. The main ones are IES VE-Ware, IES VE Toolkits. The IES VE-Toolkits are a set of analyses that can be run to help influence and direct early stage building designs. These fast analyses can be run with basic model inputs to allow indicative assessment of design options taking into account climate, building fabric, energy & carbon, thermal loads, daylighting and solar shading. VE-Ware is a free
building energy and carbon assessment software that also contains Free VE-SBEM for UK regulation compliance.

Based on Table 1, the types of human behaviour that can easily be modelled in IES-VE Pro are related to the roof, slab and door systems. Within the scope of this study, only the behaviour related to the window systems and their implications related to energy performance of buildings in terms of heating and electricity load will be investigated. This is done in the ensuing section.

5 MODELLING OF OCCUPANTS’ BEHAVIOUR IN BIM SOFTWARE SYSTEMS

5.1 Description of Scenario

As previously discussed in Section 3, a scenario will be used to clarify the concepts that underpin occupants’ behaviour and energy construction (i.e. drivers, needs, actions and systems). This scenario is about the house conditions of a pensioner who spent the Christmas-2014 in his home in Manchester. The indoor room temperature throughout the day has plummeted to below 0°C, until the pensioner has become uncomfortably cold. The pensioner then turns on the radiator to heat the home. As a result, the house temperature increases to a level deemed suitable and comfortable by the pensioner. In this example, the “driver” is the indoor temperature. The “need” is the requirement for thermal comfort of the pensioner. The “action” is the starting of the radiator by the pensioner. The “system” is the radiator. At times it is possible to perform more than one action at a time in response to meeting a single or multiple need(s) or being driven by multiple stimulating factors. For example, still in the preceding example, the pensioner might also want to put on some pullovers, take a cup of hot tea in addition to starting the radiator. In this case the “drivers” and “needs” remain the same while wearing a pullover, drinking hot tea and starting a radiator are “actions” and “systems” are pullover, hot cup of tea and radiator. Given the number of permutations involved in identifying “drivers”, “needs”, “actions”, and “systems” of household occupants’ behaviour, a system approach will be used to identify all possible cases for a generic building. In this approach, a list of all possible “drivers” are determined and summarised in a matrix table (see Table 2) that facilitates the determination of “needs”, “actions” and “systems”.

<table>
<thead>
<tr>
<th>Drivers</th>
<th>Needs</th>
<th>Actions</th>
<th>Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building too cold</td>
<td>Thermal comfort</td>
<td>Closed windows</td>
<td>windows</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Closed doors</td>
<td>doors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turn radiators on</td>
<td>radiators</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Put on thick clothing</td>
<td></td>
</tr>
<tr>
<td>Building too hot</td>
<td>Thermal comfort</td>
<td>Open windows</td>
<td>windows</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open doors</td>
<td>doors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turn air conditioners on</td>
<td>air conditioners</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turn fans on</td>
<td>fans</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turn down thermostats</td>
<td>thermostats</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduce number of clothing</td>
<td></td>
</tr>
<tr>
<td>Building too stuffy</td>
<td>Improve air quality</td>
<td>Open windows</td>
<td>windows</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open doors</td>
<td>doors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turn air exchangers on</td>
<td>air exchangers</td>
</tr>
<tr>
<td>Damp on walls</td>
<td>Dry or stop damp on walls</td>
<td>Heat the house</td>
<td>radiators</td>
</tr>
<tr>
<td>Room is too dark</td>
<td>Visual comfort</td>
<td>Open windows</td>
<td>windows</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turn lights on</td>
<td>light bulbs</td>
</tr>
<tr>
<td>Noise in the neighbourhood</td>
<td>Acoustic comfort</td>
<td>Closed doors</td>
<td>doors</td>
</tr>
</tbody>
</table>

It is important to note that while some of the “systems” above do not exist in isolation as they may be interference with socio-cultural issues leading to some of the actions not being able to be undertaken despite the presence of a “need”. For example, in an insecure urban neighbourhood, occupants may not
leave their doors or windows ajar to keep cool despite the building being too hot. Given the understanding of occupants’ behaviour (see Table 2), and the different energy simulation software (see Table 1), a case study building will be used to investigate the integration of in energy simulation software.

5.2 Description of Case Study Building

The case study building is a hypothetical 8-bedroom house with well-known information located in Westminster. The building is made of one ground floor and one first floor. The ground floor consists of 3 bedrooms and the first floor consists of 5 bedrooms. On the ground floor, there are 4 internal doors, 2 external doors and 6 external windows. On the first floor, there are 6 internal doors, and 7 external windows. The modelling of this building is discussed in Section 5.3.

5.3 Modelling Behaviour in the Case Study Building

The key tools used in this modelling process are Revit 2015 and IES. The two can be linked through the interoperability standard gbXML, a leading language for energy simulation. The simulation steps are summarised in Figure 2.

![Figure 2: A framework for integrating behaviour in BIM](image)

The first step in performing energy analysis is to draw the geometry of the building. There are three main techniques of modelling in IES-VE. The first consists of modelling in natively in the ModelIT component of IES-VE. The second consists of modelling in Sketch-Up, then importing in IES-VE with the help of an in-built plug-in. The third consists of using any BIM software that can generate gbXML which can be imported into IES-VE. The model was modelled in and imported from Revit 2015 to IES via gbXML. The output is presented in Figure 3.
The performance parameter to be analysed is total annual energy consumed by the dwelling. This consists of natural gas and electrical energy. This is performed using the MacroFlo component of IES. MacroFlo provides an opportunity to define operable windows in a model and to assess the impacts of natural ventilation on space. According to the UK Building Regulations Part L, the U-values of the major components were: a) windows=1.6 W/m²K, b) door=2.2 W/m²K, c) roof= 3.3 W/m²K. The closest weather station chosen is the London Weather station. The different opening modes used are full opening, partial and semi openings. For purposes of this study only 3 scenarios were considered. The scenarios are presented in Table 3.

Table 3: Scenarios studies for case study

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Door operation</th>
<th>Window operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All external doors are closed whether occupied or not</td>
<td>All windows closed when occupied</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>All external doors are closed whether occupied or not</td>
<td>All windows opened during the summer months (June, July, August) from 8am-6pm.</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>All external doors are closed whether occupied or not</td>
<td>All windows opened during the summer months (June, July, August) from 8am-12pm</td>
</tr>
</tbody>
</table>

The scenarios in Table 3 were edited in IES. The model is checked for correctness. For example, rooms should be properly defined in Revit with Room tag definitions. Errors will be identified if rooms are not correctly defined at this stage. This is done by clicking on red box indicated in Figure 4. Once this check is done, data such as type building, heating systems and rooms' conditions are chosen (see Figure 4).

![Figure 4: Preliminary building requirements in IES](image)

After checking the model and choosing the different parameters for the model, the simulation parameters, e.g. simulation period (January-December) are chosen (see Figure 5). One important aspect to note here is that, if the model was not properly designed with rooms properly defined, it would have been difficult to determine the different rooms involved in the simulation as depicted in the red box in Figure 5.
On running the simulations for the different scenarios the results obtained are presented in Table 4.

### Table 4: Annual energy consumption

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Duration</th>
<th>Total natural gas (MWh)</th>
<th>Total electricity (MWh)</th>
<th>Total energy (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>One year</td>
<td>22.055</td>
<td>4.771</td>
<td>26.826</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>One year</td>
<td>23.01</td>
<td>4.771</td>
<td>27.781</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>One year</td>
<td>22.56</td>
<td>4.771</td>
<td>27.331</td>
</tr>
</tbody>
</table>

From Table 4, for the period when the window is opened for longer periods as in scenario 2, more heat is required to keep the house warm. Of course, within the scope of this paper other comfort parameters such as satisfaction with ventilation when windows are locked as in scenario 1 have not been investigated.

## 6 KEY FINDINGS AND DISCUSSIONS

- Most actions are those related to the geometry of the building. Actions such as taking cup of tea and wearing more clothes are hardly part of energy simulation tools. These actions can consume (e.g. boiling tea) very limited thermal energy or offset energy that would have been used to heat the home (e.g. wearing more clothes);
- There is no direct connection between BIM and energy simulation tools that can allow automatic changes been made in BIM design tool and changes felt in the energy simulation tool. It implies that the building model in BIM should be modelled and required information incorporated to avoid back and forth movement between the two software systems;
- Although the annual energy loads are not significantly different, it is however consistent with the minimal changes or information introduced in the simulation. No detail data were inputted into the IES software;
- It is also important to mention the fact that the export from a BIM model in Revit to IES was not smooth as so many errors emerged and the building model had to be revised so many times before IES could be used.
7 CONCLUSIONS

This study was underpinned by the need to integrate human behaviour in the assessment of energy in buildings. Based on the literature, it emerged that many studies have seldom considered occupants' behaviour in performing energy analysis of buildings. However, recent studies indicate the significant contribution of human behaviour in household energy consumption. It is from this perspective that this study explored how emerging BIM can be employed in integrating human behaviour for assessing energy of buildings. The crucial aspects of this exploratory study are the establishment of human related behaviour factors, modelling of the factors in a BIM authoring and/or energy simulation software, performing analysis and interpreting results. With respect to the first, an established framework for human related behaviour was employed in identifying key human related energy factors (see Table 2). To determine how the human related factors can be modelled, the study assumed knowledge of BIM authoring systems already reviewed in other literature (e.g. Kurul et al. 2013; Abanda and Tah 2014) and then emphasis was instead placed on reviewing building energy simulation software packages (see Table 1). The study exploited the interoperability paradigm of the software to establish the connection between the BIM authoring and energy simulation software packages. IES-VE was adopted as the main software and a hypothetical case study building was used. This building was modelled in Revit, converted to gbXML and then imported into IES-VE before embedding the human related factors. It emerged that the opening and closing of windows can contribute to the energy consumption of a building. Specifically, the more windows are left opened, the more energy is lost and more is needed to keep the home comfortable. While this finding may not be entirely new, its novelty lies in the use emerging BIM to quantitatively assess the impacts virtually demonstrated through 3 scenarios. As part of future study, a detail study involving many scenarios will be conducted to establish the implications of occupants' behaviour on energy consumption. One major challenge was the export of the model from Revit into IES which was very difficult and ridden with so many errors. Also, as part of future study, other software will be explored including the IES plugin for Revit.

Acknowledgements

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References


MINIMIZING GREENHOUSE GAS EMISSIONS AND WATER CONSUMPTION OF EXISTING BUILDINGS

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Abstract: Buildings are responsible for 38\% of all carbon emissions and 14\% of water consumption in the United States. These negative environmental impacts can significantly be reduced by implementing green upgrade measures such as energy-efficient lighting and HVAC systems, motion sensors, photovoltaic systems, and water-saving plumbing fixtures. Building owners in the public and private sectors often search for an optimal set of upgrade measures that is capable of minimizing the negative environmental impacts of their buildings. This paper presents the development of an optimization model that is capable of identifying optimal selection of building upgrade measures to minimize greenhouse gas emission and water consumption of existing buildings while complying with limited upgrade budgets. The model is developed in four main development steps: metrics identification step that quantifies greenhouse gas emissions and water consumption of existing buildings; model formulation step that formulates the model decision variables, objective function, and constraints; implementation step that executes the model computations and specifies the model input and output data; and validation step that evaluates the model performance using a case study of an existing building. The results of the model illustrate its new and unique capabilities in providing detailed results, which include specifications for the recommended upgrade measures, their location in the building, and required upgrade cost to minimize greenhouse gas emissions and water consumption of existing buildings.

1 INTRODUCTION

Buildings in the United States are responsible for significant GreenHouse Gas (GHG) emissions due to significant percentage of electricity consumption (72\%), energy consumption (39\%), and water consumption (13\%) (U.S. Environmental Protection Agency 2009). These GHG emissions due to energy and water consumption contribute to negative environmental impacts including, global warming, ozone depletion, and air pollution (ICF Incorporated 1995; U.S. Environmental Protection Agency 2009, 2012; United Nation Environment Program 2007). The negative environmental impacts of buildings can be reduced by implementing sustainable measures such as energy efficient building fixtures and equipment, water-saving plumbing fixtures, and installing renewable energy systems. These sustainable measures require high upgrade costs and decision makers are often confronted with a challenging task to identify optimal selection of building upgrade measures within their upgrade budget. In order to support decision makers in this challenging task, there is a pressing need to develop optimization models that are capable of identifying optimal selection of building upgrade measures to minimize negative environmental impacts of existing buildings within available budgets.
Several systems have been developed and studies conducted to estimate the negative environmental impacts of buildings during their construction, operation and demolishing such as Building for Environmental and Economic Sustainability (BEES) (Lippiatt et al. 2010), ATHENA impact estimator (The ATHENA Institute 2013), and envest2 (Building Research Establishment 2003). Other studies focused on evaluating the implementation of various sustainability measures such as energy-efficient lighting systems, energy-efficient HVAC systems and heat pumps (Bloomquist 2001; Chiasson 2006; Das et al. 2013; International and Conference 2003; Narendran and Gu 2005; Phetteplace 2007; RUUD LIGHTING 2010), renewable energy systems (Chapman and Wiczkowski 2009; James et al. 2011; Matthews et al. 2004; State Energy Conservation Office 2006), and water-saving plumbing fixtures (GAO 2000).

Furthermore, several optimization models have been developed to minimize existing buildings' operational costs (Abdallah et al. 2014), identify optimal selection of structural and architecture design of new buildings (Bichiou and Krarti 2011; Fialho et al. 2011), and identify optimal decisions of building renovations (Brandt and Rasmussen 2002; Juan et al. 2010; Kaklauskas et al. 2005).

Despite the significant contribution of the existing research studies, limited or no optimization models exist that are capable of selecting building upgrade measures of existing buildings in order to minimize their negative environmental impacts of greenhouse gas (GHG) emissions and water consumption simultaneously. Furthermore, limited or no optimization models exist that consider various sustainability measures of building fixtures and equipment, renewable energy systems, and plans of managing solid waste simultaneously in order to minimize the negative environmental impacts of existing buildings while complying with a user-specified upgrade budget and building operational performance.

2 RESEARCH OBJECTIVE

The objective of this research study is to develop an optimization model that is capable of minimizing negative environmental impacts of existing buildings. This optimization model is designed to provide the optimal selection of building upgrade measures to minimize GHG emissions and water consumption of existing buildings while complying with available upgrade budgets and specified building operational performance. This optimization model is expected to support decision makers and building owners in their ongoing efforts to minimize negative environmental impacts of their buildings by optimal allocation of their budgets. The optimization model is developed in four main steps: (1) metric identification step, which quantifies the negative environmental impacts of buildings; (2) model formulation step that formulates the model decision variables, objective function, and constraints; (3) implementation step that executes the model computations using Genetic Algorithms (GAs); and (4) evaluation step that validates the model performance using a case study of an existing building. The following sections describe the development steps of the optimization model to illustrate the capabilities of the model and demonstrate its use.

3 OPTIMIZATION MODEL DEVELOPMENT

3.1 Metric Identification

The optimization model is developed to quantify the negative environmental impacts of existing building in terms of GHG emissions that result from buildings energy consumption; energy use for water extraction, treatment, distribution, and wastewater treatment; and buildings solid waste (ENVIRON International Corporation 2013; Flager et al. 2012; ICLEI - Local Governments for Sustainability USA 2010, 2012; Kwok et al. 2012; Liu et al. 2013; Ordóñez and Modi 2011; Safaei et al. 2012; TranSystems|E.H. Pechan 2012; U.S. Environmental Protection Agency 2006; USGBC 2014a; Zhu et al. 2013); and water consumption from plumbing fixtures.

The GHG emissions from building operation consist of carbon dioxide (CO$_2$), nitrous oxides (N$_2$O), methane (CH$_4$), and ozone (O$_3$) (TranSystems|E.H. Pechan 2012). The global warming potential factors that are developed by the Intergovernmental Panel of Climate Change (IPCC) can be used to represent all GHG emissions in terms of equivalent quantities of CO$_2$ emissions (Intergovernmental Panel on Climate Change 2007). The GHG emissions are quantified in the developed model based on the calculated (1) energy consumption of the building; (2) energy use during water extraction, treatment,
distribution, and waste water treatment; and (3) fugitive emissions of waste water, and solid waste. The GHG emissions of energy consumption are calculated based on the building electricity and natural gas consumption and the location of the building. This accounts for the types of plants that are used to generate energy for the building and associated average transmission losses. For major electricity grids in the United States, the Environmental Protection Agency provides energy emission factors and average transmission loss percentages, which can be used to estimate emissions of energy use in buildings (TranSystems (E.H. Pechan 2012). To estimate GHG emission of buildings, electricity and natural gas need to be calculated. The developed optimization model calculates electricity and natural gas consumption of the buildings using energy simulation software packages such as QUick Energy Simulation Tool “eQUEST” (U.S. Department of Energy 2013).

In addition to the GHG emissions that are created by the direct building energy consumption, the water consumption of the building create additional GHG emissions due to energy used in water extraction, conveyance and supply, treatment, and distribution. These emissions can be calculated based on annual building water consumption; and energy intensity of water extraction, water supply and conveyance, water treatment, and water distribution (ICLEI - Local Governments for Sustainability USA 2012). Similarly, the GHG emissions from wastewater treatment can be calculated based on annual building waste water; and energy intensity of wastewater collection, aerobic digesters for wastewater treatment, lagoons for wastewater treatment, attached growth of wastewater treatment, and nitrification or nitrification/denitrification of wastewater treatment (ICLEI - Local Governments for Sustainability USA 2012).

Another source of GHG emissions in existing buildings is calculated based on solid waste sent to landfill, combustion, composition, or recycling. The United Stated Environmental Protection Agency provides emission factors for each of these methods of managing solid waste (U.S. Environmental Protection Agency 2006). Accordingly, the annual equivalent carbon dioxide of solid waste in buildings can be calculated in the model based on the weight of each solid waste material and the associated emission factor calculated according to solid waste management method. According to all the aforementioned sources of GHG emissions, the model calculates the total equivalent emissions of existing buildings by aggregating all sources of GHG emissions.

Plumbing fixtures are responsible for the majority of water consumption in buildings. They include water faucets, showerheads, kitchen sinks, urinals, and toilets. Building water consumption can be calculated in the developed model based on type of building, type of plumbing fixtures, and number of occupants according the guidelines of the LEED rating system for existing buildings (USGBC 2014b).

3.2 Model Formulation

The decision variables of the optimization model are designed to represent all feasible alternatives of building fixtures and equipment that consume energy or water using integer decision variables such as lighting fixtures and bulbs, HVAC systems, water heaters, refrigerators, vending machines, hand dryers, and water plumbing fixtures. The model is also designed to integrate energy saving measures using integer decision variables such as motion sensors, solar panels, inverters, and percentage of renewable energy that can be generated at the building site. In addition, the model is designed to integrate plans of managing solid waste using integer decision variables that represents the disposal of each solid waste using landfill, recycling, combustion, or composition.

The objective function of this optimization model minimizes the negative environmental impacts of existing buildings by minimizing GHG emissions and water consumption. The model accounts for GHG emissions and water consumption of buildings using Building Environmental Performance Index (BEPI). This index ranges from 0.0 which represent a fully sustainable building to 1.0 which represent no reduction in negative environmental impacts of the building as shown in Equation (1).

\[
BEPI = W_{\text{GHG}} \times \frac{G_{\text{GHG}}}{G_{\text{GHG}}} + W_{\text{WC}} \times \frac{W_{\text{WC}}}{W_{\text{WC}}}
\]
Where: $BEPI$ is building environmental Performance index; $GHGE^R$ is building GHG emissions after implementing upgrade measures; $GHGE^E$ is existing building GHG emissions; $WC^R$ is building water consumption after upgrade measures; $WC^E$ is existing building water consumption; and $W_{GHG}$ and $W_{WC}$ are relative importance weights of GHG emissions and water consumption, respectively.

To ensure the practicality of this optimization model, it is designed to comply with two main constraints: (1) building performance constraints, and (2) upgrade budget constraint. The building performance constraint is integrated in the model to ensure that the required operational performance of the building will be maintained after replacing its fixtures and equipment, including space heating and cooling, water heating capacity, and light levels. The upgrade budget constraint is integrated in the model to ensure that the cost of upgrading the building fixtures and equipment, installing renewable energy systems, and managing solid waste will not exceed the specified upgrade budget.

### 3.3 Model Implementation

The computations of the optimization model are executed using Genetic Algorithms (Gas) due to its (1) efficiency in modeling the optimization problem with the least number of decision variables, (2) capability to model non-linearity and step changes in the objective function and constrains that are caused by replacing building fixtures and equipment, (3) capability of identifying optimal solution within reasonable computational time (Aytug and Koehler 1996; Goldberg 1989; Pendharkar and Koehler 2007).

The computation procedure of the developed model starts by searching an integrated databases in order to identify feasible replacements of HVAC systems and water heaters. The model then creates eQuest input files of feasible replacements and sends them to eQuest simulation environment to calculate their energy consumption. The model then stores the calculated energy consumption of HVAC equipment and water heaters in a database where it can be used during the optimization process. The GA computations start by generating random selection of building upgrade measures which represent the initial population. The fitness of this initial population is evaluated based on the index of negative environmental performance index and the model constraints. Solutions that satisfy all the constraints and achieve low values of negative environmental performance index are classified as solutions with high fitness values. On the other hand, solutions that achieve high values of negative environmental performance index or do not satisfy the model constraints are classified as solutions with low fitness values or infeasible solutions, respectively. Solutions with high fitness are then ranked based on their index of negative environmental performance index where the GA operators of selection, crossover, and mutation are applied to generate a new set of population. This process is iteratively repeated until no further improvements are achieved within a predefined number of iterations. It should be noted that the initial population of the model is set based on the GA string and possible values of the model decision variables (Reed et al. 2000; Thierens et al. 1998).

The developed optimization model is integrated with databases of building fixtures and equipment, components of renewable energy systems, and various types of building solid waste. These databases are designed to include general product data, cost data, energy and water characteristics, and physical characteristics of building fixtures, and components of renewable energy systems, including lighting bulbs and fixtures, motion sensors, HVAC equipment, water heater, hand dryers, vending machines, refrigerators, PCs, water coolers, solar panels, solar inverters, water faucets, urinals, and toilets. The databases also include data on energy intensity of water extraction, conveyance, treatment, distribution, and waste water treatment; and emission factors of energy consumption and solid waste according to the location of buildings in the United States. For example, the equivalent emission factors of electricity consumption, electricity savings, and average transmission losses of all electricity grids are stored in the model databases, as shown in Table 1.
Table 1: Sample emission factors and average transmissions losses of electricity grids in USA (TranSystems|E.H. Pechan 2012)

<table>
<thead>
<tr>
<th>eGRID subregion name</th>
<th>Equivalent CO₂ emission rate (lb/MWh)</th>
<th>Equivalent non-baselode CO₂ emission rate (lb/MWh)</th>
<th>Power grid average transmission loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SERC Virginia/Carolina</td>
<td>1,041.73</td>
<td>1,686.09</td>
<td>5.82%</td>
</tr>
<tr>
<td>RFC West</td>
<td>1,528.76</td>
<td>2,012.22</td>
<td>5.82%</td>
</tr>
<tr>
<td>WECC California</td>
<td>661.20</td>
<td>995.85</td>
<td>8.21%</td>
</tr>
<tr>
<td>WECC Southwest</td>
<td>1,196.58</td>
<td>1,190.97</td>
<td>8.21%</td>
</tr>
</tbody>
</table>

4 CASE STUDY

A rest area building was analyzed and optimized by the developed optimization model in order to illustrate the model capabilities and demonstrate its use. This rest area building is located in Illinois and it was selected due to its high levels of negative environmental impacts caused by its continuous operation throughout the year and its inefficient energy and water fixtures. The building was built in 1989 and renovated in 1992 with a total area of 2500 square foot. This rest area building includes men’s and women’s bathrooms, lobby, vending area, travel information desk, storage rooms, mechanical room, attic, and detached small garage. The rest area also has parking lots for visitors that accommodate cars and semi-trucks. The major contributors of energy consumption in the building include interior and exterior lighting systems, water heater, HVAC systems, six vending machines, four hand dryers, five water coolers, PC, surveillance system, and five code blue emergency phones. The major contributors of water consumption in the building include eight toilets, two urinals, and six water faucets.

In order to minimize the negative environmental impacts of the rest area building, the optimization model requires input data of (1) building characteristics, including building size, construction materials, air infiltration, doors and windows, operational schedule, allocation of building activities, temperature set points, and airflow, as shown in Table 2; (2) characteristics of building equipment and fixtures which can be selected from the model databases, as shown in Table 3; (3) amounts of building solid wastes, as shown in Table 4; and (4) importance weights of building negative environmental impacts which were specified at 80% and 20% for GHG emissions and water consumption, respectively. It should be noted that the importance weights can vary from one decision maker to another, and the model enables them to specify their own weights accordingly.

Table 2: Sample input data of the building characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Building characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building envelop (roof surfaces)</td>
<td>Wood advanced frame 24” with dark brown shingles roofing and R-30 batt.</td>
</tr>
<tr>
<td>Building envelop (above grade walls)</td>
<td>6” CMU with brick exterior finishing and perlite filling</td>
</tr>
<tr>
<td>Building infiltration</td>
<td>1.0 ACH for perimeter and core</td>
</tr>
<tr>
<td>Building interior construction</td>
<td>Lay-in acoustic tiles flooring with R-11 batt, and mass interior walls.</td>
</tr>
<tr>
<td>Building operation schedule</td>
<td>24 hours</td>
</tr>
</tbody>
</table>
Table 3: Sample input data of the building fixtures

<table>
<thead>
<tr>
<th>Building fixture</th>
<th>Feasible Alternatives</th>
<th>Input Data</th>
<th>Number of fixtures</th>
<th>Working hours per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men’s bathroom</td>
<td>1</td>
<td>Square fluorescent fixture with 2 T8 U-shaped lamps of 28 W and 2265 lumens</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>– Set 2</td>
<td>2</td>
<td>Square fluorescent fixture with 2 T12 U-shaped lamps of 34 W and 2279 lumens</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Square fluorescent fixture with 2 T12 U-shaped lamps of 35 W and 2235 lumens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building HVAC</td>
<td>1</td>
<td>Electric HVAC system</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>System # 1</td>
<td>2</td>
<td>Gas Energy Star rated HVAC system</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Ground-source heat pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Electric Energy Star rated HVAC system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men’s bathroom</td>
<td>1</td>
<td>Hand dryer - 2300 W and 30 sec drying time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– hand dryers</td>
<td>2</td>
<td>Hand dryer - 1100 W and 12 second drying time</td>
<td>2</td>
<td>Per use</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Hand dryer - 1100 W and 15 second drying time</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Touchless paper towel dispenser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Women’s bathroom</td>
<td>1</td>
<td>Electronic flushing toilet with 3.5 gallons per flush</td>
<td>8</td>
<td>Per use</td>
</tr>
<tr>
<td>– toilets</td>
<td>2</td>
<td>Electronic flushing toilet with 1.6 gallons per flush</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Electronic flushing toilet with 1.28 gallons per flush</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Sample of managing solid waste at the rest area building

<table>
<thead>
<tr>
<th>Solid Waste</th>
<th>Annual Weight (ton)</th>
<th>Managing solid waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum cans</td>
<td>0.1</td>
<td>Landfill</td>
</tr>
<tr>
<td>Newspaper</td>
<td>0.3</td>
<td>Landfill</td>
</tr>
<tr>
<td>Food scraps</td>
<td>0.5</td>
<td>Landfill</td>
</tr>
<tr>
<td>Mixed paper</td>
<td>0.3</td>
<td>Landfill</td>
</tr>
<tr>
<td>Mixed plastics</td>
<td>0.3</td>
<td>Landfill</td>
</tr>
</tbody>
</table>

The optimization model was used to minimize the negative environmental impacts of the rest area with various upgrade budgets that ranged from $10K to $100K. The model was able to identify the optimal upgrade decisions for all the specified upgrade budgets, as shown in Figure 1. For example, solution (a) in Figure 1 identified by the model as an optimal solution for an upgrade budget of $50K, and it provides a moderate reduction in the negative environmental performance index of (BEPI = 0.519) with an upgrade cost of $49,673. On the other hand, solution (b) is identified by the model as an optimal solution for an upgrade budget of $100K, and it provides minimum negative environmental performance index of (BEPI =
0.397) that caused reduction in GHG emissions by 58% and water consumption by 69%, as shown in Figure 1.

![Figure 1: Results of minimizing negative environmental impacts of the rest area building](image)

The model is designed to provide an action report for the generated optimal solutions which include detailed information of all the recommended building upgrade measures. For example, the model generated the recommended upgrade measures and solid waste management plans for optimal solution (a) in Figure 1 as shown in Table 5 and Table 6, respectively. The results of the model identify the optimal selection of building upgrades based on an identified upgrade budget which helps decision makers and building owners in their ongoing task of maximizing the sustainability of their building while complying with their available budgets.

**Table 5: Sample recommended replacements of the building fixtures for upgrade budget of $50K**

<table>
<thead>
<tr>
<th>Room</th>
<th>Recommended Replacements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men's &amp; women's bathrooms, lobby, &amp; information rooms</td>
<td>Replace 32 existing T12 U-shaped lamps of 35 W, 2235 lumens, and 18,000 hours life expectancy with 22 T8 U-shaped lamps of 28 W, 2380 lumens, and 30,000 hours life expectancy.</td>
</tr>
<tr>
<td>Men's &amp; women's bathrooms, information, vending storage, &amp; garage</td>
<td>Replace 28 existing longitudinal fluorescent T12 lamps of 34 W, 2280 lumens, and 20,000 hours life expectancy with 10 longitudinal fluorescent T8 lamps of 25 W, 2280 lumens, and 40,000 hours life expectancy.</td>
</tr>
<tr>
<td>Building</td>
<td>Replace existing HVAC equipment with EnergyStar rated gas furnace and EnergyStar rated condensing units.</td>
</tr>
<tr>
<td>Vending storage</td>
<td>Replace existing fridge with energy efficient unit.</td>
</tr>
<tr>
<td>Men's &amp; women's bathrooms</td>
<td>Replace existing hand dryers of 2300w and 30 sec. drying time with touchless paper towel dispenser.</td>
</tr>
<tr>
<td>Building</td>
<td>Install photovoltaic system to generate 8.5% of the total building energy demand.</td>
</tr>
<tr>
<td>Men's &amp; women's bathrooms</td>
<td>Replace 6 existing water faucets of 1.5 gallons per minute with electronic faucets of 0.5 gallons per minute.</td>
</tr>
<tr>
<td>Men's &amp; women's bathrooms</td>
<td>Replace 8 existing toilets of 3.5 gallons per flush with water efficient toilets of 1.28 gallons per flush.</td>
</tr>
<tr>
<td>Men's bathroom</td>
<td>Replace 2 existing urinals of 1.6 gallons per flush with water efficient urinals of 0.125 gallons per flush.</td>
</tr>
<tr>
<td>Men's &amp; women's bathrooms</td>
<td>Install motion sensors to turn off the lighting automatically in men’s and women’s bathrooms when there is no occupants.</td>
</tr>
</tbody>
</table>
Table 6: Sample recommendations of managing solid waste for upgrade budget of $50K

<table>
<thead>
<tr>
<th>Solid Waste</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum cans</td>
<td>Collect aluminum cans and send them to recycling</td>
</tr>
<tr>
<td>Newspaper</td>
<td>Collect newspapers and send them to recycling</td>
</tr>
<tr>
<td>Food scraps</td>
<td>Collect food scraps and send them to composting</td>
</tr>
<tr>
<td>Mixed paper</td>
<td>Collect mixed paper and send it to recycling</td>
</tr>
<tr>
<td>Mixed plastics</td>
<td>Collect mixed plastics and send them to recycling</td>
</tr>
</tbody>
</table>

5 SUMMARY AND CONCLUSIONS

This paper presents the development of an optimization model that is capable of minimizing negative environmental impacts of existing buildings by minimizing their GHG emissions and water consumption. The model is designed to identify the optimal selection of building upgrade measures while complying with a specified upgrade budget and preferred building operational performance. The model was developed in four main steps: metric identification step, model formulation step, implementation step, and evaluation step. The metrics identification step identified novel metrics for quantifying the negative environmental impacts of existing buildings in terms of GHG emissions and water consumption. GHG emissions were calculated based on energy consumption, energy use of water extraction, treatment, distribution, and wastewater treatment; and buildings solid waste. The formulation step identified the model decision variables, objective function, and constraints. The model is designed to include decision variables that have impact on GHG emissions and water consumption including building fixtures and equipment, renewable energy systems, and water plumbing fixtures. The objective function is designed to minimize GHG emissions and water consumption using an index that account for these impacts using importance weights. The model integrated a number of constraints to comply with specified upgrade budgets and building operational performance.

The model implementation step include the execution of the model computations using Genetic Algorithms (GAs) and the development of databases to facilitate input and output data of the model. The evaluation step validated the model performance using a case study of a rest area building. The model was able to identify the optimal selection of building upgrade measures for various budgets that range from $10K to $100K. The model is designed to provide detailed results for the identified optimal solutions which include an action report that lists the details of the recommended upgrade measures. The new and novel capabilities of the developed optimization model provide needed support for decision makers and building owners in their ongoing efforts to minimize the negative environmental impacts of their existing buildings while complying with their limited upgrade budgets. Future expansion of the model and more in-depth analysis are needed to further study the impact of feasible upgrade measures of the building envelope such as type of insulation, windows, and doors to consider their effects on reducing the building negative environmental impacts especially for buildings that have their energy consumption dominated by HVAC systems.

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PROGRESS TRACKING OF MULTIPLE PROJECTS USING EMAIL AND VOICE

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Abstract: This paper introduces a framework developed to automatically track the daily progress details of multiple small/medium construction projects, simultaneously. The framework has been designed with several features: Geographic Information System (GIS); cloud-based email/IVR services; activity-initiated communication to relevant supervisors; flexible user-revised email/IVR surveys; multi-project status reporting; and input/output to Microsoft Project scheduling software. The paper discusses the components of the proposed framework and comments on the performance of a prototype system on multiple simultaneous projects. A case study was used to demonstrate the usefulness of the timely collected data to improve the visualization of progress status and schedule updates, as well as project control decisions. The system can also collect data about the worker-related factors (e.g., morale) on projects. The developed framework supports efficient management of multiple projects for small/medium contractors. The proposed framework facilitates efficient communication between site and head office, to help construction companies work more cost effectively within the competitive business of construction.

1 INTRODUCTION

Timely and efficient progress tracking is a key issue for project payments, early warnings, and corrective action planning. One of the biggest challenges facing construction managers is to keep track of all actions that take place on site in order to detect potential problems and to select appropriate corrective actions. Progress tracking is even much more challenging in the case of managing multiple projects, which is a common case in construction where small/medium companies get involved in many jobs at the same time. Because progress information of each project are scattered in many formats like daily site reports, minutes of meetings, and correspondences, schedule updates are often problematic and the management of multiple projects can become a nightmare, ending with delays, cost overruns, and lost business.

While the Construction Industry includes many large companies, statistics indicate that over two-thirds of construction firms in the United States have less than five employees (Halpin 2006). The majority of these small firms are specialty subcontractors working with the general contractor. For those small players, the simultaneous management of multiple projects is an everyday situation. As reported in the literature, up to 90% by value of all projects occur in the multi-project context (Payne 1995). Generally, these projects are small and do not, therefore, have the luxury of dedicated resources, but must share at least some resources with other projects.

Commercial scheduling tools can help planners produce realistic baseline schedules that are suitable for planning purposes (Gould 2005). Due to rapid growth in Information Technology (IT) (Chen and Romano 2003), many systems have recently incorporated high level of communication and collaboration tools.
Because 25% to 30% of total project work is always spent on communication and collaboration (Helbrough 1995), the surge in IT-related features undoubtedly brings great benefits to the management of projects. On the other hand, however, the core scheduling, tracking, and control functions of commercial software remained mostly unchanged over the past four decades. For example, existing software tools still do not have functions for time-cost trade-off analysis, automated tracking, or schedule optimization.

While the management of individual projects is difficult, it's even much more complicated in the case of multiple ongoing projects (Dooley et al. 2005). Commercial project management tools are not efficient to handle multiple projects, particularly when it comes to project control (Evaristo and Fenema 1999). Despite the high rate of utilization in the industry, research on the management of multiple projects is also very limited (Patanakul and Milosevic 2009). Recent work (e.g., Besikci et al. 2015) focuses on optimizing the planning and resource management before construction, and none focuses on progress tracking and control.

Among the key challenges in project control for individual and multiple projects is the inability to track and utilize sufficient progress details in an easy manner. Currently, schedules represent progress in terms of activities’ actual start and finish times, and percentage complete, while keeping the important intermediate events (slow progress, rework, acceleration, etc.) hidden in other correspondences, daily site reports, or other paper-based documents. Thus, the low level of detail in progress tracking is considered inadequate to support corrective actions or the analysis of project delays (Hegazy and Menesi 2012). Without the mid-activity events of various parties recorded on the as-built schedule, forensic analysis of project delays becomes a complex task of sifting through mountains of scattered information and then trying to understand, a long time after the fact, how the progress events affected the schedule.

To enhance current project control for multiple projects, this paper proposes a new progress-tracking framework that has three key functions: (1) improved As-Built data representation; (2) user-defined system for email and voice tracking of progress and for verifying the quality of the progress data obtained; and (3) a visual reporting system to facilitate schedule analysis and corrective action planning. Each of these is discussed in the following sections.

2 AS-BUILT DOCUMENTATION ON THE SCHEDULE

As-built documentation has mainly been a manual process that is time-consuming and error-prone (Trupp et al. 2004), thus contributing to misunderstandings, incorrect assessment of project performance, and lack of early warnings. To facilitate project control decisions, enough details are required on how the progress events of all parties have evolved. Traditionally, the activities in existing commercial scheduling software, such as MS Project and Primavera, are represented as blocks of time (Left part of Figure 1). This representation, however, does not show the mid-activity events made by the various parties. As opposed to this representation, Hegazy and Menesi (2010) presented a rich representation of mid-activity events, called Critical Path Segments (CPS), as shown in Figure 1. In the figure, activity durations are divided into daily segments that can hold progress amount or other events made by any party on the specific timing of that segment, in addition to notes, hyperlinks to related documents, and explanations. Recording (or averaging) the progress percentage on the daily segments clearly conveys information related to speed of construction (actual vs. planned) and the evolution of events, not just the final status of each activity. The daily segments also can represent the events that are caused by the owner “O”, the contractor “C”, and/or neither “N” (e.g., weather). Rework amount is also represented as a negative percentage complete recorded on the relevant time segment. Such a generic activity representation clearly shows the evolution of all as-built events and allows a more granular level of detail at the segment level, which is general enough to facilitate corrective actions and schedule analysis. Due to its rich visualization and its usefulness for project control, the CPS representation has been used in this paper.
### Representation

<table>
<thead>
<tr>
<th>Traditional</th>
<th>CPS: Mid activity events:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(% complete = 50%)</td>
<td>Interruption by owner = “O”</td>
</tr>
<tr>
<td></td>
<td>Interruption by Contractor = “C”</td>
</tr>
<tr>
<td></td>
<td>Neither (e.g., weather) = “N”</td>
</tr>
<tr>
<td></td>
<td>Acceleration = high progress value</td>
</tr>
<tr>
<td></td>
<td>Slow progress = low progress value</td>
</tr>
<tr>
<td></td>
<td>Rework = negative progress value</td>
</tr>
</tbody>
</table>

| Activity is a continuous bar of a given duration with no intermediate details |

| Activity is a chain of separate daily time segments that show the timing of intermediate events |

**Figure 1: Traditional versus CPS representation of progress events**

### 3 FRAMEWORK FOR MULTI-PROJECT PROGRESS TRACKING

Since the daily CPS details may require a large effort to manually collect data from site, this paper automates the data collection process using low-cost email and interactive voice response (IVR) tools. In the literature, many researchers examined different information technology tools for site data collection (e.g., Trupp et al. 2004; McCullouch 1997; Liu 2000; Egbu and Boterill 2002; and El-Omari and O. Moselhi 2009). Among these tools, email and voice-based systems have rapidly grown over the years as technology advances fast. Recently, the use of voice has matured and has incorporated advanced features such as voice recognition and voice commands (Sunkpho and Garret 2000; and Reinhardt and Scherer 2000). Previous work by the authors (Hegazy and Abdel-Monem 2012) used email and Interactive Voice Response (IVR) to automatically collect as-built progress details for single projects, which is extended in this paper for multiple projects.

In order to track the progress of multiple projects simultaneously, the proposed framework integrates several components (as shown in Figure 2): progress database; Geographic Information System (GIS); dynamic survey creation; communication tools; visual location tracking; and reporting for single/multiple projects. These are as follows:

1. Database: at the core of the framework is a relational Microsoft Access database that includes information about projects (location, start date, finish date, etc.), company accounts (email address, IVR account, etc.), personnel (Supervisors’ emails and phones as well as the contacts of the person(s) responsible for answering any requests for information), activities’ daily tracking details (progress percentage, delay reasons, quality control issues, photos, attachments, etc.), and activities’ digital drawing files;

2. Geographic Information System (GIS): GIS has been incorporated so that all projects can be represented visually on a map system. Such visual representation facilitates the management and tracking;
Figure 2: Multi-Project Progress-Tracking Framework

3. Survey Creation Tool: To collect progress details or any type of information, a survey creation tool (Figure 3) was developed to allow the user to easily customize pre-set questions an email or a voice (phone) survey. Survey questions are of two categories: typical progress queries (progress amount; events by different parties and their reasons; quality control/safety issues; and request for information); and other generic questions to be used for custom surveys (e.g., Yes/No; Multiple choice; and Comment message).

Figure 3: Add/Edit Interactive Voice Response (IVR) Survey.
The resulting custom IVR or email survey is dynamic in the sense that the sequence of questions is changed depending on the user's answer to a previous question (e.g., progress or delay). The customized surveys are saved in the system as templates to be used for tracking any project; 4. Communication tools: An IVR Cloud-Service, Ifbyphone server (Ifbyphone 2012), is used to collect progress details by phone from multiple participants simultaneously, according to a selected IVR survey form. It has high quality voice, unlimited parallel calls, customizability, and flexible send/receive features. For email, Jotform cloud server (Jotform 2014) is used to send emails to multiple supervisors, according to any selected email form; 5. Scheduling tool: Microsoft Project scheduling tool has been used to prepare projects for progress tracking, including the activities, relationships, and costs; 6. Work location visualization tool: In addition to IVR and email communications, better visualization of progress location on related drawing files enables project managers to better visualize the evolution of progress. In the proposed framework, the activity is first associated with an appropriate CAD or image file that refers to the location of that activity. This file is always attached to the email survey form for progress tracking to allow supervisors to indicate the elements that have been completed to date and to record pictures, sound, etc.; and 7. Custom reporting tool: provides a log of all communications, an updated schedule, CPS progress report, and overall summary of projects’ progress.

4 PROTOTYPE AND CASE STUDY APPLICATION

The developed system has been applied to a simple case study to track five projects simultaneously. The progress tracking process is shown in Figure 4. The main interface (top of Figure 4) shows the list of projects, the GIS map, and the setup options for company, projects, personnel, and surveys. The automated tracking process starts by the system identifying the running projects and the eligible activities for progress tracking. It then identifies their relevant supervisors and the predefined survey forms. The data collection process is all cloud-based to retrieve supervisor responses, verify responses, and update the schedule.

Project setup can be done through importing projects and all related information from MS Project as well as edit/add the date and time for progress tracking. Personnel can be added to the company personnel list of the supervisors who will respond to progress information requests and the persons who will respond to any request for information (RFIs).

To demonstrate the automated progress tracking process. Project 1 activities are used as an example. The project is expected to take 16 working days (22 days including weekends), starting from May 7th, 2014 and finish on May 28th, 2014. The developed system enables project activities to automatically request progress from their relevant supervisors, and all received information will be legibly visualized on the daily segments for each activity. The as-built tracking, as it applies to Project 1 summarized in Figure 4. Detailed step-by-step process is as follows:

**Identify Progressing Projects:** for each project, the system checks tracking date, tracking time, project % complete, project start and project finish. If current date is larger than or equal tracking date then check if the project's percentage complete is less than 100% then starting progress tracking process for that project. **Identify progressing activities:** for each of progressing project (e.g., Project 1 in this case study) the process starts by automatically identifying the activities that are planned to start (their predecessors are completed), or continuing on the current progress date. In the case study, activities 1 and 2 are the ones to start on the first day of the project;
**Identify progressing activities:** For each progressing project (e.g., Project 1 in this case study), the system automatically identify the activities that are planned to start (their predecessors are completed) or continuing on the current progress date. In the case study, activities 1 and 2 of project 1 were planned to start on the first day of the project;

![Diagram of multi-project progress tracking process]

**Figure 4:** Multi-project progress tracking process
Retrieve the communication list and IVR/email surveys: Upon identifying the eligible activities, the system retrieves the pre-defined project communication list (middle columns of Figure 5) and loads the supervisor's contacts, email surveys, the index number to the related IVR surveys, and visual files of the current eligible activities;

![Figure 5: Assign IVR/email surveys, and visual files](image)

Send Email/IVR progress request: In this step, according to the preset preference of each supervisor, the system automatically sends an email or a request to the IVR cloud-based service to initiates phone calls to the selected supervisors;

Read responses: Once the supervisor(s) reply to the phone calls or email requests, their responses, and any attachments, are collected by the cloud-based service and email system, which send these responses as email files to the project email account. The system then loads the latest email responses, saves the information into the project database along with other documents such as voice notes;

Update project information: Upon reading the new as-built information, the system updates the project schedule and saves all site events related to each activity, with any attached file(s) in the log of communications. In addition, two important reports are generated: an automated update to the MS Project file of the project with the cumulative percentage complete for each activity adjusted according to latest information; and a detailed CPS report of the schedule with the evolution of all as-built events, with all details shown as comments on their associated activities days. All visual files received with supervisor comments show the progress evolution for each activity. Such visual progress reports greatly facilitate understanding progress details, and facilitate decision makers' decisions. An example of a multi-project status update is shown in Figure 6 with the detailed CPS report of a sample project. The summery status of each project is also shown with color-coding to highlight the projects that have issues or require user attention; and
Respond to RFIs: After updating the project schedule with received information, the system automatically checks if there are any requests for information (RFI), quality control issues, or safety issues. Accordingly, the system automatically forwards the RFI emails/voice message to the responsible person’s email/phone predefined in the communication list. The answer to this RFI is then sent back automatically to the initiating supervisor.

5 CONCLUDING REMARKS

This paper proposed enhancements to the visual representation of a schedule, using time segments, to efficiently use the schedule as a decision support tool for project control. The proposed representation is coupled with an automated framework to legibly document full as-built events of multiple simultaneous projects directly on the schedule. The framework can accurately document all daily as-built detail using email and Interactive-Voice-Response (IVR) technologies. In addition, it allows supervisors to mark the elements accomplished for each activity, along with their location on digital plans. The visual progress files indicate the evolution of the progress of the activities, which helps project participants easily form a complete picture of the finished work to date. All the as-built details are thus saved automatically in a communication log and are attached to the relevant daily segments for each activity. The system has been uniquely designed for bidirectional voice/Email communication. It allows activity supervisors to initiate calls/Emails for progress updates; and allows eligible activities on the office server to automatically initiate contacts. In addition, the system automatically communicates any requests for information, and their responses, to the appropriate parties. The system’s flexible feature of allowing custom site surveys to be generated and communicated using email and IVR are currently being utilized to collect a new layer of site information related to workers’ stress level and morale. This information can be used to forecast realistic estimates of project completion time and cost, and can trigger warning signs. A prototype system has been applied to a simple case study to demonstrate its benefits. The paper contributes to improving multi-project tracking and control through enhanced bidirectional communication between site and head office to help construction firms collect timely and accurate as-built information for decision making.
6 REFERENCES


MODELING SUBWAY RISK ASSESSMENT USING FUZZY LOGIC

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\textsuperscript{2} monabuhamd@yahoo.com

Abstract: According to the Canadian Urban Transit Association (CUTA 2012), 140 Billion CAD is required to maintain, rehabilitate, and replace subway infrastructure between the years 2010 and 2014. However, transit authorities are faced by a fund scarcity problem which is hindering them from addressing all the network rehabilitation requirements in an efficient manner. The solution according to the 2013 America’s infrastructure report card is to adopt a comprehensive asset management system to maximize investments. This research develops a risk assessment model for subway stations. Probability of failure of different subway elements are developed using Weibull reliability curves. Consequences of failure are measured against three predefined attributes these are financial, operational, and social impacts of failure. Finally, a criticality index measures the respective station criticality derived from its particular size, location in proximity to different attraction types, and, nature of use. A qualitative approach with the help of expert judgment is adopted to integrate the indices using the Fuzzy Analytic Network Process with application to Fuzzy Preference Programming. The three models are integrated into a fuzzy rule based risk index model to compute element and station expected risk index. The output of the model is a comprehensive risk index that can be used to prioritize elements across stations for rehabilitation. The model is verified through an actual case study comparing elements across six stations and computing probability of failure, consequence of failure, criticality and the risk index. This paper illustrates the general framework of the proposed methodology which will help decision makers prioritize stations and elements across stations for rehabilitation based upon their risk index.

1 INTRODUCTION

Subway systems failure is associated with consequences like multiple fatalities or injuries, partial or complete loss of service, major traffic disruptions, and, different socio-economic effects. A subway network is composed of diverse components and systems operating simultaneously to deliver the required service. The component diversity causes a level of complexity which complicates the process of assessing and maintaining the network at the desired level of service. In addition, the problem of fund scarcity faced by most public authorities converts it into a tough task. According to (Semaan 2011), “Société de Transport de Montréal” estimated a required amount of 5.1 Billion CAD for maintenance of its subway system for the next ten years. Different systems operating in a subway network compete for rehabilitation priorities while having various consequences of failure and multiple failure modes which turns the prioritization process into a tough task. Moreover, elements operating in a subway network pose diverse rehabilitation and maintenance needs based on their role in the network hierarchy and operation. The current method used for prioritizing subway stations is visual inspection. Hastak and Baim (2001) stated that in the subway stations context, inspections are used to identify the needed assessment for rehabilitation work. However, since no federal or state regulatory is used for inspections; the development and the implementation of the inspection standards in mainly the transit management responsibility
(Russel et al. 1997). This research aims at developing a risk assessment model on a network level based upon the visual inspection reports subway structural elements. This is a four-phased model in which sub-models for measuring the components of a risk equation, namely probability and consequence of failure, are first developed. The paper proceeds to suggest an addition to the classical risk equation to be better suited for the case of subway networks. The risk equation components are then combined using the fuzzy inference system.

The following section presents a background for the current practices adopted in addition to the available researches. The background is followed by the methodology section in which the developed models are explained in details. Finally, a case study is presented to demonstrate how the model works and its validation.

1.1 Background

1.1.1 Subway Assessment Efforts

The literature demonstrates research and industrial efforts to assess the condition of subway stations and rank stations for maintenance and rehabilitation. California transit authority developed an evaluation system for stations and ranked them on a scale from excellent to poor based on predefined criteria combined using a weighted average technique (Abu-Mallouh 1999). Whereas, Metropolitan Transit Authority of New York Transit developed a ranking system for condition assessment by assigning points to different functional factors (Abu-Mallouh 1999). London Transit developed the Key Performance Indicator to evaluate the performance of stations from its customers’ point of view using a direct evaluation of customer satisfaction through surveys and interviews. The Paris Rapid Transit Authority worked on developing a selection procedure for stations in need of rehabilitation, the model used a seven functional criteria selection procedure.

Subways domain was shyly researched in academia with only a handful models assessing subway stations. Abu-Mallouh (1999) developed a model to optimize the number of stations accommodated within a given capital program for full and partial rehabilitation. Semaan (2009) developed a condition assessment model to diagnose specific subway stations and assess their conditions using an index (0-10). In a corresponding effort, (Farran 2006) developed a model to address life cycle costing for a single infrastructure element with probabilistic and condition rating approach for condition state. And finally, (Semaan 2011) developed a model to evaluate structural performance of different components in a subway network using performance curves for components and the entire network using reliability-based cumulative Weibull function.

It is noted that the reported transit management practices adopted a qualitative functional perspective to inspect and prioritize subway stations for rehabilitation. On the other hand, the academia focused mainly on structural quantitative models through condition assessment and deterioration models. While these two perspectives of assessment are vital; none of the reported literature integrates the functional and structural aspects of a subway station into a single model.

1.2 Methodology

The developed methodology aims at combining structural and functional perspectives of a subway network into a single risk assessment model. The structural integrity is assessed through a probability of failure sub-model whereas the functional perspective is assessed through the consequence of failure and criticality index sub-models. The output of the three sub-models is then integrated into a risk index model using 30 rules extracted from experts’ knowledge. This section starts by presenting the network hierarchy used through the analysis and proceeds with the sub-models and model development.

1.2.1 Subway Hierarchy

A generic subway network hierarchy is presented in Figure 1. A typical subway line is composed of a number of station buildings. They operate by means of their composing systems such as electrical, mechanical, security and communication, and, structural. This research focuses only on the operational
risk failure derived from the structural systems in a network. Therefore, the structural system is identified as a composition of stations, tunnels and auxiliary structures. These are composed of the elements located at the lowest level of the hierarchy. This hierarchy will be the basis of calculations through model development and its associated sub-models.

1.2.2 Probability of Failure Sub-Model

The Probability of Failure (PoF) sub-model builds upon the performance model developed by (Semaan 2011). Semaan (2011) used reliability-based cumulative Weibull function to evaluate the structural performance of different components in a subway network and develop performance curves for subway components and the entire network. Reliability-based cumulative Weibull function takes a probabilistic approach that yields a reliability index, which is the inverse of the PoF. Therefore, PoF can be estimated as the inverse of the reliability and is shown in Equation [1]

\[ \text{PoF}_f = 1 - R(t) = 1 - e^{-\left(\frac{t-\delta}{\tau}\right)^\alpha} \]

Where,
\[ R (T) = \text{Reliability}, t = \text{Time}, \delta = \text{deterioration parameter}, \alpha = \text{location parameter}, \tau = \text{scale parameter}, \delta = \text{and} \ e = \text{exponential}. \]

Different system configuration requires different calculations for PoF values. The series-parallel reliability technique (Hillier and Lieberman 1972) entitles that any system is composed of components outlined in parallel, in series, or, in a combination of both. A system in parallel is a redundant system where components work simultaneously; hence, it can operate even if one of its components fails. This is the logic used to calculate the different PoF values. A subway network is composed of lines, stations, and auxiliary structures, the PoF is calculated for each system based on the configuration shown in Figure 2.
Station System (STA): In a subway station system, the slab and stairs are redundant systems and can be considered as a parallel system. The wall system is a series system in which if any wall “fails” to perform, the whole station becomes unsafe, and thus does not perform. PoF of a station system can be computed using equation [2]

\[ P_{STA} = 1 - \prod_{i=1}^{n}(1 - P_{STEi}P_{STII}) \left( 1 - P_{STIII} \right) \left( 1 - P_{WRI} \right) \left( 1 - P_{WELi} \right) \]

Where,
- \( P_{STAi} \) = Probability of station j failure,
- \( P_{STEI} \) = Probability of exterior stairs failure,
- \( P_{STII} \) = Probability of interior stairs failure,
- \( P_{STIII} \) = Probability of external slab failure,
- \( P_{STIV} \) = Probability of internal slab failure,
- \( P_{WRI} \) = Probability of internal wall failure,
- \( P_{WELi} \) = Probability of external wall failure, and, \( i = 1, 2 \ldots n \) = station floor.

Tunnel System (TUN): A tunnel system operates in series in which it fails if any of its components fail, therefore, PoF values are calculated using equation [3]

\[ P_{TUN} = 1 - \left( 1 - P_D \right) \left( 1 - P_w \right) \left( 1 - P_s \right) \]

Where;
- \( P_{TUN} \) = Probability of tunnel failure,
- \( P_D \) = Probability of Dome failure,
- \( P_w \) = Probability of wall failure,
- \( P_s \) = Probability of slab failure.

Auxiliary structures System (AS): These systems operate in series in which it fails if any of its components fail, therefore, PoF are calculated using equation [4]

\[ P_{Aux St} = 1 - (1 - P_{w}) \left( 1 - P_{TS} \right) \left( 1 - P_{BS} \right) \]

Where;
- \( P_{Aux St} \) = Probability of auxiliary structure failure,
- \( P_{w} \) = Probability of walls failure,
- \( P_{TS} \) = Probability of top slab failure, and, \( P_{BS} \) = Probability of bottom slab failure.

A Line System: is composed of all stations, tunnel, and auxiliary structure systems operating on the line. These systems together operate in series whereas; the composition of each system operates in parallel. The stations systems are redundant system, they operate in parallel and will fail to operate when all stations in a line fail. Likewise, a line failure occurs when all tunnels on the line fail to operate. Same applies for the auxiliary structure, operating is parallel in a line systems. On the other hand, the three systems operate in series. If any of the systems fails entirely that means the subway line is in a failure status and can no more function effectively. The line hierarchy is shown in Figure 2 (a) and is computed using equation [5]
Where:

\[ P_{\text{line}_i} = 1 - \left[ \left( 1 - \prod_{n}^{i=2} P_{\text{STA}_i} \right) \left( 1 - \prod_{n}^{i=2} P_{\text{TUN}_i} \right) \left( 1 - \prod_{n}^{i=2} P_{\text{AUX}_i} \right) \right] \]

**Subway Network:** A subway network is composed of all the lines operating in the network. It can be concluded that the lines in a network operate in parallel. Hence, the network only fails when all the lines operating in the network fail. This can be computed using equation [6] and concluded from Figure 2 (b).

\[ P_{\text{Net}} = \prod_{n}^{i=1} P_{\text{line}_i} \]

Where:

\( P_{\text{Net}} = \) Probability of network failure, \( P_{\text{line}_i} = \) Probability of line failure.

![Network Hierarchy](image1)

![Line Hierarchy](image2)

**Figure 2:** Schematic diagrams for network and line hierarchy.

### 1.2.3 Consequences of Failure Sub-Model

A generic risk management system should identify PoF and Consequences of Failure (CoF) to be combined later to produce a representative risk index. A formal review of failure consequences diverts attention away from maintenance tasks having little or no effects and focuses on maintenance tasks that are more effective. This ensures the maintenance spending is optimized and guarantees the inherent reliability of equipment is enhanced (Gonzalez et al. 2006). Indirect impacts of failure of a subway station include, but are not limited to, service disruption, passenger delay, loss of reputation, loss of revenue in addition to other socio-economic impacts reflected as the extent to which the failure affects adjacent services and customers benefiting from the service and the ease of providing an alternative service. However, only a fraction of the expected CoF can be monetized whereas most of the expected indirect CoF are difficult to monetize and measure (Muhlbauer and W Kent. 2004). One way to overcome the difficulty inherent in these calculations is measuring CoF using indices, which facilitates comparing between expected CoF and highlights areas of higher failure impacts.

This research determined factors affecting CoF calculations in terms of tangible and intangible impacts using the Triple Bottom line approach. This revealed a wide spectrum of consequences occurring at element and station levels. A station is composed of a number of elements operating simultaneously; based on the location of the element and its nature, the element failure might cause total, partial, or no station closure. This suggests CoF are element-dependent, Figure 3 outlines the CoF model. Based on
literature and expert opinion, CoF are broadly grouped into financial, social, and, operational impacts of failure. It is noted that some factors could fall under two different perspectives simultaneously.

\[
CF_i = C_{wi} \times S_{si}
\]

**Figure 3: Consequences of failure model outline.**

The defined impacts of failure along different categories are interdependent; hence, the effect of a single impact cannot be measured independently without considering how other impacts affect and are affected by its occurrence. Therefore, Fuzzy Analytical Network Process (FANP) is selected to obtain relative weights of these factors. FANP addresses the interdependency inherent in the relation between these factors and accounts for the uncertainty caused by using expert opinions. The reader is referred to (Abouhamad and Zayed 2013a) for further model details. For each subway element, the consequence of failure index \( (C_{OF_i}) \) is computed using equation [7]

\[ [7] C_{OF_i} = C_{Wi} \times S_{Si} \]

Where;

\( C_{OF_i} = \) Consequence of Failure Index, \( C_{Wi} = \) Criteria weight obtained using questionnaire survey and FANP, \( S_{Si} = \) Severity score calculated from network data and inspection reports, \( i \) = elements operating per station.

Financial impacts are twofold; repair/replacement cost defined as the direct cost of repair or replacement and loss of revenue defined as the profit loss due to service interruption. Operational impacts is measured in terms of ease of providing alternative and time to repair. The ease of providing alternative is
measured by means of available bus stops and reroutes in case of no service whereas, the time to repair is the time required to return the component to a full functioning state. The social impacts are measured by user traffic frequency, maximum allowable interruptions per year per station and the degree of service interruption whether partial, total or no interruption at all.

1.2.4 Criticality Index Model

This research introduces criticality for the scope of subway networks as the Criticality index. The subway network breakdown structure is assessed differently, the element is selected such that its criticality level is dominant and diverse enough to prevail over other network components. Consequently, subway stations are selected to be the focus of criticality analysis. Systems and subsystems share the same major role of delivering the service; however, their criticality is derived from their respective locations in stations that vary in criticality according to several factors. From this discussion, the concept of criticality propagation is introduced; criticality level propagates upwards and downwards in a hierarchy of a subway network such that they acquire the same criticality level as stations where they operate. Similarly, a line criticality is computed as the sum of criticality indices of stations existing on this line. For interconnecting systems such as tunnels and auxiliary structures, CR is computed as the higher index of the two corresponding stations through which this system connects.

Factors contributing to station CR are identified through historical data, expert opinion and by consulting current structure and map of several subway networks. Station criticality is a complex decision based on different attributes defined as; number of lines, number of levels, station use whether end or intermodal, and station proximity to different attraction locations. CR factors defining a station differ in significance, thus, a weight component is introduced to the CR equation to accommodate the subjective variability in attributes weight. Attribute scores are computed based upon the network under examination and individual station information. Station criticality is defined in terms of three main factors and seven sub factors or attributes. Amongst attributes identified, the station location is the most diverse. For further details about this model, the reader is referred to (Abouhamad and Zayed 2013b). Station criticality attributes are strongly connected, hence, cause and effects loops flow between them. Therefore, FANP with application to Fuzzy Preference Programming is used to compute the attributes weight. The Criticality Index model is outlined in Figure 4.

![Criticality Index Model Diagram](image)

**Figure 4:** Criticality Index model outline.

Criticality Index per station \( C_{\text{R}} \) is computed using equation [8]

\[
C_{\text{R}} = \sum_{i=1}^{n} C_{\text{R}w_i} \times C_{\text{R}s_i}
\]

[8]
Where; $C_R$= Criticality Index per station, $c_{RW}=$ Criticality attributes weights calculated using questionnaire surveys and FANP, $c_{RS} =$ Criticality scores calculated using current network data, and $i=1,2, \ldots ,n$, $n=$ criticality attributes

1.2.5 Risk Index Model

Risk by definition is a combination of PoF and the severity of adverse effects (Lowrance 1967). When studying the risk level, it should be noted that elements with similar PoF might show wide variation in terms of consequences of failure and vice versa. In addition, critical elements with high consequences of failure usually compose a smaller portion of the overall network. Accordingly, focusing only on these elements would result in an unbalanced management practices since unexpected failures may occur in less-critical elements, which constitute the majority of the network. Furthermore, a comprehensive risk assessment should consider the relative importance of different components and systems of a subway network. A criticality index is introduced to measure the relative importance and consider it in the risk index development. Consequently, a new term is added to the risk equation, named as the criticality index ($C_R$). Several methods exist to compute the risk index value, ranging from simple straightforward multiplication to more sophisticated computation of risk matrix.

The Fuzzy Rule Based (FRB) technique was selected to compute the risk index in this research. This method permits users to integrate their experience into the decision support system through using “if-then” rules. Fuzzy sets allow for a more precise presentation of element’s membership particularly when it is difficult to determine the boundary of the set as crisp values. An FRB consists of a set of if-then rules defined over fuzzy sets (Masulli et al. 2007). The rules are usually created using “expert knowledge” (Castillo et al. 2008). The relationship between different fuzzy variables is represented by if-then rules of the form “If antecedent…… Then Consequent”. In cases where the antecedent has more than one part, the fuzzy operator is applied to obtain one number representing the consequence for the antecedents of that rule. This is the number used afterwards to obtain the output function. The Mamdani fuzzy inference system (Mamdani and Assilian 1975) uses the min-max composition as defined in equation [9]

$$\mu_{ck}(z) = \max\{\min[\mu_{Ak}(input(x)),\mu_{Bk}(input(y))]|k\}$$

Where;

$\mu_{ck}, \mu_{Ak}, \mu_{Bk}$ are the membership functions for output “z” for rule “k”, $x$ and $y$ are inputs.

Whereas in our case, the antecedent and the consequent are fuzzy propositions. The proposed model is performed using MATLAB® fuzzy logic toolbox. Mamdani algorithm based on experts’ knowledge is used to construct the rule base. The model combines PoF, CoF, and $C_R$ expressed as triangular membership functions. The min-max composition is used whereas the defuzzification was done using the Centre of Area method. The fuzzy risk equation solves equation [10] and is shown in equation [11]

$$\text{Risk Index} = \text{Probability of Failure} \times \text{Consequence of Failure} \times \text{Criticality Index}$$

$$R_i: \text{IF PoF is } X_i \text{ and CoF is } Y_i \text{ and } C_R \text{ is } Z_i \text{ then Risk is } L_i$$

Where, $i= 1, 2, 3 \ldots ,k$ , $X_i, Y_i, Z_i,$ and $L_i$ are linguistic constants as defined in model, $k =$ number of rules
The threshold for risk values are set based on the maximum allowable PoF and CoF values. This eliminates the major drawback of a risk matrix in differentiating between the two extreme cases of high PoF with low CoF and vice versa. It also ensures the highest priority is given to elements with most emerging rehabilitation need whether derived from high PoF or high CoF. Based upon feedback from experts, CoF is categorized into three levels based upon the combined effect of failure on financial, social, and operational levels. Criticality serves to define stations into normal stations with moderate importance and critical stations with higher criticality. All data incorporated in the risk index calculations is reserved for a detailed analysis of each station. The membership functions were selected based on literature review and unstructured interview with subway experts. A set of 30 rules (5 rules for PoF, 3 for CoF and 2 for CR) is generated to develop the Risk Index.

1.3 Case Study and Model Implementation

An actual case study was conducted on a sub network in Montreal metro to validate the model and proof its robustness. Montreal subway is one of the oldest networks in North America, with 68 stations spreading on four lines and covering the north, east, and centre of the Island of Montreal. Six stations (SEG 1 to SEG 6) on three different lines are analysed in the model with one station being the interconnecting station. SEG 1 to SEG 3 fall on the same line given the name Line A, SEG 4 and SEG5 both fall on the second line B. SEG 6 falls on line C whereas, SEG 2 is the interconnecting station for the three lines. Stations were selected from literature review (Semaan 2011) and based upon availability of inspection reports for different indices calculations.

1.3.1 Sub-Models output

PoF is calculated using year 2014 as the base for calculations. The subway system hierarchy together with the equations presented earlier were used to compute PoF values for elements at the lowest level of the hierarchy then aggregated upwards to compute the integrated PoF values for stations, tunnels and auxiliary structures, identified as a segment (SEG). Sample output PoF values are illustrated in Figure 5.

A questionnaire survey was launched to gather the required data for CoF and Criticality models' development. The questionnaire conducted pairwise comparisons between attributes, sub-attributes and goals for each of the two sub-models. It also contained open ended questions for experts to provide their opinion on model development and suggest any required modifications. The output of the questionnaires are local and global weights for attributes in CoF and CR models. Further details about the resultant weights can be found in (Abouhamad and Zayed 2014). FANP calculations are done using MATLAB® software and FPP as a prioritization tool.

Scores for CoF attributes were obtained from literature review (Farran, 2006) and current information of Montreal subway. Sample calculations for CoF index are seen in Figure 5. As stated earlier, CoF are calculated for elements at the lower level of the hierarchy then aggregated upwards. It is evident that CoF are highly affected by PoF value for each system since all the factors accounted for in the model are directly proportional with PoF value. Calculations for CR were done for the entire Montréal subway network (68 stations). Two stations with maximum and minimum criticality levels were set as thresholds for normalizing the index for the six stations under study. Criticality index is defined as the functional role a station plays and thus is calculated on stations level. A tunnel criticality index is taken as the higher value for the two connecting stations, while auxiliary structures acquire the criticality index of corresponding subway station. This explains the constant CR value per segment as seen in Figure 5. Unlike PoF and CoF where values are upwards aggregated, for an element level analysis, CR values for a given element are the same as the station where it operates.
1.3.2 Risk Index Model

The output of the preceding three submodels is used as the input for the risk index model. Using rules derived from experts as seen in Figure 5, each submodel is assigned a value based on the degree to which it belongs to its membership function. The risk Index is calculated on the elements level where PoF and CoF are calculated. The series-parallel technique is then used to aggregate the risk index to higher levels of the hierarchy based upon the scope of analysis. Figure 5 demonstrates the expected risk index calculated per elements and aggregated upwards per segments to the second level of the network hierarchy. Figure 6 shows a sample rules configuration used to develop the model. Figure 7 illustrates the resultant risk surface.

The station in SEG4 has the highest risk index. This is the complied effect of a high PoF and CR values despite somehow moderate expected CoF. It is noticed that the tunnel and auxiliary structure in the same segment share the same CR level yet their risk index is low. This is clearly due to the low probability of operational failure of the two elements derived from low PoF and CR. This resultant risk value is only available through a fuzzy risk index where the CR affects the risk index only in case of an existent risk value. The station in SEG 6 comes next with an expected risk index of 0.5. This risk index is mainly affected by the moderately high PoF in spite of low CoF and CR values. This also is attributed to the fuzzy risk model which triggers the expected risk index value based on interrelated criteria just like a human expert. The risk index for the remainder elements is considered within acceptable range since they all have low combinations of PoF, CoF and CR values.
1.4 Conclusion

This paper presented an overview of a network level risk assessment model. The risk index is developed using three sub-models and the fuzzy inference engine to incorporate experts’ knowledge. The illustrated case study verifies the model can be used for ranking element in a subway hierarchy based upon its risk index. Furthermore, the sub-models can be used as standalone models for ranking stations for rehabilitations based on one perspective (Structural or operational) only rather than the combined risk effect. The use of fuzzy logic facilitates incorporating experts’ knowledge into the model to account for the data scarcity and problem complexity. In addition, it overcomes the shortcomings of the conventional risk assessment techniques. The presented model is novel and expected to be of great benefits to academia, since the topic is poorly researched as well as industry, since the model is easy to use and straightforward.

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MULTI-STAGE BIDDING FOR CONSTRUCTION CONTRACTS: A GAME THEORY APPROACH

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Abstract: In the construction industry, auctions have long been used as a method for allocating contracts. Not addressed in the literature (engineering or economics) is the fact that most, if not all, large jobs are awarded to a general contractor who in turn subcontracts most, if not all, actual engineering services. Optimal bidding strategies in this setting require the general contractor to not only account for the optimal bidding strategies of rivals, but subcontractors as well. Because the true cost of construction is not known until after the completion of the contract, adverse selection occurs when the winner of the contract is the one that most has underestimated the true cost. Due to the multi-stage bidding environment, adverse selection may be compounded. Therefore, not accounting for the potential for adverse selection by bidders may result in requested change orders by the general and subcontractors or lower quality services. Either state ultimately results in an adversarial relationship between the subcontractor and general contractor, and the client as well. This paper uses game theory to determine to what extent the multi-stage aspects of large construction contract bidding may contribute to inefficient allocation of contracts. This should better help in creating an efficient and effective contracting environment that result in less conflicts, claims and disputes for all the associated stakeholders.

1 INTRODUCTION

Construction has long history since the beginning of human civilization. A great example is the Egyptian pyramids which had been constructed in 2600 before Christ. Nowadays, construction works are an integral part of everyone’s daily life. The construction industry is not only important for its final product, but also provides a numerous job opportunities. Therefore, understanding the basic processes within the construction industry is essential for contractors to maintain a competitive position within the market, and also for nations’ economy to operate effectively and efficiently.

According to Kuluanga (2001), the construction industry incorporated simple and straightforward processes in the early years. However, the construction industry is getting more complex and...
sophisticated in today’s world. Nowadays, one of the complicated areas in the construction industry is the contract allocation process. Competitive bidding has long been used as a method for allocating contracts in the construction industry (Seydel 2003). In the public sector, competitive bidding has been considered as a legal requirement. Furthermore, it is argued that one of the main factors that have a great effect on the success of construction projects is the firms’ bidding decisions.

Generally, in the construction bidding process, submitted bids are evaluated technically, and then the technically approved bids are evaluated financially or based on the submitted price. For the financial evaluation of the submitted bids, there are many methods such as the low bid method, the second lowest bid method, the average bid method, and the below average bid method. According to Ioannou and Awwad (2010), the low bid method is the most common method for construction contracts in the US. In the low bid method, which is applied in this paper, the contract is awarded the contractor who is technically approved, and has the lowest price among the submitted bids. Accordingly, the winning contractor is expected to construct the project based on the agreed price, schedule, and to provide, at least, the required level of quality.

The main difference between construction projects and other types of projects is the high level of uncertainty of events that may occur during the project’s life cycle. For instance, contractors must contend with inevitable and unforeseen input price increases, Labor issues, and construction conditions that must be accounted for when developing a bid for a long term project. Therefore, at time of submitting bids, contractors cannot know with certainty the actual project construction cost. As such, the construction industry relies on estimates of the project cost based on their current information, past experience, and utilizing methods such as RS means. The RS method is a construction cost estimation database based on historical data, that is used by professional estimators for calculating project cost, based on its type and region, prior to beginning of construction. Thus, in construction bidding, contractors, who underestimated project cost and bid less than the realized project construction cost, face the problem of adverse selection. Adverse selection results in what is known as the “winner’s curse”.

2 GOALS AND OBJECTIVES

The goal of this paper is to identify the degree of the winner’s curse in two common construction bidding settings. The authors aim to compare the construction bidding environments of “single-stage bidding vs. multi-stage bidding”. Furthermore, this research would provide an effective tool for contractors to mitigate the winner’s curse.

3 BACKGROUND INFORMATION

3.1 Construction Bidding and Common Value Auctions

Historically, auctions have been used over thousands of years to sell numerous types of goods and services. In our today’s world, auctions are of great practical importance because the value of goods being exchanged in auctions, in both public and private sectors, is relatively high (Kagel and Levin 2002). From the perspective of game theory, auctions are considered one of the most outstanding applications of games with incomplete information, because participants in auctions have different private information which is the main factor affecting their strategic behavior.

Generally, the same logic of auctions applies to construction bidding. Basically, contractors have two sources of incomplete information at time of submitting their bids; (i) actual project construction cost, and (ii) their competitors’ estimates of the project construction cost. In auction theory, auctions are classified into two types; (i) private value auctions, and (ii) common value auctions. In private value auction, the bidders know their own value of the item being auctioned with certainty, but they do not know other bidders’ values. On the other hand, in common value auction, the item being auctioned has the same value to everyone, but none of the bidders know this value with certainty. Each bidder generates different estimate about the true value, which is generally being observed after the auction is over (Kagel and Levin 2002).
According to Dyer and Kagel (1996), construction bidding is considered as a common value auction. This is due to the unknown true cost of construction projects which cannot be realized with certainty until completion of the project. Furthermore, the auction theory also refers to bidding for construction contracts as a reverse auction, where bidder usually wins the project, based on the low bid method, when they have the lowest estimate of the project cost.

3.2 The Winner's Curse

According to Kagel and Levin (2002), the story of the winner’s curse was firstly introduced by Capen, Clapp, and Campbell (1971). The three petroleum engineers claimed that oil companies had suffered unexpectedly low rates of return in early outer continental shelf (OCS) oil lease auctions. Thereafter, many researchers have claimed the same problem of the winner’s curse, such as in book publication rights (Dessauer 1981), in corporate takeover battles (Roll 1986), and in real-estate auctions (Ashenfelter and Genesore 1992).

The winner’s curse can be described in many ways. In construction industry, the winner’s curse can be defined as the situation when the bidder, with the most optimistic information and project cost estimate, wins the project contract based on a submitted bid less than the true project construction cost. Such a bidder, who fails to take the winner’s curse problem into account, ends up with negative or below normal profits.

According to Dyer and Kagel (1996), in construction bidding, US general contractors usually utilize one of the following three mechanisms to avoid the winner’s curse:

- One mechanism is that most states’ law allows low bidders to withdraw their bids for public projects in case of arithmetic errors, and without being subjected to penalty. The meaning of arithmetic errors is broad and not well defined, and contractors can benefit from this to escape from the winner’s curse by withdrawal of their submitted low bids.
- Second mechanism is depending on the relationship between general contractors and sub-contractors. General contractors can bid too high with the assistance of their sub-contractors to cover that. Usually, sub-contractors assist their general contractors in that in order to get the job, and for the usual long term work relationship between general contractors and sub-contractors.
- Third mechanism to avoid the winner’s curse is through change orders. Change orders refer to situations in which clients or owners adjust the original scope of construction of the project after signing the contract. Usually, the price of a change order is established through negotiations between associated stakeholders. Through tough negotiations, general contractor, who underbid a project, can recover at least his losses, and in some instances, make some profit.

Generally, the aforementioned mechanisms are considered ineffective, especially the third mechanism of change orders which is considered ineffective due to its many disadvantages such as the resulted adversarial between the sub-contractor and general contractor, and the client as well, and its potential legal costs. Therefore, in order to avoid the winner’s curse problem, and due to the relatively ineffectiveness of the aforementioned mechanisms, contractors must carefully consider all factors while preparing their bids such as market factors as location of the project, number of competitors, and time, and project factors as its size, type and scope. Being the case, the following section provides the contractors with guidelines in order to obtain the optimal strategic bid to submit and avoid the winner's curse.

3.3 The Symmetric Risk Neutral Nash Equilibrium (SRNNE) Bid Function

From past research in auction theory, Wilson (1977) developed the first Nash equilibrium solution for first price sealed-bid common value auctions. Thereafter, Dyer et al. (1989) presented the symmetric risk neutral Nash equilibrium bid function (SRNNE) for a sealed-bid first price common value auctions. Furthermore, Dyer et al. (1989) utilized this optimal bid function to analyze a series of laboratory sealed-bid common value auctions, in which bidders were competing for the right to supply an item of unknown
cost such as construction contracts. Dyer et al. (1989) focused primarily on analyzing and comparing the behavior of experienced executives in the construction industry with inexperienced students.

According to Dyer et al. (1989), it was found that both inexperienced students and experienced executives were almost similar in suffering from the winner’s curse. Furthermore, it was concluded that the use of SRNNE optimal bid function guarantee that bidders would not suffer the winner’s curse problem, subject to winning the project contract.

As aforementioned, the actual cost of construction project \( C \), is unknown at the time of submitting bids. Therefore, each contractor \( (i) \) has a different estimate of the project cost. Generally, the winner of the construction project contract expect to earn a profit which is equal to the difference between his bid and the actual cost of the project, as shown in the following equation 1:

\[
\text{[1] Profit} = \text{Winner's bid} - \text{Actual Cost}
\]

When the winner’s profit is negative or below normal profits, then the winning bidder is considered a prey to the winner’s curse. In deriving the SRNNE optimal bid function, the actual cost of project \( C \), is assumed to be randomly drawn from a uniform distribution on \([X_1, X_2]\). Furthermore, each bidder receives a private signal \( c_i \), about the true cost. This private signal is assumed to be randomly drawn from a uniform distribution on \([C-\epsilon, C+\epsilon]\). Moreover, it is also assumed that the uniform distributions of the actual cost \( C \), the private signal \( c_i \), \( \epsilon \), and the number of bidders \( N \), are a common knowledge to all participating bidders.

The SRNNE optimal bid function, as stated by Dyer et al. (1989), in the interval \([X_1+\epsilon < c_i < X_2-\epsilon]\) is as follows:

\[
\text{[2] } b(c_i) = c_i + \epsilon - Y
\]

Where \( Y = \left[2\epsilon/N+1\right] \exp\left[-(N/2\epsilon)(X_2-\epsilon - c_i)\right] \), and \( N \) is the number of bidders. The variable \( \epsilon \) represents the range of private signal around the true cost, and depends on the accuracy of bidder’s estimate. It is important to notice that the \( Y \) term diminishes rapidly as \( c_i \) moves below \((X_2-\epsilon)\). Also, the SRNNE implies that signals are just marked-up by a value equal to \( \epsilon \), which represents a strategic profit, just to avoid the winner’s curse problem of negative profits.

The main objective of SRNNE optimal bid function is to determine the optimal amount a bidder shall submit without being subjected to the winner’s curse problem, in case of winning the contract. It is logical that if the bidder bids based on estimating the project cost close to \((X_1+\epsilon)\), he may lose money in case of winning. This fact is expected to happen most of the times but not always. Sometimes, improbable things happen which turns bad decisions to be good. However, if this bidding competition is played many times and the bidder always estimates a project cost close to \((X_1+\epsilon)\), he will lose money eventually, in expectations, based on the winner’s curse concept.

## 4 RESEARCH METHODOLOGY

In this paper, the authors apply the aforementioned theoretical approach of SRNNE using some real projects dataset conducted by California Department of Transportation. Furthermore, the authors compare the results to those of the implemented model, which simulates the bidding procedure in reality. The main purpose is of the simulation model is to analyze the behavior of sub-contractors and general contractors towards the threat of the winner’s curse. Moreover, the authors aim to examine the effect of the nature of construction bidding environment (single-stage bidding vs multi-stage bidding) on the results from the winner’s curse perspective. As aforementioned, it is expected that multi-stage bidding will result in that the winner will suffer more losses, than in single stage bidding. To this end, this research uses a three-step research methodology in which the authors (1) design the single-stage and multi-stage bidding games; (2) set up the basic assumptions and considerations required for the simulation model; and (3) collect some real projects dataset to be utilized in the simulation model.
4.1 Design of the Single-Stage and Multi-Stage Bidding Games

In the single-stage bidding game, as shown in Figure 1, there are only three general contractors who are competing to win a similar project contract in each round. The contract is awarded to the general contractor who submits the lowest bid following the low bid method concept. The projects in SSG are designed to be the same as those in MSG.

![Figure 1: Single-stage bidding game (GC=General Contractor)](image)

On the other hand, in the multi-stage bidding game, as shown in Figure 2, there are three general contractors. Each general contractor receives bids from three sub-contractors for a symmetric part of the project. In MSG, it is assumed that the general contractor subcontracts up to 30% of the project work. Based on the low bid method, the winning sub-contractor for each general contractor is the one who submits the lowest bid. Thereafter, the three general contractors are competing in between to win the project and submit their joint bids to the owner. Eventually, the contract is awarded to the lowest of the three submitted joint bids by the general contractors, and consequently, his winning sub-contractor wins the project contract.

![Figure 2: Multi-stage bidding game (GC=General Contractor, SC=Sub-Contractor)](image)

4.2 Basic Assumptions and Considerations

In order to reduce the variability and facilitate the comparison between the two game types (MSG and SSG), there are some basic assumptions and considerations for each game type in each round. Those assumptions serve as the rules for the simulation model, which are as follows:

- In both SSG and MSG, there are six projects’ categories and each category is represented by 15 different projects.
- At each round in both SSG and MSG, each subcontractor and general contractor is randomly given a different private signal which represents his estimate of the true construction cost of his part in the project. All the given private signals, at each round, are within the range of the expected estimate’s error ($\epsilon$).
- The true cost is considered unknown for contractors at the time of submitting their bids.
- The simulation model is designed such that, at each round, the contractors would choose randomly to bid within the range of $\epsilon$, which is shown in table 1, around the given private signal.

For example, for general contractors who are bidding for one of the projects in category 1 in the SSG, the true cost is assumed to be randomly drawn from a uniform distribution with the range from $25,000 to $50,000. Furthermore, the private signals are randomly drawn within $750, which represents the value of $\epsilon$, around the true cost. This implies that, at each round, the true cost of the project would be within ±$750.
around the private signal. Figure 3 illustrates the distribution of the private signals and the true cost at a round for in category 1 in SSG as an example.

![Diagram showing distribution of private signals and true cost](image)

Figure 3: An example of the true cost and private signal distributions (C = True Cost, PS = Private Signal)

### 4.3 Simulation Model Dataset

As previously mentioned, the simulation is implemented using some dataset, which is based on real projects conducted by California Department of Transportation, to simulate the construction bidding process in reality. Either MSG or SSG is divided into six categories, based on the true cost of the project. Each category is represented by 15 projects in each game type in the simulation model. Furthermore, the value of $\epsilon$ is different from one category to another in order to be reasonable relative to the true cost of the project and simulate, as possible, the accuracy of contractors’ estimates in reality, e.g. 2%. The following Table 1 shows the six categories, and the value of $\epsilon$ for each category.

<table>
<thead>
<tr>
<th>Category</th>
<th>Range</th>
<th>MSG $\epsilon$ for SC</th>
<th>MSG $\epsilon$ for GC</th>
<th>SSG $\epsilon$ for GC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$25,000 -- 50,000</td>
<td>$222</td>
<td>$528</td>
<td>$750</td>
</tr>
<tr>
<td>2</td>
<td>$50,000 -- 100,000</td>
<td>$450</td>
<td>$1,050</td>
<td>$1,500</td>
</tr>
<tr>
<td>3</td>
<td>$100,000 -- 500,000</td>
<td>$1,800</td>
<td>$4,200</td>
<td>$6,000</td>
</tr>
<tr>
<td>4</td>
<td>$500,000 -- 1,000,000</td>
<td>$4,500</td>
<td>$10,500</td>
<td>$15,000</td>
</tr>
<tr>
<td>5</td>
<td>$1,000,000 -- 5,000,000</td>
<td>$18,000</td>
<td>$42,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>6</td>
<td>$5,000,000 -- 10,000,000</td>
<td>$45,000</td>
<td>$105,000</td>
<td>$150,000</td>
</tr>
</tbody>
</table>

Note: (MSG = Multi-stage Bidding Game; SSG = Single-Stage Bidding Game; SC = Sub-Contractor; GC = General Contractor)

To this end, the simulation model of the single-stage bidding game, and multi-stage bidding game was implemented on NetBeans IDE 7.4 platform using JAVA programming language.
5 RESULTS AND ANALYSIS

5.1 Results of the SSG and MSG

In the single-stage bidding game, based on the results of the conducted simulation model, it was found that, in 75 projects out of the 90 projects in all the six categories of projects, the winning general contractor suffered from the winner’s curse, by winning the project contract with a submitted bid less than the actual true cost of the project, which represents 83.3% of all the projects being bid for.

Based on past literature, this result was expected according to the four experiments conducted by Dyer et al. (1989), in which the authors found that both inexperienced students and experienced executives suffered the winner’s curse by earning negative profits in three of the four experiments, and profits were not statistically different from zero in the other experiment. Figure 4 shows the winning general contractor’s actual bid and compares it to the actual true cost of the project for the 15 projects in category 1, as an example.

![Figure 4: Category 1: GC actual bid vs. joint project true cost (GC = General Contractor)](image)

Furthermore, in the multi-stage bidding game, the results indicated the winning sub-contractors, in their part of the project, suffered in 83 projects, out of the 90 projects being bid for, from the winner’s curse, which represents around 92% of the projects. On the other hand, the winning general contractors, also in their part of the project, suffered in 77 projects, out of the 90 projects being bid for, from the winner’s curse, which represents around 86% of the projects.

Moreover, the results indicated that in the MSG, all the projects, except one project, in which the winning general contractors earned some profits (13 projects) in the part of the project, their corresponding winning sub-contractors suffered from the winner’s curse and vice versa. Therefore, it is important to highlight that based on the characteristics of the construction competitive bidding and non-cooperative game theory, in the MSG, each of the winning sub-contractors or general contractors is considered liable to his submitted bid for his part of the project. In other words, the party who suffers some losses in his part of the project considered liable to them, while the other will earn the profits based on his submitted bid for his part of the project.

Furthermore, it is noticeable that the winning general contractors have avoided the winner’s curse more than the winning sub-contractors. This refers to one of the mechanisms stated by Dyer and Kagel (1996), in which the general contractors benefit from the low submitted bids by the sub-contractors to earn more profits and at the same time, submit low joint bids which guarantee them the winning of the project contract.

In the MSG, based on the low bid method, a general contractor must submit a joint bid less than the joint bids submitted by his competitors in order to win a project contract. In preparing the joint bid, a general contractor considers the bid of his winning sub-contractor plus the bid prepared for his part of the project. Based on the results of the conducted simulation model, it was found that in 85 projects out of the 90 projects, the overall winning joint bid is less than the joint true cost of the project, which represents...
around 94% of the projects. Despite that in some projects either the winning sub-contractor, general contractor, or both made some profits, this results is due to the high losses in part of one of them.

Figure 5 shows the joint actual bids of the winning general contractor and his winning sub-contractor, and the joint true costs of the 15 projects in category 1 as an example.

Figure 5: Category 1: the winning joint actual bid vs joint project true cost (MSG = Multi-Stage Bidding Game)

5.2 Case of Using SRNNE Optimal Bid Function in Bid Preparation for Both SSG and MSG

The SRNNE optimal bid function provides the contractors with a tool to avoid falling as a prey to the winner’s curse. Moreover, the SRNNE is derived to be used for symmetric bidders within the same stage. Thus, it is assumed that the SRNNE would be used separately at each stage of bidding for the MSG. Based on the results of both SSG and MSG; it was found that using the SRNNE optimal bid function gives positive profits in 100% of the projects. In other words, all optimal bids are more than the true cost of the projects. It is important to highlight that using SRNNE optimal bid function does not guarantee that the contractor will win the project contract. But, it guarantees that the contractor will not suffer from the winner’s curse in case of winning the project contract.

Furthermore, the optimal bids give only a strategic profit only to be above the project true cost. Based on the implemented model’s results, the average of the overall earned profits is 1.31% and 1.27% relative the joint project true cost for SSG and MSG, respectively. Figure 6 shows the comparison between the joint actual winning bids’ profits or losses and the earned joint optimal profits for the 15 projects in category 1 for both SSG and MSG. It is important to highlight that the X-axis (zero in Y-axis), in Figure 6, represents the joint true cost of the project.

Figure 6: Category 1: the joint optimal vs. joint actual profits or losses {(a) SSG = Single-Stage Bidding Game; (b) MSG = Multi-Stage Bidding Game}
5.3 The Comparison between Single-Stage Bidding Game and Multi-Stage Bidding Game

Based on the results of the implemented simulation model, it was found that the SSG is giving less losses as compared to the overall losses of the MSG. This result was observed to occur in 56 of the total 90 projects, representing approximately 62 percent of all projects, as shown in table 2.

In fact, this result was expected because in the MSG, the winner’s curse is expected to happen twice, one in part of the winning sub-contractors and the other in part of the winning general contractors. Not addressed in the literature is the fact that most, if not all, large jobs are awarded to a general contractor who in turn-subcontracts most, if not all actual engineering services. Therefore, due to the multi-stage bidding environment, adverse selection and the winner’s curse problem is compounded in most of the projects in the MSG. Being the case, the projects which incorporates multi-bidding environment, is expected, due to suffering more losses than those of single-stage bidding environment, to face more conflicts, claims, and disputes for all the associated stakeholders.

From the general perspective, the results indicated that the winning general contractors suffered, on average, approximately the same percentage of losses relative to the true cost of their part of the project, as shown in table 2. Therefore, the general contractors have no preference to either MSG or SSG from the winner’s curse perspective. They might prefer the SSG over the MSG due to the aforementioned increased amount of conflicts, claims, and disputes associated with the MSG. On the other hand, they might prefer the MSG over the SSG based on the size of the project. Figure 7 shows the comparison between the overall actual profit or losses of the MSG and those of the SSG for each project in category 1 as an example. Moreover, the X-axis (zero in Y-axis) in the figure 7 represents the joint true cost of the projects in category 1.

Table 2: Comparison between MSG and SSG from The Winner’s Curse Perspective

<table>
<thead>
<tr>
<th>Case</th>
<th>% of the projects which give positive profits</th>
<th>% of the projects which give less losses than the other case</th>
<th>Average % of losses relative to the overall project true cost</th>
<th>Average % of GC losses relative to the GC part of the project</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSG</td>
<td>16.66%</td>
<td>62.22%</td>
<td>1.20%</td>
<td>1.19%</td>
</tr>
<tr>
<td>MSG</td>
<td>5.56%</td>
<td>37.78%</td>
<td>1.38%</td>
<td>1.21%</td>
</tr>
</tbody>
</table>

Note: (MSG = Multi-stage Bidding Game; SSG = Single-Stage Bidding Game; SC = Sub-Contractor; GC = General Contractor)

Figure 7: Category 1: overall MSG vs SSG actual profit or losses (SSG = Single-Stage Bidding Game; MSG = Multi-Stage Bidding Game)
6 CONCLUSION

The winner’s curse is a major concern associated with construction bidding. The results and analysis conducted in this study demonstrate that in construction bidding, the majority of the winning subcontractors as well as general contractors suffer from the winner’s curse in both single-stage and multi-stage bidding environments. However, the winner’s curse is more severe in the multi-stage bidding environment. A question which arises here is why contractors suffer from the winner’s curse in reality? Actually, this might happen for variety of reasons as follows:

- Inaccurate estimates of project cost.
- New contractors intend to enter the construction market.
- Minimizing losses in case of recession of construction industry.
- Strong competition within the construction market
- Opportunity costs which can affect the behavior of contractors towards the winner’s curse.
- The intention to win the project, then remedy the losses through change orders, claims, and other mechanisms.

Therefore, it is obvious the need for a tool which aids contractors in preparing more accurate bids to initially avoid the winner’s curse. It has been also demonstrated that the SRNNE optimal bidding methodology, in both bidding environments, provides the contractors with a tool to avoid the winner’s curse problem and gain strategic positive profits.

Furthermore, the aforementioned SRNNE optimal bid function considers only a strategic amount of profit to avoid the winner’s curse. For further research, the authors recommend the extension of the SRNNE optimal bid function to include more factors associated with bid preparation such as mark-up, overhead costs, contingency costs.

References

COMPARITIVE STUDY OF CURRENT PRACTICE IN BRIDGE CONDITION ASSESSMENT

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Abstract: Bridges play a vital role in road infrastructure networks. According to Statistics Canada, bridges and overpasses accounted for 8% of total public assets in 2007. Ontario ranked as the third among provinces in terms of having old bridges. In 2007, Bridges in Ontario accounted for 7% of its public infrastructure, while in Alberta, bridges account for 9% of total public infrastructure. Bridge condition assessment is conducted to determine load rating capacity for bridge elements. The identification of current condition of each element provides early warning of necessary maintenance. Condition rating is performed during the inspection process. This paper provides a comparative study of current practices in bridge condition rating worldwide, with emphasis on the United States and Canada. The study includes 4 main criteria: inspection levels, inspection principles, inspection frequencies and numerical ratings for 4 provinces in North America: Alberta, Ontario, Quebec and state of Oregon and 5 countries outside North America: United Kingdom, Denmark, Portugal, Sweden and Australia. The Limitations of current practices are discussed and recommendations for improved inspection are provided. The study is expected to assist professionals and inspectors in selecting feasible method/s for effective bridge condition assessment.

1 INTRODUCTION

Bridge Management System (BMS) is the process of monitoring, inspection, repair and replacement of deteriorated bridges. All bridge management decisions require inspection data to identify current condition of bridges. Moreover, it provides decision making with tools to select the appropriate solution, such as bridge rehabilitation or replacement. BMS is facing imbalance between the need for repairs or replacements and many challenges due to incorporating of multi objectives; structural safety, serviceability, optimum maintenance and economic considerations. Therefore, BMS cannot make decisions without accurate and detailed data of bridge conditions. Thus, decision makers can avoid the worst consequences of underestimating the degree of deterioration and avoid the costly consequences of overestimating the degree of deterioration. The main goal of BMS is to gain the maximum performance with using minimum cost and this can be achieved by efficient techniques and technologies that can be automatically updated. Consequently, the service life of bridges can be increased within effective cost. (Rens et al. 2005; Steart et al. 2002, Wang et al.2007). Structural health monitoring, inspection process and condition assessment are considered main components of BMS.

Bridge condition assessment is conducted to determine load rating capacity for bridge components. The main components of bridges are deck, superstructure and substructure. Each component has different role in bridge structure with specified relative importance. Bridge condition assessment defines the
structural importance of each bridge element. The identification of current condition of each element provides with early warning of necessary maintenance. The main difficulty in bridge condition assessment is the large number of bridges in the network which requires regular inspection. However, condition rating is performed using the inspection data. These collected data are converted to a rating to assess bridge condition (Xia and Brownjohn, 2004; Yehia et al. 2007). This paper presents a detailed comparison of current practices of condition assessment of bridge structures in different countries.

2 CURRENT PRACTICE IN BRIDGE CONDITION ASSESSMENT IN NORTH AMERICA

According to Federal Bridge Inspection Standard (FBIS), the levels of service deficiencies are based on comparisons of the actual load capacity of bridge with the level of service. The evaluation of bridge condition deficiency (BCD) includes an assessment of the condition of each of the three primary elements of the bridge: Super structure (SPD), Substructure (SBD) and bridge deck (BDD). After the total deficiency has been established for all bridges, costs associated with replacement and rehabilitation should be determined (FHWA, 2012; Branco and de Brito, 2004).

\[
BCD = SPD + SBD + BDD \tag{Eq.1}
\]

Condition ratings for each element of the bridge are assigned every two years and are then aggregated into overall condition ratings for super, sub structure and deck, the ratings are numerical values from 0 to 9. Bridges are considered structurally deficient if any of deck, substructure or superstructure is equal or less than 4 (poor). If the structural evaluation is equal or less than 2, then the bridge is having high priority for replacement (FHWA, 2012; Branco and de Brito, 2004). According to the manual for maintenance inspection, AASHTO describes two basic load rating procedures: (1) the allowable stress, (2) Load rating, LR. In the United States, bridges are periodically rated according to their structural capacity. The rating can actually increase with time in bridges inspected regularly with maintenance programs, where the live load limits are checked by traffic police.

2.1 Bridge Condition Assessment in Alberta Transportation

According to Bridge Inspection Manual of Alberta Transportation, the condition rating system in Alberta consists of a numerical rating range of 1 to 9 (BIM 2004; Branco and de Brito 2004). This rating applies to all inspection elements as well as the general rating for each category. The rating is representative of the condition of the element and the ability of the element to function as originally designed. Bridge can be rated 9 if it is in excellent condition. Additionally, the rating of the element also reflects any safety concerns and maintenance priority. The rating of an element is determined by the rating of the worst item within the group. The inspector should describe, and explain the condition, why the post has a low rating and where it is located.

The rating of the element is visual inspection and based on what the inspector can see. The inspector should be able to see enough of the element to be comfortable assigning a rating. If the element is inaccessible or is not visible for the inspector to assign a rating, the element is rated ‘N’. If a particular element does not apply to the structure being inspected, the element is rated ‘X’. In situations where an element does not exist but is required in the judgment of the inspector, the element is rated ‘X’ with a comment provided in the ‘Explanation of Condition’ section which illustrates within a maintenance recommendation (BIM 2004). The general rating for each category is determined by the ratings assigned to critical load carrying elements or members of the structure. The general rating must also reflect any safety concerns related to the function of the structure. The general rating is not an average of the element ratings; as the general rating cannot be higher than the lowest critical element rating.

All bridges are to be inspected in accordance with the following intervals to ensure an appropriate level of safety: major bridges, Standard bridges, in highways with numbers less than 500 or greater than or equal to 900 are within 21 months interval. Major bridges, standard bridges in highways with numbers equal to or greater than 500 but less than 900 are within 39 months interval. Major bridges in parks that carry pedestrian traffic only are inspected within 57 months interval. All new bridge structures are to be inspected immediately after construction is complete and within 24 months after completion. All bridge
structures are to be inspected immediately after any significant maintenance or rehabilitation is completed. The inspector may specify shorter intervals depending on the age, traffic characteristics and known deficiencies (BIM 2004; Branco and de Brito, 2004).

Most major bridges, standard bridges, are inspected by a certified bridge inspector on a routine basis which is known as Level 1 inspection. However, certain major bridges or components of standard bridges require inspection with specialized knowledge, tools and equipment. Almost all bridges will require specialized inspections which are known as Level 2 inspections. Specialized inspection includes ultrasonic tests on steel bridges, CSE tests on deck concrete, coring test. Level 2 inspections are essential for high load and overload damage, or where critical or significant deficiencies are determined (BIM 2004; Branco and de Brito, 2004). Level 1 is a general inspection which requires completion of the BIM report and use of basic tools and equipment. This level of inspection must be undertaken by certified bridge inspectors. Level 1 inspections are general visual inspections conducted using standard tools and equipment. This level must be performed at time intervals not exceeding those specified by Department policy. Level 1 inspection rate the worst part of each element and do not take the overall element condition into account.

Level 2 inspection is an in-depth inspection which requires completion of the BIM report, and use of specialized tools, techniques, and equipment. Level 2 inspections are quantitative inspections conducted using specialized tools. This level of inspection gathers detailed information on the condition of a particular bridge. In Alberta, concrete deck inspections are currently performed on approximately 120 bridge sites per year throughout Alberta on a 4 to 5 year inspection cycle. Additional Level 2 deck inspections may be completed as part of a bridge assessment that identified in a previous Level 1 inspection. The quantified condition data that are collected provide information on the element and this condition can be monitored over time. The condition rating for Level 2 inspections are grouped together into categories. Therefore ratings from 9-7 are grouped as very good condition ratings, and then ratings 6 and 5 are grouped as adequate ratings. Ratings of 4 and 3 are grouped as ratings that are the most critical and give priority of the element. Ratings of 2 and 1 are grouped as these ratings are required immediate maintenance or repair. The inspector should rate the general condition and not just the worst case. The inspector should note that if the damage is significant to the structural capacity.

Level 1 rating should be used to reflect the worst damage to the element. A rating of 5 or higher is for elements that are functioning as designed. For a rating of 5 an element may have minor structural flaws, but these flaws should not impact the structural capacity of the member. A rating of 4 is a low maintenance priority, and these elements would generally be scheduled for repair in more than 3 years. A rating of 3 is a medium priority for maintenance, as repairs would typically be scheduled from 6 months to 3 years away. A rating of 2 is a high priority for maintenance and repairs would likely be less than 6 months away. A rating of 1 requires urgent and immediate action.

The Chloride Test is a field test to determine the chloride content of concrete. It is most often performed on a deck because these are the areas of the bridge that are commonly exposed to the de-icing salt. This test is performed in level 2 inspection. Chloride testing is destructive because holes are drilled into the component that is being tested. This testing is also time-consuming as the samples must be extracted and tested. The destructive and time-consuming nature of the test means that only a limited number of samples can be gathered and tested. Copper Sulfate Electrode (CSE) test is a repeatable, non-destructive field test. Alberta Transportation remains one of the few agencies that use CSE testing as a predictive tool for preventative maintenance programs. CSE testing, also referred to as half-cell testing is used to determine the potential of corrosion in reinforcing steel, but they do not indicate a corrosion rate. Test results from one year to another are compared to assess the advancement of corrosion and predict the future deck condition. The CSE data are used to develop prediction models and to determine the ideal time to rehabilitate a deck. CSE data is also used to evaluate the effectiveness of various rehabilitation methods. CSE testing is quick, and cost-effective. The limitation of CSE testing is that, suddenly the readings become higher, lower, as the ground connection may be broken, the voltmeter connections may have worked loose, or the grounding wire may be broken. In this case, inspector should stop and verify the validity of the ground connection or check if the deck is not wet enough for accurate results.
2.2 Bridge Condition Assessment in State of Oregon, USA

The Oregon department of transportation (ODOT) considers the routine inspection report to be the primary tool for reporting the condition of a structure. The routine inspection report is a summary of condition assessment data that is generated via a number of more detailed types of inspections. A Routine Bridge Inspection is a regularly scheduled inspection that generally consists of visual observations that are needed to determine the functional condition of the bridge, and Recommend any repairs or other services that may be needed. Standard routine inspection frequency is two years. However, the NBIS requires inspections be performed annually when conditions rating of bridge is 3 or less or the bridge has an operating load rating factor of less than 1.0 for any of the legal load types (ODOT 2012). In depth evaluation of bridge is needed to supplement the visual inspection. The bridge inspector may employ either nondestructive testing techniques or destructive techniques such as chipping, drilling and core drilling which are the most common in-depth exploratory methods. Nondestructive methods need expertise that is required to interpret the results in the field. The steps for in-depth evaluation of a concrete structure are:

1. Visual Inspection with the last bridge inspection report in-hand.
2. Revision of engineering data, design, construction documentation, operation and maintenance records.
3. Revision of inspection reports and then mapping of the various deficiencies.
4. Monitoring and using nondestructive evaluation methods.

The steel location and depth of cover can be determined non-destructively using a device called a pachometer. This device measures variations in magnetic flux caused by the presence of steel. If the size of reinforcement is known, the amount of concrete cover can be determined. In general, these devices can measure cover to within ¼ inch at 0 to 3 inch from the surface. The accuracy of the devices is dependent on the amount of reinforcing steel that is present in the concrete. The more congested the reinforcing, the less accurate the device becomes. In some cases, when other bars interfere, the device cannot identify either location or depth of cover. Other techniques, such as ground-penetrating radar (GPR) or x-ray, can be used for locating steel rebar which the pachometer fails to provide the necessary information. Between GPR and x-ray, x-ray is more accurate in locating steel rebar. The corrosion of steel rebar can be determined by using the CSE methods (ODOT 2012).

The state of Oregon uses destructive in depth testing such as chloride content test, depth of carbonation and core test to determine the compressive strength of concrete. Hammer sounding and chain dragging are used to determine delamination in concrete. While these methods are not expensive, they are time consuming to perform. Petrographic analysis is a detailed examination of concrete to determine the formation and composition of the concrete and to classify its type, condition, and serviceability. Petrographic examination helps determine some of the freeze-thaw, sulfate attack and alkali-aggregate reactivity. Petrographic examination is a highly specialized practice requiring skilled and well trained technicians. The most common defects encountered in steel superstructures include corrosion, fatigue cracking, heat damage, and overload damage. One of the primary methods to mitigate corrosion is painting with an acceptable coating. Dye penetrate and ultrasonic are used as non-destructive evaluation methods for fracture critical members bridge inspection (ODOT 2012; FHWA 2012).

2.3 Bridge Condition Assessment In Quebec

Bridges in Quebec are managed by MTQ (Manuel d’entretien des structures). Bridge condition inspections in Quebec are classified to visual examination which can be used to document and record the severity and overall condition of bridges. A photographic record of this information is essential. Some testing can supplement observations and measurements. Some of the techniques that can be used during ordinary inspections are: acoustic impact (hammer sounding, chain dragging) for detection of delamination, debonding, voids, and other defects underneath the surface; rebound hammer to evaluate the concrete strength and quality on a comparative basis. NDE methods are used for advanced
inspection. However, these methods still need more development regarding data interpretation. Using combination of visual inspection half-cell potential, acoustic methods and coring are the most widely used techniques in bridge inspection practice.

There are currently three types of bridge inspection Practice in Quebec. These are as follows:

- Routine inspection: It is a visual inspection and is done once a year where defects are observed and recorded. Routine inspection provide inspector with general knowledge about the condition of the bridge.
- General Inspection: This type of inspection is more accurate type and is performed by an engineer or technician who has been trained by a regional bridge engineer. It remains a visual examination, that is supplemented by hammer sounding, general dimension measurements and crack measurements. The frequency of this inspection varies from 3 to 6 years depending on the bridge type; concrete bridges are inspected every 5 years.
- Special inspection: This type of inspection usually follows the general inspection where significant deterioration is found and when the inspector has difficulties to assess the condition. This type of inspection is carried out as requested and can be done with the help of a structural engineer. The bridge condition rating index in Quebec ranges from 1 to 6, where 1 is the lowest value and 6 is the highest: 1-critical, 2-defective, 3-mediocre, 4-acceptable, 5-good, 6-excellent and for elements that don’t exist, the index value is 0.

2.4 Bridge Condition Assessment In Ontario

Ontario structure inspection management systems (OSIMS) was developed to store and manage the inspection data that is collected during the detailed structure inspections. OSIM is capable of creating, updating and storing inspection rating data for structures owned and maintained by the ministry of Transportation. The data are stored in data base and then can be used to generate reports on condition rating. The general information for a structure is obtained from Ontario structure inventory system (OSIS). In the past, inspectors relied on their background and experience in reporting bridge condition. OSIM sets standard for detailed routine inspection and condition rating for structures and their components (OSIM, 2000; Branco and de Brito, 2004). In order to classify defects, severity level should be illustrated. As an example, severity is considered light when delamination area measured is less than 150mm in any direction; medium when delamination area is between 150mm to 300mm; severe when delamination area is within 300 mm to 600 mm and very severe when area is more than 600mm. The defects are divided into material defects and performance defects. OSIM presents the material defects that are found in concrete and steel bridges and it is related to building materials regardless of any consequences to the structure. Performance defects are problem that may impact the structure as a whole. The material and performance condition rating are numerical systems in which a number from 1 to 6 is assigned to each component of the structure. Number 0 is assigned to a component when it doesn’t exist and number 9 is assigned to a component that is not visible at the time of inspection. In some cases, performance defect exists as a result of defects in design or construction. The lowest performance condition rating of primary component should be the performance condition rating of the structure (OSIM 2000; Branco and de Brito, 2004).

The inspection system in Ontario is classified into general inspection, detailed inspection and condition survey. General inspections are based on visual inspections; routine general inspection can talk place daily, monthly or annually for bridges within span over 6 m. Non routine general inspection is performed when inspection is needed for specific problem. Detailed Inspection can be routine or non-routine inspection and should be done by using measurement tools, tabs, camera and thermometers. Inspectors should review all previous inspection reports, details and all records. The inspectors should take sketches and photographs. Condition Survey inspection requires measurements and documents of all areas of defects and deterioration. It requires access to all area of the structure. Routine condition survey can be done every 5 years on selected number of structure and it incorporates the load carrying capacity assessment. For bridge deck condition survey, assessment can be done using GPR and thermograph.
<table>
<thead>
<tr>
<th>CURRENT PRACTICE</th>
<th>INSPECTION LEVEL</th>
<th>INSPECTION TYPE</th>
<th>INSPECTION FREQUENCY</th>
<th>NUMERICAL RATING</th>
<th>NDE METHODS</th>
<th>SHORTCOMING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alberta</td>
<td>Level 1 (Routine Inspection)</td>
<td>Visual Inspection</td>
<td>Set Up by the department.</td>
<td>range of 1 to 9</td>
<td>-</td>
<td>Level 1 rating is subjective. Level 2, the overall rating still not accurate. Chloride Test is time consuming, destructive test. The inspector should verify the reading.</td>
</tr>
<tr>
<td></td>
<td>Level 2 (Specialized Inspection)</td>
<td>In-depth inspection</td>
<td>Grouped together into categories. ratings from 9-7, 6-5, 4-3, 2-1</td>
<td>Ultrasound for steel bridges, CSE for concrete deck.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ontario</td>
<td>-Routine General Inspection</td>
<td>Visual Inspection</td>
<td>-Daily, monthly or annually</td>
<td>-</td>
<td>Camera, tab, thermometers</td>
<td>The detailed Condition survey still use destructive methods. Use of NDT methods need high level training to interpret the results.</td>
</tr>
<tr>
<td></td>
<td>-Non Routine General Inspection</td>
<td>Visual Inspection</td>
<td>When needed for specific problem</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-Detailed Inspection</td>
<td>Sketches and measurement tools</td>
<td>Two years</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-Condition Survey</td>
<td>In depth Inspection using load carrying capacity assessment</td>
<td>5 years</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Oregon, USA</td>
<td>Routine Inspection</td>
<td>-Visual Inspection</td>
<td>2 years</td>
<td>1-9</td>
<td>N/A</td>
<td>rely on destructive methods chloride content test, and core test. Hammer sounding and chain dragging are time consuming.</td>
</tr>
<tr>
<td></td>
<td>In-depth inspection</td>
<td>-use nondestructive methods and destructive test like core sampling, hammer and</td>
<td>5 years</td>
<td>-</td>
<td>Pachometer, X-ray and GPR, Dye penetrate and</td>
<td>-</td>
</tr>
</tbody>
</table>
3 CURRENT PRACTICE IN BRIDGE CONDITION ASSESSMENT OUTSIDE NORTH AMERICA

3.1 Bridge Condition Assessment In United Kingdom

In United Kingdom, bridges are subjected to general inspection every 2 years and to more principal inspection every 6-10 years. These inspections are visual inspection that record only damage or deterioration that are seen. Defects that have main concern are inspected within special inspection, such as half-cell potential and cores sampling are examined to check the presence of alkali reaction. Special inspection measures the depth of concrete cover, carbonation, chloride, sulfate contents. The condition of each element is given a rating on scale of 1 to 5 at the time of inspection based. Each element is given a location factor based on its structural importance. The overall condition rating of bridge is given using the equation 2.
BCI = \(100 - f_1 \times \left[ \frac{F_2 \times (E_{fp} \times S_f)}{N_p} + F_3 \times \left( \frac{E_{fs} \times S_f}{N_s} \right) \right]\) \hspace{1cm} \text{EQ2}

Where, \(E_{fp}\) is element factor from 1 to 10 of primary element, \(E_{fs}\) is element factor of secondary elements, \(S_f = \text{The extent of damage} / \text{Severity factor} 1 - 10\). \(N_p\) is the number of primary elements, \(N_s\) is the number of secondary elements and \(F_1, F_2\) and \(F_3\) are the severity factors. Superstructure and substructure are both divided into a number of elements and receive score of 1 to 8. The element rating percentage can be calculated from EQ2. The overall condition rating for substructure and superstructure is taken as the lowest element rating. Bridge condition assessment in UK has some shortcoming as there is little use of nondestructive evaluation methods and there is no relationship between bridge age and maintenance cost. Current practice with countries outside North America are illustrated in Table 2

Table 2: Current Practice outside North America

<table>
<thead>
<tr>
<th>CURRENT PRACTICE</th>
<th>INSPECTION LEVEL</th>
<th>INSPECTION PRINCIBALE</th>
<th>INSPECTION FREQUENCY</th>
<th>NUMERICAL RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>General Inspection</td>
<td>Visual Inspection</td>
<td>2 years</td>
<td>range of 1 to 5, overall condition rating is taken as the lowest element</td>
</tr>
<tr>
<td></td>
<td>Principal Inspection</td>
<td>In depth inspection</td>
<td>6-10 years</td>
<td>Half-cell potential test</td>
</tr>
<tr>
<td>Denmark</td>
<td>-Routine superficial Inspection</td>
<td>Visual Inspection</td>
<td>- Annually</td>
<td>Final condition rating is based on bearing capacity and importance of each element</td>
</tr>
<tr>
<td></td>
<td>-Principal Inspection</td>
<td>Visual Inspection</td>
<td>-3 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Technical Inspection</td>
<td>More investigation. In depth Inspection using load carrying capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portugal</td>
<td>-Ordinary Inspection</td>
<td>-Visual inspection</td>
<td>3 to 6 years</td>
<td>1-7 defect rating</td>
</tr>
<tr>
<td></td>
<td>Principal inspection</td>
<td>-Visual inspection and simple use of nondestructive methods</td>
<td>3 years</td>
<td>1-The defect degree doesn’t increase.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2-doesnot require intervention</td>
</tr>
<tr>
<td>Sweden</td>
<td>-Regular Inspection</td>
<td>Visual Inspection</td>
<td>Quick monthly</td>
<td>-Defect Rating 0 to 3</td>
</tr>
<tr>
<td></td>
<td>-Superficial Inspection</td>
<td>Visual Inspection</td>
<td>Each 1 year</td>
<td>0-gurantee for next 10 years, 1-gurantee for next 3-10 years, 2- same before 3years, 3-defective function found, Ultrasound and</td>
</tr>
<tr>
<td></td>
<td>-General Inspection</td>
<td>Done by well-trained inspector</td>
<td>3 years</td>
<td></td>
</tr>
</tbody>
</table>

- Degree of urgency 0 to 2
- 0-no action required
- 1-The same within 1 year
- 2-action require within 3 years
- 3-getting evolving
- 4-require not urgently intervention
- 5-doesnot influence structure
- 6-doesnot impair structural safety
- 7-it reduces safety coefficient
<table>
<thead>
<tr>
<th></th>
<th>Complete examination</th>
<th>6 years</th>
<th>radiography.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia</strong></td>
<td>-Level1 Inspection</td>
<td>-Visual Inspection</td>
<td>Ground Penetrating Radar and impact echo are used to determine voids. Ultrasonic Pulse Velocity is used to determine cracks, concrete strength, location of reinforcement can be measured using GPR. Half-cell potential used to detect steel corrosion and rebound hammer for concrete strength. Steel bridges deterioration can be determined by using Eddy current, Dye penetrates Radiographic and ultrasonic testing. Concrete cover can be measured also using cover meter.</td>
</tr>
<tr>
<td></td>
<td>-Level2 Inspection</td>
<td>-Visual Inspection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Level3 Inspection</td>
<td>In-depth Inspection</td>
<td></td>
</tr>
</tbody>
</table>

### 4 SUMMARY AND CONCLUSION

The current practice for bridge condition assessment and inspection in Alberta has some limitations. For example their Level 1 inspection is visual and the rating is subjective and depends on the inspector experience. Level 2 inspection, the overall rating might not be accurate as the areas that are not visible cannot be accurately assessed. In Level 2 inspection, chloride test is used to determine the chloride content in concrete. This test is time consuming and destructive test. When CSE test is used in level 2, the inspector should stop when reading is getting so high or low, and verify the validity of the ground connection or check if the deck is not wet enough for accurate results. CSE test can determine the presence of corrosion but cannot determine the corrosion rate.

The state of Oregon still rely on destructive methods where samples should be taken in specific positions from the bridge to perform in depth inspection such as chloride content test, depth of carbonation and core test. Hammer sounding and chain dragging are time consuming. Pachometer that used for depth of cover measurements sometimes fail to give accurate information. Petrographic examination is a highly specialized practice requiring skilled and well trained technicians.

The current practice in Quebec has some of shortcoming. The condition rating values cannot be used to evaluate the structural capacity of the element. These values are used for general condition of the structure and for evaluation of deterioration. Also, the special inspection is not clearly defined and the system that is followed for reporting is not provided. Inspectors and engineers should be well trained; they should increase their knowledge regarding the material behavior. General inspection is still visual inspection without condition evaluation for specific elements. Special inspections should include in-depth condition evaluation including load-carrying capacity evaluation.

Inspection system outside North America is based on number of visits to the bridge at fixed time interval which is called periodic; the other type of inspection that is not based on interval is called non periodic inspection. The general system of inspection is classified into: superficial inspection that usually done every one year; it is visual inspection with portable support measurements. Through inspection which is called detailed inspection and usually done within period equal to a multiple of the superficial inspection; it is checkup of the structure with detailed visual inspection and usually done with inspector with high
experience. Special inspection is usually not periodic inspection; it is done based on specific defects that was detected; this inspection usually done using specialized equipment and test with the use of NDE methods. Bridge condition assessment in other countries is almost the same. Bridge inspection levels are classified according to inspection interval where the inspection intensity varies with inspection interval. There are three levels of inspection that are defined based on the interval: Short interval check of safety, medium interval of maintenance needs and long intervals, in depth assessment. Identifications of repairs needed are identified during the inspection within medium interval. Inspection with less interval are used together with the inspection of long interval. There is less use on non-destructive evaluation methods in the special inspection. However, MRWA Australian manual is incorporating the use of many NDT methods.

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MOTIVATION FOR INTERFACE MANAGEMENT IN CONSTRUCTION: A PROJECT COMPLEXITY PERSPECTIVE

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Abstract: Understanding project complexity is crucial for determining—or designing—the tools, methods, and skills required to effectively deal with interface issues in a construction project. However, understanding project complexity is not an easy undertaking; the concept of project complexity is composed of many interrelated sub-concepts, and thus is complex in itself. Given this background, this research aimed to define the dimensions of project complexity based on empirical data focusing on the variations in the project complexity factors between projects. To achieve this research objective, data for project complexity factors were collected via semi-structured interviews from 45 large-scale construction projects, and were analyzed using principal component analysis. As a result, 6 interpretable principal components were extracted from the dataset: ‘unclear scope of work for multiple stakeholders in the definition and design of projects with new technology’, ‘the uncertainty in boundaries and communication relative to other complexity factors’, ‘unfamiliarity with other project participants’, ‘the multiplicity of stakeholders relative to the amount of cost pressure and execution risks’, ‘the relative multitude of engineered items’, and ‘the high-level program/project administration’. These complexity dimensions can help with understanding sources of project complexity and determining the skills, tools, and systems to effectively cope with the sources of project complexity. Additionally, the analysis results hint that organizational interfaces should be effectively managed to prevent project failure in construction projects, and therefore support the need for advanced interface management in complex projects.

1 INTRODUCTION

Interface management (IM) is an emerging practice in the construction industry. In a broad sense, IM is defined as “the management of communication, relationship, and deliverables among two or more interface stakeholders” (CII 2014). IM usually involves formalized ways of communication and coordination between parties involved in a project—e.g., formal procedures for interfacing between parties involved, designated interface managers/coordinators, and software systems for IM (Shokri et al. 2014). In traditional construction projects, interfacing between parties have mostly relied on informal and less organized means, such as verbal communication in face-to-face meetings, memos, phone conversations, and emails. However, these ways of dealing with interfaces become insufficient and ineffective for managing a complex project, and IM has recently emerged as an approach to better cope with complexity in construction projects (Shokri et al. 2014).

Therefore, understanding project complexity is crucial for determining—or designing—the tools, methods, and skills required to effectively deal with interface issues—i.e., level of systematization of practices for
IM—in a construction project. In other words, a better understanding of project complexity can give us an insight into how IM practices can help prevent—or, at least, mitigate—the adverse impact of complexity on performance in construction projects. In more general terms, understanding the sources of project complexity, the interrelationships between the sources, and to what extent the sources are salient and important for effectively managing a complex project might help with determining the tools, methods, and skills for not only IM but also for effectively dealing with project complexity in general (Remington et al. 2009; Maylor et al. 2008; Baccarini 1996). Project complexity has been known as one of the greatest factors of difficulty of project management (Remington et al. 2009; Baccarini 1996; Gidado 1996), and project failure (Parsons-Hann and Liu 2005), in the construction industry.

However, understanding project complexity is not an easy undertaking; the concept of project complexity is composed of many interrelated sub-concepts, and thus is complex in itself. Project complexity is multifaceted (Maylor et al. 2008), and it has many sources (i.e., dimensions)—“Not all projects are complex in the same way” (Remington et al. 2009). Due to this nature of project complexity, it is not clear which specific dimensions of project complexity can be addressed by IM, and how IM practices can help in dealing with those particular dimensions.

A number of researchers have attempted to define the dimensions of project complexity, and to assess the impacts that each of the project complexity dimensions has on project performance. Several research approaches have been proposed and used in this line of attempts, including framework development by aggregating the complexity factors found in the literature (Bosch-Rekvedlt et al. 2011; Vidal and Marle 2008), Analytic Hierarchy Process (Vidal et al. 2011), workshops with industry practitioners (Maylor et al. 2008), surveys via interviews (Remington et al. 2009), and surveys and statistical analysis (Tatikonda and Rosenthal 2000 (factor analysis)).

In most of these proposed methods, complexity factors and dimensions were directly identified and assessed by research participants’ perceptions and evaluations. Therefore, the complexity dimensions that are defined by these methods are essentially a result of a human perceptual phenomenon (Liu 1999). This approach would be most useful in studying the subjective aspect of project complexity (e.g., perceived difficulty of project management). This view of project complexity is echoed in Fioretti and Visser’s (2004) statement that “complexity matters only because of the cognitive problems it gives rise to” (p.12), and Remington et al.’s (2009) statement that “[what matters is] how it is understood by the people who are affected…. [therefore] complexity is most usefully conceptualised in cognitive terms.” However, this approach has limitations in producing objective knowledge about the interrelationships between project complexity factors and the levels of project complexity that may vary between different projects.

With this background in mind, this research aims to identify the dimensions of project complexity by looking at the main sources of variations in the project complexity factors in an empirical dataset. In other words, this research suggests that project complexity dimensions can be statistically defined based on empirical data for various project complexity factors.

In the next section, a literature review on the definitions and factors of project complexity is provided. Then, the methodology and results of this research are presented in the following section. Subsequently, the implications of the results for IM as well as for general project management are discussed.
2 LITERATURE REVIEW ON PROJECT COMPLEXITY

2.1 Definitions of Project Complexity

Table 1 shows several selected definitions of project complexity found in the project management literature. As shown in this table, some disagreement and different—but, inter-related—perspectives exist in the definitions of project complexity in the literature (Bosch-Rekveldt et al. 2011; Vidal et al. 2011; Remington et al. 2009; Vidal and Marle 2008; Gidado 1996). One perspective to project complexity seems to be centered on managerial complexity (i.e., difficulty of management), which means that project complexity is the property of a project that makes managing the project difficult, and therefore requires more sophisticated managerial skills and systems. And, the other perspective seems to be more focused on the nature of the multitude of inter-related and interacting entities in projects (e.g., stakeholders, disciplines, trades, resources, processes, technologies etc.) and uncertainty. The concept of project complexity of interest in this research is in line with the latter view.

Table 1: Definitions of project complexity in the project management literature

<table>
<thead>
<tr>
<th>Authors</th>
<th>Definition of Project Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baccarini (1996)</td>
<td>The degree to which a project consists of many varied interrelated parts with regard to any project dimension relevant to the project management process, such as organization, technology, environment, information, decision making and systems</td>
</tr>
<tr>
<td>Gidado (1996)</td>
<td>The measure of the difficulty of implementing a planned production work flow in relation to any one or a number of quantifiable managerial objectives</td>
</tr>
<tr>
<td>Vidal and Marle (2008); Vidal et al. (2011)</td>
<td>The property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system</td>
</tr>
<tr>
<td>Remington et al. (2009)</td>
<td>The degree to which a project demonstrates a number of characteristics that makes it extremely difficult to predict project outcomes, to control or manage the project</td>
</tr>
</tbody>
</table>

2.2 Project Complexity Factors

A large number of various sources—i.e., factors—of project complexity also have been discussed in the literature, and researchers have often attempted to categorize them. Table 2 shows several classifications of project complexity found in the project management literature. As shown in this table, many researchers have categorized and analyzed project complexity factors in different ways, while the most commonly used categories were organizational factors and technical factors. The project complexity factors that were looked at in this research can be categorized into these two groups from a broad perspective.
Table 2: Classifications of project complexity factors in the project management literature

<table>
<thead>
<tr>
<th>Authors (year)</th>
<th>Classification of Project Complexity Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gidado (1996)</td>
<td>‘Within-tasks’ complexity factors (i.e. those that are inherent in the operation of individual tasks and originate from the resources or the environment) and ‘among-tasks’ complexity factors (i.e., those that originate from bringing different parts together to form a workflow)</td>
</tr>
<tr>
<td>Williams (1999)</td>
<td>Structural uncertainty (i.e., the number and interdependence of elements) and uncertainty in goals and means</td>
</tr>
<tr>
<td>Maylor (2003)</td>
<td>Organizational factors (e.g., the number of people, departments, organizations, locations, nationalities, languages, and time zones involved in a project), technical factors (e.g., the level of novelty of any technology, system or interface), and scale/resource factors (e.g., the scale of the project and the size of the budget)</td>
</tr>
<tr>
<td>Xia and Lee (2004)</td>
<td>Structural/ dynamic organizational factors (i.e., types of and number of relationships among hierarchical levels, formal organizational units, and specialization) and structural/dynamic technological factors (i.e., types of and number of relationships among inputs, outputs, tasks, and technologies)</td>
</tr>
<tr>
<td>Remington and Pollack (2007)</td>
<td>Structural (i.e., interactions between many interconnected tasks), technical (i.e., unknown or untied design characteristics), directional (i.e., not agreed-upon goals and goal-paths), and temporal factors (i.e., volatility over the duration of the project)</td>
</tr>
<tr>
<td>Vidal and Marle (2008)</td>
<td>Technological factors and organizational factors, in terms of the size of project system, the variety of project system, independencies within project system, and context-dependence</td>
</tr>
</tbody>
</table>

3 RESEARCH METHODOLOGY

3.1 Data Collection

A survey questionnaire was developed as a tool for collecting empirical data for project complexity factors. (This survey questionnaire was developed as a part of a larger survey conducted by Construction Industry Institute Research Team 302 (CII RT 302). More information about this CII research project can be found in CII 2014.) Table 3 shows the project complexity factors included in the questionnaire. These factors were selected based on the result of the literature review and discussions with sixteen experienced project engineers/managers who participated in the questionnaire development process. The project characteristic factors that can be identified at a project’s onset were focused on in this research, and thus dynamic factors such as change orders and changes in the economic environment were excluded. As mentioned above, the complexity factors included in this research cover the organizational aspect as well as the technical aspect of project complexity, and are, especially, in line with the project complexity factors identified in Bosch-Rekveldt et al. 2011, Geraldi and Adlbrecht 2007, and Vidal et al. 2011.
Table 3: Project complexity factors included in the survey

<table>
<thead>
<tr>
<th>No.</th>
<th>Project Complexity Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cost Pressure</td>
</tr>
<tr>
<td>2</td>
<td>Schedule pressure</td>
</tr>
<tr>
<td>3</td>
<td>Extended/uncertain scope</td>
</tr>
<tr>
<td>4</td>
<td>Execution risks</td>
</tr>
<tr>
<td>5</td>
<td>Multiple owners (e.g., JV)</td>
</tr>
<tr>
<td>6</td>
<td>New technology</td>
</tr>
<tr>
<td>7</td>
<td>Large number of suppliers/subcontractors</td>
</tr>
<tr>
<td>8</td>
<td>Multiple engineering centers</td>
</tr>
<tr>
<td>9</td>
<td>Government rules/regulations</td>
</tr>
<tr>
<td>10</td>
<td>Multiple general contractors/EPCs</td>
</tr>
<tr>
<td>11</td>
<td>Large number of engineered items</td>
</tr>
<tr>
<td>12</td>
<td>Multiple languages</td>
</tr>
<tr>
<td>13</td>
<td>Unfamiliar partners/collaborators</td>
</tr>
<tr>
<td>14</td>
<td>Not-aligned software/design standards between parties</td>
</tr>
<tr>
<td>15</td>
<td>Unclear geographical boundaries within project (“battery limit”)</td>
</tr>
<tr>
<td>16</td>
<td>Unclear requirements between involved parties</td>
</tr>
<tr>
<td>17</td>
<td>Unclear responsibilities between involved parties</td>
</tr>
</tbody>
</table>

Then, the surveys were administered directly by the authors. The authors had either a face-to-face meeting or a web conference call with project engineers/managers/interface managers representing a project. The interviewees were asked to rate the project complexity factors on a 10-point scale by the question, “How much does this factor contribute to the complexity of your current project? (1 for the lowest and 10 for the highest)?” Also, the interviewees were asked to give responses solely based on their current project, or their most recently completed project if there was no current project to which they belonged.

The survey was conducted during 2013. In total, 46 projects owned or managed by US- or Canada-based organizations were studied in this survey, and the data that was valid for the analysis presented in this paper were collected for a total of 45 projects. The average rating of complexity factors ranges from 1.94 to 7.76 with a mean of 5.21 in the sample. This distribution of average complexity score shows that the sample included a wide range of projects in terms of project complexity. More detailed description of data collection method as well as the sample is available in Shokri et al. 2014.

3.2 Data Analysis

The collected data were analyzed by principal component analysis (PCA). PCA is a widely used statistical method used for reducing the dimensionality of a dataset while retaining the variations in the dataset as much as possible. In PCA, the original data are transformed into a smaller number of new variables called principal components (PCs). Although there are several variants of the analysis method, one of the most common methods to define PCs is finding the eigenvectors of the correlation matrix of the original variables (Jolliffe 2002), which is the method used in this research. If the original variables are interrelated, the first few PCs—i.e., those with a large eigenvalue—retain most of the variations that were distributed over the original variables. If an appropriate number of PCs are selected, therefore, the PCs can retain most of the ‘information’ in the dataset, and that is why PCA can be used for reducing the number of dimensions in the dataset. In this research, PCs were used to define the major dimensions of project complexity extracted from the empirical dataset.
4 RESULTS

As mentioned in the previous section, selecting a suitable number of PCs is crucial in PCA, because PCA has two conflicting goals; they are reducing the number of PCs and maximizing the variances accounted for by the PCs. Many rules-of-thumb for this process are available in the literature, but there is no single best rule (Jolliffe 2002). Among these rules, one of the most common criteria, called Kaiser’s rule, was used in this research. According to this criterion, only the PCs whose eigenvalue is greater than 1 are selected, and as a result, a total of 6 PCs were extracted from the dataset.

Figure 1 shows the total variance that is accounted for by each of the PCs, and the cumulative percentage of total variance of the 6 PCs. As shown in this Figure, the percentage of total variance that is accounted for by each of the 6 PCs is 27.76%, 10.83%, 10.53%, 8.61%, 6.76%, and 6.25%, and the cumulative percentage of total variance accounted for by the PCs is 70.73%.

![Figure 1: Percentage of total variance and cumulative percentage of total variance of the principal components of project complexity](image)

Table 4 shows the loadings for the 6 PCs. Interpretation of PCs is primarily done by looking at the general pattern of the loadings (i.e., coefficients for the original variables) for the PCs (Jolliffe 2002). As shown in this table, the first PC has positive loadings for all original variables, and especially has a high level of loading for ‘unclear responsibilities between involved parties’, and ‘unclear requirements between involved parties’, ‘new technology’, and ‘extended/uncertain scope’, all of which are related to either the clarity of scope or the newness of technology in the design. Therefore, this PC can be interpreted as ‘unclear scope of work for multiple stakeholders in the definition and design of projects with new technology’.
Table 4: Loadings for the first 6 PCs of project complexity*

<table>
<thead>
<tr>
<th>Principal Components</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost pressure</td>
<td>0.17</td>
<td>0.39</td>
<td>0.38</td>
<td>0.47</td>
<td>0.53</td>
<td>-0.10</td>
</tr>
<tr>
<td>Schedule pressure</td>
<td>0.58</td>
<td>0.39</td>
<td>0.36</td>
<td>0.20</td>
<td>-0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>Extended/uncertain scope</td>
<td>0.65</td>
<td>0.15</td>
<td>-0.03</td>
<td>0.24</td>
<td>-0.24</td>
<td>-0.40</td>
</tr>
<tr>
<td>Execution risks</td>
<td>0.38</td>
<td>0.34</td>
<td>-0.30</td>
<td>0.39</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>Multiple owners (e.g., JV)</td>
<td>0.53</td>
<td>-0.07</td>
<td>-0.19</td>
<td>0.10</td>
<td>0.46</td>
<td>-0.01</td>
</tr>
<tr>
<td>New technology</td>
<td>0.66</td>
<td>0.07</td>
<td>-0.34</td>
<td>0.07</td>
<td>-0.01</td>
<td>-0.33</td>
</tr>
<tr>
<td>Large number of suppliers/subcontractors</td>
<td>0.56</td>
<td>0.38</td>
<td>-0.14</td>
<td>-0.36</td>
<td>0.08</td>
<td>-0.40</td>
</tr>
<tr>
<td>Multiple engineering centers</td>
<td>0.59</td>
<td>0.19</td>
<td>0.24</td>
<td>-0.57</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Government rules/regulations</td>
<td>0.38</td>
<td>0.39</td>
<td>0.25</td>
<td>0.21</td>
<td>-0.14</td>
<td>0.54</td>
</tr>
<tr>
<td>Multiple general contractors/EPCs</td>
<td>0.44</td>
<td>0.27</td>
<td>-0.28</td>
<td>-0.41</td>
<td>0.30</td>
<td>0.44</td>
</tr>
<tr>
<td>Large number of engineered items</td>
<td>0.35</td>
<td>0.34</td>
<td>0.18</td>
<td>-0.26</td>
<td>-0.55</td>
<td>0.02</td>
</tr>
<tr>
<td>Multiple languages</td>
<td>0.30</td>
<td>-0.35</td>
<td>0.77</td>
<td>-0.06</td>
<td>-0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Unfamiliar partners/collaborators</td>
<td>0.54</td>
<td>-0.27</td>
<td>0.45</td>
<td>-0.09</td>
<td>0.13</td>
<td>-0.18</td>
</tr>
<tr>
<td>Not-aligned software/design standards between parties</td>
<td>0.47</td>
<td>-0.52</td>
<td>0.21</td>
<td>0.12</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>Unclear geographical boundaries within project</td>
<td>0.53</td>
<td>-0.32</td>
<td>-0.19</td>
<td>-0.34</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>Unclear requirements between involved parties</td>
<td>0.72</td>
<td>-0.32</td>
<td>-0.34</td>
<td>0.27</td>
<td>-0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>Unclear responsibilities between involved parties</td>
<td>0.74</td>
<td>-0.46</td>
<td>-0.18</td>
<td>0.16</td>
<td>-0.23</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*Note. In bold type are the loadings whose absolute values are greater than half the maximum loading for the PC.

The second PC has negative loadings for the variables such as ‘unclear responsibilities between involved parties’, ‘unclear requirements between involved parties’, ‘unclear geographical boundaries within project’, ‘not-aligned software/design standards between parties’, ‘multiple languages’, ‘unfamiliar partners/collaborators’, all of which are related to either the clarity of boundaries or communication between parties. In the meantime, the second PC has positive loadings for many other variables such as ‘cost pressure’, ‘schedule pressure’, ‘execution risks’, ‘large number of suppliers/subcontractors’, ‘government rules/regulations’, and ‘large number of engineered items.’ Therefore, the second PC contrasts the uncertainty in boundaries and communication with the rest of the complexity factors, and implies that after the issues of the clarity of scope and of the newness of technology in the design have been accounted for, the main source of variation in the dataset is the uncertainty in boundaries/communication relative to the rest of the complexity factors.

The third PC has an outstanding loading for ‘multiple languages’, and ‘unfamiliar partners/collaborators’ follows in term of the size of loading. These two variables are thematically inter-related in general, and reflect that there are project participants with unfamiliar backgrounds. Therefore, this PC can be interpreted as ‘unfamiliarity with other project participants’.

The fourth PC has negative loadings for the variables such as “multiple engineering centers”, ‘multiple general contractors/EPCs’, and ‘Large number of suppliers/subcontractors’, whereas it has positive loadings for ‘cost pressure’ and ‘execution risks’. Therefore, the fourth PC contrasts the multiplicity of stakeholders with cost pressure/risks, and implies that after the variances that are accounted for by the first three PCs, the main source of variations in the dataset is the multiplicity of stakeholders relative to the amount of cost pressure and execution risks.
The fifth PC has a relatively high level of negative loading for 'large number of engineered items' while having positive loadings for 'cost pressure', 'multiple owners', and 'multiple general contractors/EPCs'. Therefore, the fifth PC contrasts the multitude of engineered items with cost pressure and the multiplicity of owners/general contractors, and implies that after the variances that are accounted for by the first four PCs, the main source of variations in the dataset is the multitude of engineered items relative to cost pressure and the multiplicity of owners/general contractors.

The sixth PC has the highest positive loadings for 'government rules/regulations' and 'multiple general contractors/EPCs', while having negative loadings for 'extended/uncertain scope', 'large number of suppliers/subcontractors', and 'new technology'. Government rules/regulations and multiple general contractors/EPCs are related to the high-level program/project administration, and the sixth PC contrasts these factors with lower-level scope and technology factors.

5 DISCUSSION

As shown in the previous section, PCA was used in this research for finding the main sources of variations in the dataset, which can be defined as major dimensions of project complexity. As a result of this method, 6 interpretable PCs were defined, and these PCs combined to explain more than 70% of the total variance in the dataset. In other words, the number (17) of original variables was reduced to the smaller number (6) of new variables by PCA, while 30% of the total variance was sacrificed. One should not take from this that the 30% of the total variance excluded in the 6 PCs are not important, but, given that the data were collected by surveys, and that the data are under the influence of random errors as well as the sample size, it seems acceptable to say that the 6 PCs capture the majority of the sources of variations in the dataset.

An interesting finding from this analysis is that the complexity factors that were highly rated for most of the projects, such as 'cost pressure', 'schedule pressure', and 'execution risks', did not have much variations in the dataset, and therefore contributed to the first few PCs relatively less than other factors. This shows that PCA is useful for distinguishing the complexity factors that actually vary between projects from the factors that are shared by most of the construction projects studied. Therefore, the results of PCA might be useful for specifically developing the managerial approaches to address the complexity factors that vary between projects and the managerial approaches to address the complexity factors that are common among projects.

The fact that the first PC is positively related with every original variable tells us that all of the original variables are inter-related to some extent, and the first PC can serve as a kind of composite indicator of the level of overall project complexity. This implies that some projects in the dataset are more complex in general than others, and that the score for the first PC can tell us overall how complex a project is. Therefore, this PC might be useful for determining the level of systematization of project management system required in a project. The project complexity dimensions defined by later PCs indicate more specific aspect (i.e., source) of project complexity and explain a smaller variance in the dataset.

Notably, complexity dimensions defined by the PCs are related to organizational interactions (e.g., unclear scope of work for multiple stakeholders in the definition (1st PC), uncertainty in boundaries and communication (2nd PC), unfamiliarity with other project participants (3rd PC), and the multiplicity of stakeholders (4th PC)). These results hint that organizational interactions (i.e., interfaces between parties involved) are a major source of complexity in many projects. This implication is in line with observations/findings in previous research works. Vidal et al. (2009) reported that 11 project complexity drivers (i.e., factors) identified from their survey belong to the family of "project interdependencies", and this takes up 61.1% of the entire project complexity drivers they identified. From this result, they also argued that their result helps justify the tools and methods that been recently developed to deal with interactions and interdependencies in projects.

Vidal and Marle (2008) stated that classical tools and methods of project management are not sufficient in dealing with the level of complexity in modern projects, and therefore, the current level of project complexity justifies the need for a new project management approach that can assist the existing ones,
such as IM. Similarly, Baccarini (1996) argued that project complexity should be treated by more efforts for integration such as coordination, communication, and control. Therefore, more advanced managerial skills and tools for interface management would be required to effectively manage complex projects, and in particular, it seems that such development of advanced skills and tools for project management should aim at those projects that have complex organizational structure and a large number of interfaces in it. An efficient implementation of managerial functions can influence the impact of project complexity on project performance (Gidado 1996), and therefore is expected to mitigate the adverse impact of complexity on performance in many construction projects. More research is strongly warranted in this area.

6 CONCLUSION

Although many researchers have attempted to define project complexity and have investigated various factors that would affect complexity in construction projects, it is unclear what the dimensions of project complexity are and how they can be measured. This lack of knowledge about project complexity has been one of the main reasons that the construction industry has displayed great difficulty in effectively dealing with complexity in projects. Given this situation, this research aimed to define the dimensions of project complexity based on empirical data. To achieve this research objective, a questionnaire was developed as a tool for collecting data for project complexity factors, surveys were administered in semi-structured interviews, and the collected data for 45 major construction projects were analyzed using PCA. As a result, 6 interpretable PCs were extracted from the dataset: ‘unclear scope of work for multiple stakeholders in the definition and design of projects with new technology’ (1st PC), ‘the uncertainty in boundaries and communication relative to other complexity factors’ (2nd PC), ‘unfamiliarity with other project participants’ (3rd PC), ‘the multiplicity of stakeholders relative to the amount of cost pressure and execution risks’ (4th PC), ‘the relative multitude of engineered items’ (5th PC), and ‘the high-level program/project administration’ (6th PC). These dimensions of project complexity defined by the PCs tell us not only what the possible dimensions of project complexity are, but also which dimension explain the most variations in the dataset. Therefore, these complexity dimensions can help with assessing the level of complexity of a project at its onset and with determining the skills, tools, and systems that will be required to effectively cope with the sources of complexity in the project. Additionally, the analysis results hint that organizational interfaces should be effectively managed to prevent project failure in construction projects, and therefore support the need for IM in complex projects.

This research has several limitations that can be addressed in future research. First, the complexity factors included in this research are limited. More research efforts to investigate a broader set of project complexity factors are strongly warranted to gain a comprehensive view of various complexity factors that may play an important role in construction projects. Secondly, the sample size used in this research is modest. Since PCA is a data-driven method, a larger sample size may be required to gain a greater confidence with the PCs extracted in this research. Thirdly, the impacts of the project complexity dimensions identified in this research on project performances, such as cost and schedule, are yet to be investigated. Therefore, more future research efforts are strongly warranted to relate the levels of project complexity with project performance measures, and to investigate the effectiveness of approaches to address project complexity in this relationship.

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References


INVESTIGATION ON CONSTRUCTION WORKERS’ SOCIAL NORMS AND MANAGERS’ DESIRED NORMS REGARDING ABSENCE: PRELIMINARY RESULTS FROM A NORM ELICITATION STUDY

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Abstract: Researchers have found that construction workers’ absence behavior is under the influence of social norms existing in work groups. Although the previous research efforts on social absence norms in construction have significantly expand our understanding of how they might develop in work groups and exert on workers’ absence behavior, we have limited knowledge about what the absence norms actually existing in construction work groups are. Given this background, the objective of this research is to measure the absence norms shared by construction workers in their work groups as well as the norms desired by construction managers. To achieve this, a novel approach to elicit norms in organizations that were developed by Krupka and Weber (2013) has been used in this research. In this approach, experiment participants are asked to evaluate several hypothetical actions plausible in a given situation using their understanding of what a typical member of their team would think about the actions as well as their own opinions on the actions. The elicitation of social norms is facilitated by a coordination game structure and monetary incentives in the experiment. Using this method, construction workers’ social norms and personal standards, managers’ belief about workers’ social norms, and managers’ desired norms, regarding worker absence behavior were elicited at a construction site. Analyses on the differences between workers’ social norms and managers’ desired norms reveal that there is a general pattern of alignment, but also a measurable difference, between workers’ social norms and managers’ desired norms regarding absence at the site.

1 INTRODUCTION

In their influential paper published in 1982, Johns and Nicholson defined absence culture as “the set of shared understandings about absence legitimacy in a given organization and the established ‘custom and practice’ of employee absence behavior and its control......” Since they introduced the concept of absence culture in organizational behavior research, many researchers have investigated the impacts of such social aspects on employees’ absence behavior in organizations, and have demonstrated that absence behavior is indeed subject to social norms in organizations. Among those researchers, some have looked at construction workers’ absence behavior, and have found that construction workers’ absence behavior is also under the influence of social norms existing in their work groups (Ahn and Lee 2015; Ahn et al. 2014; Ahn et al. 2013; Sichani et al. 2011; AbouRizk et al. 2010). Given that construction work groups are known to have a high level of social identity and solidarity in general, social absence norm is an important subject for studying and improving workers’ attendance at jobsites.
Although the previous research efforts on social absence norms in construction have significantly expanded our understanding of how they might develop in work groups and exert on workers’ absence behavior, we have limited knowledge about what the absence norms actually existing in construction work groups are. For example, some previous research has investigated to what extent construction workers’ absence behavior are influenced by their social awareness (c.f., Ahn et al. 2014), but few research attempts have been made to measure what the actual absence norms (i.e., collectively held opinions and beliefs regarding absence) are. Given this background, the objective of this research is to measure the absence norms shared by construction workers in their work groups as well as the norms desired by construction managers. To achieve this, a novel approach called norm elicitation technique has been used in this research.

An overview of this technique is provided in the following section. Subsequently, the results from a preliminary study using this technique are provided, and a discussion on the results will follow.

2 RESEARCH METHOD

2.1 Norm Elicitation Technique

Researchers have tried to measure the social norms in work groups in several ways, and among them the most common is survey questionnaire. Although survey questionnaire is a cost-effective and scalable means to collect real world data, one of the main weaknesses of this method is the difficulty in measuring group-level latent variables such as collectively held norms (Burks and Krupka 2012). To address this issue, Krupka and Weber (2013) developed a novel method for measuring social norms in organizations using hypothetical vignettes and a coordination game structure, called norm elicitation technique. In this method, vignettes describing a situation with which experiment participants will be familiar—because it is a situation that they can observe or experience in the workplace on a daily basis—are provided. A vignette is given along with a range of actions a person might choose from in the situation. Then, participants are asked to rate each alternative action for each vignette using a 4-point Likert scale, each of which means ‘Very inappropriate’, ‘Somewhat inappropriate’, ‘Somewhat appropriate’, and ‘Very appropriate’.

In the experiment, participants are asked to repeat the rating task several times for each vignette. First, participants are asked to try to match their ratings to those of a typical member of a group—either a group they belong to or another group, and they are told that their responses will be compared with the responses of a randomly selected respondent from the group, and that they will be paid if their responses match the responses of the target respondent (i.e., a coordination game structure with monetary incentives). Second, participants are asked to provide their personal opinions (i.e., ratings based on their own personal standards) without trying to match their responses with anybody else’s.

This technique has been used in this research for identifying social norms of construction work groups (i.e., crews) and personal standards regarding absence. As a first step to do this, a list of behaviors regarding absence with which construction workers will be familiar was developed. A focus group discussion with three construction managers was used in this process. Table 1 shows the list of behaviors regarding absence used in this study, sorted in order of appropriateness as identified by the focus group’s ex-ante ranking. (The behaviors were re-sorted in the experiment, and therefore these behaviors were not presented in this order to participants.)
Table 1: List of behaviors regarding absence used in the experiment

<table>
<thead>
<tr>
<th>Absence Behavior</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavior 1</td>
<td>James takes absence without a notice when he does not want to work.</td>
</tr>
<tr>
<td>Behavior 2</td>
<td>James takes absence when he does not want to work, and he informs his absence to his foreman early in the morning.</td>
</tr>
<tr>
<td>Behavior 3</td>
<td>James takes absence when he has a hangover, and he informs his absence to his foreman early in the morning.</td>
</tr>
<tr>
<td>Behavior 4</td>
<td>James takes absence when he has minor illness such as colds and headaches, and he informs his absence to his foreman early in the morning.</td>
</tr>
<tr>
<td>Behavior 5</td>
<td>James takes absence when he has some personal situation like sickness of a family member, and he informs his absence to his foreman early in the morning.</td>
</tr>
<tr>
<td>Behavior 6</td>
<td>James takes absence when he feels too sick to work well, and he informs his absence to his foreman early in the morning.</td>
</tr>
<tr>
<td>Behavior 7</td>
<td>James does not take absence at all unless he has an emergent situation like severe injury or sickness.</td>
</tr>
</tbody>
</table>

2.2 Participants

For conducting the experiment, a building construction site (“Site A”) in Ann Arbor, Michigan, US, was approached. Site A was a large-sized engineering research complex building construction site located on the University of Michigan campus. At the time the site was contacted, the project was in the final phase of construction, and therefore many on-going processes were for the finishing work. The number of workers operating daily at this site was about 40–50 with some variation.

With an agreement with the construction managers to conduct the experiment at this site, construction workers to participate in the experiment were recruited. The purposes and processes of this experiment were explained to the foremen in a weekly meeting at the site, and the foremen verbally advertised the experiment to their team members. In this way, the construction workers were informed when and where the experiment was going to take place, and the workers voluntarily participated in our experiment. As a result, a total of 26 workers (of 9 different trades and of 10 different companies) participated in the experiment. In addition to this, the 3 construction managers of the general contractor participated in the experiment.

2.3 Experiment Procedure

Participants among workers were asked to provide their evaluation of these behaviors twice. On the first pass, the participants were asked to match their ratings with those of a typical member of their own crew; on the second pass, they were asked to provide their personal opinions. As mentioned above, the elicitation of social norms is facilitated by a coordination game structure and monetary incentives in this experiment. The participants were informed that a subset of all of the participants in this experiment will be randomly selected, and their responses on the first pass will be compared with the responses of another randomly selected participant from their crew, and they will be paid $10 for each of their matching responses. This incentivizing method was clearly explained before the experiment began.

Participants among construction managers (of the general contractor) were also asked to provide their evaluation of the behaviors twice, but in a slightly different manner. On the first pass, the participants were asked to match their ratings with those of a typical construction worker working at the site, and on the second pass, they were asked to match their ratings with their fellow managers at the site. The
construction manager participants were also informed that their responses on the first pass will be compared with the responses of a randomly selected worker participant, and their responses on the second pass will be compared with a randomly selected manager participant.

The experiment was taken during crews’ breaks during work hours (e.g., morning break, lunch time, afternoon break) to avoid interrupting the construction work. Construction workers voluntarily visited the area where the experiment administrators were, and participated in the experiment. When a worker or workers arrive at the experiment place, the experiment administrators briefly introduced the experiment’s purpose and processes, including the information about the incentives. Then, a consent form, the evaluation sheet, and pens were provided to the participants. The experiment administrators gave an instruction, then participants provided their response in each pass. In total, the experiment took approximately 20–25 minutes. Every participant was paid a $10 participation fee at the end of the experiment.

3 RESULTS AND DISCUSSION

The participants’ evaluations of the behaviors were converted into numerical scales: -1, -1/3, 1/3, and 1, for “Very inappropriate,” “Somewhat inappropriate,” “Somewhat appropriate,” and “Very appropriate,” respectively. Tables 2 and 3 present a summary of the evaluations for the absence behaviors provided by the workers and the managers, respectively. Each row in these tables corresponds to an absence behavior that was evaluated by the participants, and these tables separately summarize the participants’ evaluations made during the first pass and the second pass (Workers’ evaluations during the first pass and the second pass are labeled as “Workers’ social norms” and “Workers’ personal standards” in Table 2, and managers’ evaluations during the first pass and the second pass are labeled as “Managers’ desired norms” and “Managers’ belief about workers’ social norms” in Table 3.) The columns of these tables present the mean (M) and the standard deviation (SD) of the responses, and then the number of responses for each option (N(-1), N(-1/3), N(1/3), and N(1)), for each behavior in the list.

<table>
<thead>
<tr>
<th>Behaviors</th>
<th>Workers’ social norms</th>
<th>Workers’ personal standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Absence Behavior 1</td>
<td>-0.97</td>
<td>0.13</td>
</tr>
<tr>
<td>Absence Behavior 2</td>
<td>-0.67</td>
<td>0.62</td>
</tr>
<tr>
<td>Absence Behavior 3</td>
<td>-0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>Absence Behavior 4</td>
<td>-0.13</td>
<td>0.48</td>
</tr>
<tr>
<td>Absence Behavior 5</td>
<td>0.59</td>
<td>0.37</td>
</tr>
<tr>
<td>Absence Behavior 6</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>Absence Behavior 7</td>
<td>0.95</td>
<td>0.18</td>
</tr>
</tbody>
</table>

*Note. The numbers in bold type are the mode of responses for each behavior.
Table 3: Managers’ evaluations summary for the absence behaviors**

<table>
<thead>
<tr>
<th>Behaviors</th>
<th>Managers’ desired norms</th>
<th>Managers’ belief about workers’ social norms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Absence Behavior 1</td>
<td>-1</td>
<td>0.0</td>
</tr>
<tr>
<td>Absence Behavior 2</td>
<td>-1</td>
<td>0.0</td>
</tr>
<tr>
<td>Absence Behavior 3</td>
<td>-1</td>
<td>0.0</td>
</tr>
<tr>
<td>Absence Behavior 4</td>
<td>-0.11</td>
<td>0.31</td>
</tr>
<tr>
<td>Absence Behavior 5</td>
<td>0.78</td>
<td>0.31</td>
</tr>
<tr>
<td>Absence Behavior 6</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>Absence Behavior 7</td>
<td>1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Note. The numbers in bold type are the mode of responses for each behavior.

The fact that the modal response for any behavior received more than 46% of the responses when the task is matching their responses with the responses of a peer shows that there is a general consensus in the belief about the normative evaluations made by the members of their groups, whether it is workers or managers. Also, the fact that a relatively high level of consensus in the normative evaluations exists among all the workers at this site means that to some extent the crews at this site have similar social norms when it comes to which absence behavior is acceptable and which is not.

Tables 2 and 3 show a general pattern of alignment, but also a measurable difference, between workers’ social norms and managers’ desired norms regarding absence. The mode of responses from workers and from managers were identical for four behaviors, while the mode of responses for the other three behaviors was measurably different. To visualize the degree of alignment between workers’ social norms and managers’ desired norms, the mean of the responses from these two groups for each behavior was plotted, as shown in Figure 1. Then, each line in this figure can be seen as a profile of norms held by workers or managers. As shown in this figure, workers’ social norms and managers’ desired norms regarding worker absence behavior shows a complete agreement as to valence (i.e., whether a behavior is in the “appropriate” side or in the “inappropriate” side); both groups agreed that absence behaviors 1–4 are considered inappropriate, whereas behaviors 5–7 are considered appropriate. However, the two groups show some disagreement in the intensity of the evaluations. For absence behavior 3, “James takes absence when he has a hangover, and he informs his foreman of the absence early in the morning,” for example, all of the managers said that this behavior is “very inappropriate,” whereas workers were more likely to say that it is just “somewhat inappropriate.” This shows that there is a subtle but measurable misalignment between workers’ social norms and managers’ desired norms about absence caused by alcohol.
Another interesting, measurable misalignment between workers’ social norms and managers’ desired norms was observed for absence behavior 6, “James takes absence when he feels too sick to work well, and he informs his foreman of the absence early in the morning.” All of the managers said that this behavior is “very appropriate”, while a majority of workers said that it is just “somewhat appropriate”—4 workers even said that it is “somewhat inappropriate.” This result shows that many workers believe that being sick may not be an excuse for an absence that his/her peers would approve of, although managers think that absence due to sickness is perfectly OK.

Although measurable misalignment between workers’ social norms and managers’ desired norms was observed for specific behaviors, managers were found to have a fair understanding of workers’ social norms. Figure 2 compares workers’ social norms with managers’ belief about workers’ social norms. As shown in this figure, the average distance between the two lines is much smaller than that of Figure 1. This supports the idea that the social norms regarding absence actually exist in the workers’ group, and they are even visible to out-group members such as managers—although it may not be as clear as to the in-group members.
4 CONCLUSIONS

To address the lack of our understanding of what the absence norms are in construction work groups, this research aimed at measuring and quantifying actual absence norms shared by construction workers as well as norms desired by managers. To accomplish this goal, a norm elicitation technique developed by Krupka and Weber (2013) was used to collect and analyze empirical data for social norms and personal standards regarding absence.

Using the norm elicitation technique, construction workers’ social norms and personal standards, managers’ belief about workers’ social norms, and managers’ desired norms, regarding worker absence behavior at a construction site were elicited, and they were visualized as a profile represented by a line connecting 7 points in the plots (e.g., the lines in Figures 1 and 2). Analyses on the differences between workers’ social norms and managers’ desired norms revealed that there is a general pattern of alignment, but also a measurable difference, between workers’ social norms and managers’ desired norms regarding absence.

Although this paper demonstrates that the norm elicitation technique is effective for measuring social norms regarding absence in construction projects, more research efforts are warranted to produce more generalizable knowledge in the subject. The greatest weakness of this paper is the small sample size included in the analysis. Therefore, obtaining more data is strongly required in order to generalize the findings from the results presented in this paper. Another, and related, weakness of this paper is that the data used in the analysis were from a single site. Therefore, obtaining more data from multiple projects from different regions or of different types, or of different phases is strongly required to improve the representativeness of the sample. This is crucial because different construction projects may have different characteristics in terms of project environment and context, which can affect absence norms in the projects. As the title of this paper suggests, this paper presents only a pilot study, and therefore, these weaknesses of this paper will be addressed in our future research.

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References

BIM MATURITY ASSESSMENT AND CERTIFICATION IN CONSTRUCTION PROJECT TEAM SELECTION

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Abstract: To implement BIM in a construction project successfully, all the project participants as BIM users must have minimum BIM capabilities. Before any project starts, assessing BIM capabilities of project stakeholders is a concern for construction clients. The main problem of public clients regarding BIM is that they have no mechanism to ensure that the key participants, they hire for a BIM project, have the minimum capabilities (i.e. BIM Infrastructure, processes and qualified resources) to participate in design and delivery of the project. The high variability of firms’ readiness to work with BIM may impose a high cost for the client and other mature members of the supply chain. Therefore, construction clients need a way to ensure minimum BIM maturity of participants, such as a maturity audit to assess BIM competency of potential project team members. From a client’s perspective, “minimum BIM qualification” means “minimum capability to use BIM”. The current BIM maturity models try to assess BIM capabilities level of firms, but lack BIM uses assessment. This research proposes a prototype that focuses on capability of firms in specific BIM uses, while measuring their general BIM capabilities. The research methodology is based on an iterative literature review followed by focus group discussions. Through literature review, the researchers propose BIM platform maturity model. Then, BIM experts discuss on possible improvements. It is expected that by using this model, construction clients may achieve more BIM benefits, i.e. reduced cost, time, and increased quality of project, through selection of BIM-qualified project team members.

1 INTRODUCTION

The construction industry has been facing many problems and barriers, such as cost overruns, time delays, prolonged contractual claims (Liberda et. al., 2003), disputes (Musonda, 2011), and labor productivity decline (Teicholz, 2004), leading to low performance and productivity. In addition, the project-oriented nature of the construction industry and the uniqueness of every project (Wegelius-Lehtonen, 2001), multi-disciplinary, cross-organizational, and changing make-up of Architectural, Engineering, and Construction (AEC) project teams (Liston, 2009) with fragmented supply chain (Cox and Ireland, 2002) increases the complexity of working on large construction initiatives. To improve productivity of the construction industry, different solutions, such as digital construction, are observed. Digital construction aims to address the growing fragmentation problems and improve productivity by using technologies such as Building Information Modeling (BIM) for integrating processes throughout the entire lifecycle of a construction project. BIM proposes a consistent digital information platform to be used by the
stakeholders throughout the lifecycle of the project. To date, many construction projects have reported benefits from the use of BIM technology and recommended it as a remedy for productivity issues (Mihindu and Arayici, 2008). According to McGraw-Hill (2009) the most notable reported BIM benefits of a project, include: reduced conflicts during construction, improved collective understanding of design intent, improved overall project quality, reduced changes during construction, reduced number of RFIs (Requests for Information), and better cost control/predictability.

To implement BIM successfully, in a project, and fully get the benefits, all the project members, as users of BIM should demonstrate minimum BIM capabilities. However public clients have no mechanism to measure the minimum BIM capabilities (i.e. BIM Infrastructure, processes and qualified resources) of the key suppliers to participate in the design and delivery of the project using BIM technology. High variability of BIM maturity level of project members may result in high cost for the client and the most mature members of the supply chain. Therefore, having members who obtain and provide an independent BIM maturity certificate beforehand would help in solving this issue.

This paper reviews the current BIM maturity models, which are developed for the purpose of BIM qualification assessment in project team selection. Since there is a lack in development of maturity levels of BIM Uses in the current BIM maturity models, it proposes a practical BIM maturity model in order to evaluate both general BIM capability and specific ‘BIM Uses’ capability of firms, which are two main concerns of construction clients. Finally a hypothetical sample part of this model, namely 3D Coordination, is developed at maturity level 1, to demonstrate the potential evaluation process used with the proposed maturity model.

2 BIM CAPABILITY MATURITY ASSESSMENT FOR PROJECT TEAM SELECTION

A “maturity model” can be defined as “... a conceptual framework, with constituent parts, that defines maturity in the area of interest. [...] In some cases, [...] a maturity model may also describe a process whereby an organization can develop or achieve something desirable, such as a set of Capabilities or practices” (OPM3, 2003). The term 'BIM Maturity' refers to the quality, repeatability and degrees of excellence of BIM services (Succar, 2010b). Current BIM maturity models in construction were developed for different purposes. Reviewing three of these models, which were developed for the purpose of BIM qualification assessment in project team selection stage (i.e. BIM Indiana University, 2012; CIC, 2012; Sebastian and Van Berlo, 2010), can help researchers in a) understanding what the construction client expects from a BIM maturity assessment tool during the project team selection and qualification, b) what BIM topics should be assessed for such a process, and c) how a BIM maturity assessment should be done in practice. The authors believe that an industry guardian (evaluator) can alleviate burdens from the client by independently conducting such a process beforehand.

Sebastian and Van Berlo (2010) developed the BIM Quick Scan tool to benchmark current BIM performance level of AEC organizations for the Dutch construction industry. The purpose was to justify qualification of project parties to be involved in projects and to “… raise awareness and establish a common strategy for innovation through BIM” (Sebastian & Van Berlo, 2010). In this approach, a certified BIM consultant carries out the assessment upon request of an organization and produces an assessment report. This approach combines quantitative and qualitative assessments of the ‘hard’ and ‘soft’ aspects of BIM at a) corporate level, b) ICT infrastructure level, and c) model/modeling level. Four main chapters of an organization, including organization and management, mentality and culture, information structure and information flow, and tools and applications, are assessed by the BIM Quick Scan tool. Each one of these chapters contains a number of Key Performance Indicators (KPIs) “… in the form of a multiple-choice questionnaire. (KPIs). […] With each KPI, there are a number of possible answers. For each answer, a score is assigned. Each KPI also carries a certain weighting factor. The sum of all the partial scores after considering the weighting factors represents the total score of BIM performance of an organization” (Sebastian & Van Berlo, 2010, pp. 258 and 259). KPIs are assessed using a percentile scale and the chapters are assessed in a five-level scale of 0 to 4 (Sebastian & Van Berlo, 2010). The tool asks about presence of ‘BIM Uses’ in the firm, but there is a problem associated with categorization of BIM Uses. While some of these BIM Uses are specific, such as planning (4D) and quantities/costing, the others are very general, such as simulations, design, architectural, construction, etc. In addition,
although it asks for presence of a BIM Use, the maturity level of a specific BIM Use is not evaluated by the tool. For example, if a firm has BIM 4D planning, this assessment tool cannot assess how well the firm is using BIM for planning (4D) in a scale.

According to CIC (2012), it is suggested that the BIM maturity level of applicants must be evaluated during the team selection stage, namely during Request For Qualification (RFQ) and Request For Proposal (RFP). At the project team selection stage, to enable the owner to assess the BIM maturity level of applicants, a BIM capability and maturity model is needed. The owner asks about BIM experience and expertise of applicants in RFQ. Applicants must provide proof of qualifications they claim to have. In RFP, the applicants must propose the BIM services that they can provide for the project. After reviewing the BIM qualifications and BIM proposed services of all applicants, they will be scored in a BIM maturity matrix. Considering the results of BIM maturity assessment, the owner selects the applicants who best match with the required criteria. The categories in "BIM Qualifications Scoring Matrix" and "Proposal Scoring Matrix" are shown and presented in Table 1, according to CIC (2012).

Table 1: BIM qualification and proposal assessment categories (CIC, 2012)

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>1. BIM Project Execution Planning Experience:</strong> Experience the team has with planning for BIM on projects.</td>
<td><strong>1. Price:</strong> What is the total price for the listed services</td>
</tr>
<tr>
<td><strong>2. Collaboration Experience:</strong> Willingness of the team to collaborate with others and their experience collaborating.</td>
<td><strong>2. Additional BIM Uses:</strong> What additional BIM services are proposed</td>
</tr>
<tr>
<td><strong>3. BIM Tools:</strong> Competence of the project team in implementing various BIM tools.</td>
<td><strong>3. Project Team Qualification:</strong> How much experience and success has the proposed project team had</td>
</tr>
<tr>
<td><strong>4. Technical Capabilities:</strong> Abilities of the organization to perform BIM</td>
<td><strong>4. Collaboration Procedure:</strong> What collaboration procedure is included in the proposal</td>
</tr>
<tr>
<td><strong>5. Deliverables:</strong> What are the deliverables proposed</td>
<td></td>
</tr>
</tbody>
</table>

Although this model (CIC, 2012) considers the proposed BIM Uses of applicants, it fails to measure the maturity level of a firm in performing specific BIM Uses, such as 3D Coordination, 4D Modeling, etc. The BIM assessment categories of ‘BIM tools’, ‘Technical Capabilities’, and ‘Deliverables’, are general in BIM maturity assessment. The authors of this paper believe that clients should not have to expend effort on a case-by-case basis to do this assessment every time. Having an independent certification body where BIM maturity certification is obtained, managed by independent certified assessors (i.e. like ISO) would be simpler for the clients and would better control quality of assessment for the whole industry.

Another BIM maturity model, in form of a matrix, was developed by the Indiana University (IU) to evaluate BIM expertise and experience of construction project participants (consultants) (BIM Indiana University, 2012). “IU BIM Proficiency Matrix” must be submitted to Indiana university by the design team before the contract award for its construction projects of $5M or greater and for the construction projects which have already used BIM. For other projects, it is encouraged but not required to submit. The consultant scores the matrix based on the examples of previous projects with use of BIM. The IU can understand the BIM level of expertise and experience of design team by evaluating the maturity matrix. Interested contractors can submit an “IU BIM Proficiency Matrix” to the university at the bid submittal stage (BIM Indiana University, 2012). This matrix contains eight categories, comprising of four sub-categories. A total of thirty-two subcategories are scored with a score ranging from 0 to 1. A maximum total score of thirty-two can be achieved based on this mechanism. The achieved total score locates the BIM maturity level of firm on a defined range: total score of 0 to 12 is assigned for “Working Towards BIM” category, 13 to 18 for “Certified BIM”, 19 to 24 for “Silver”, 25 to 28 for “Gold” and 29 to 32 is assigned for “ideal”. The problem with this scoring system is that for each subcategory a value from 0 to 1 is earned based on subjective judgement from maturity level. This approach is not very accurate. For example, although a score of 0.45 represents a higher maturity level than a score of 0.4, it is not defined clearly how to justify this scoring
and its performance measurement. This model considers some BIM Uses, such as ‘Design side collision detection’, ‘Coordination modeling’, in maturity assessment. However, lack of development of capabilities within different maturity levels, is a deficiency. According to Succar (2010a), “the matrix focuses on the accuracy and richness of the digital model (as an end-product) and has less focus on the process of creating that digital model”. In addition, the matrix has very little consideration for BIM resources. For example, the sub-category of “Model managers role defined” asks about the presence of a model manager for each discipline. However, the level of BIM expertise, experience, and knowledge of model managers are not considered in the scoring. The matrix also has other weaknesses, for example in BIM technological resources assessment. Although delivering a rich and accurate digital model is the focus point of this model, the required technological infrastructure was not considered in maturity assessment.

It is important for construction clients to measure how well a potential project member can use a specific BIM application. All the reviewed models have a common problem, which is lack of development of capabilities in maturity levels of BIM Uses. There is a need to address this issue.

3 PROPOSED BIM MATURITY MODEL FOR INDEPENDENT CERTIFICATION

As mentioned in section 1, construction clients need a way to ensure that the participating firms of project meet minimum BIM requirements in order to qualify for a project. From the perspective of a client, “minimum BIM qualification” can be translated to “minimum capability to use BIM” and this is practically what is wanted by a certification: ‘how well does this participant uses BIM technology in a construction project’. This is accepted as as a principal assumption of this study. Clients want to know whether a firm is capable of using BIM, and if yes, to what level. This perspective offers an opportunity to adapt existing BIM maturity models to reach that goal. There is a lack, in the current BIM maturity models, to look at BIM through this lens. The existing BIM maturity models provide a rich base of information to achieve this goal. However, no model has focused on development of maturity levels of ‘BIM Uses’. “A BIM Use is a unique task or procedure on a project which can benefit from the integration of BIM into that process” (CIC, 2011). This paper proposes a new approach in assessing BIM capability maturity of firms in performing specific BIM uses, while measuring their general BIM capabilities at the same time. This approach represents the clients’ expectation of a maturity model. They want to know how well a project stakeholder uses BIM to delivers a BIM product or service. Therefore, the authors propose a BIM platform maturity model that provides information about maturity of BIM Uses that will meet clients’ expectation.

Client perspective in maturity assessment

The software industry has considerable experience in adopting capability maturity model from quality management field to software industry processes (i.e. Capability Maturity Model Integration (CMMI)). Although processes in the software industry are quite different from processes in the construction industry, but the notion of process maturity is the same. To develop our proposed model in this study, we have studied a maturity model from the software industry, namely Software Maintenance Maturity Model-S3m (April, 2005), which is based on the client perspective and is designed from using both industry references, and national and international standard practices. This model helps software “maintainers identify their process maturity level and guide them to higher maturity processes…. The maintenance maturity model was developed to address the uniqueness of software maintenance” (April, 2005, p. 143). S3m uses the architecture of the CMMI (SEI, 2010a) and draws practices from two international software standards: ISO12207 and ISO 14764. The reason that S3m is studied is that the relation of our proposed maturity model to the other BIM maturity models (i.e. IU and CIC) is a similar relation of S3m to CMMI. S3m maps practices from CMMI and ISO standards in the same way our proposed model maps to several BIM maturity models (i.e. Succar, 2010a,b; Succar et al., 2012; Sebastian and Van Berlo, 2010; CIC, 2012; BIM Indiana University, 2012; NIBS, 2007, 2012) to cover unique expectation of client (BIM uses).

3.1 Proposed architecture of the BIM Platform Maturity Model (BIMPMM)

April (2005) organized software maintenance activities in a hierarchical architecture from the most general definitions to most specific practices. The first level of this hierarchy (less specific) to fourth level (most specific) includes respectively “process domain”, “Key Process Areas (KPAs)”, “Roadmaps”, and
“Practices”. Our proposed BIM platform maturity model is inspired from S3™ architecture while using the processes and activities that are BIM specific, as shown in Table 2.

Table 2: Proposed architecture of the BIM Platform Maturity Model (BIMPMMD)

<table>
<thead>
<tr>
<th>BIM Domain</th>
<th>Key Process Area (KPA)</th>
<th>Practices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>BIM Uses</td>
<td>3D Coordination</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Design Reviews</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Design Authoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other BIM Uses</td>
</tr>
<tr>
<td>Resources</td>
<td>General BIM Capability</td>
<td>Project Management</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Infrastructure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Human resources</td>
</tr>
</tbody>
</table>

3.1.1 BIM domains

Various domains are defined for BIM in the literature. This first study just focuses on the domains of “BIM Process” domain and “BIM Resources” domains as they pertain to the construction industry to address the construction clients concern regarding assessment of minimum BIM capabilities of applicants in their project. The “BIM Process” domain considers BIM capabilities regarding specific “BIM Uses” and the maturity level of BIM project management. This domain is very important as a client wants to know how well a firm is using and managing BIM technology in this area. The “BIM resources” domain evaluates the required resources to perform the BIM Processes in general. The available resources of applicants are an important factor for project team selection from the perspective of the construction clients.

3.1.2 Key Process Areas (KPAs)

In this study, KPAs of the “BIM Process” domain include BIM uses and project management. BIM uses are about specific applications of BIM in construction projects. Top three most frequent uses of BIM, which include “3D Coordination”, “Design Reviews”, and “Design Authoring” according to Kreider et al. (2010) study, are selected to introduce example of BIM Use specific KPAs in the proposed BIM platform maturity model. The proposed ‘project management’ KPA refers to the quality of management in using BIM. We know that BIM project management can include various activities, such as designing BIM execution plan in project, defining and procuring required BIM resources, defining BIM collaboration processes, etc. The proposed “BIM Resources” domain includes KPAs related to BIM “infrastructure” and “human resources”. In the other words, the allocated infrastructure and human resources to BIM at the organization/project levels will be assessed in this domain and within these KPAs. The proposed maturity model, considers BIM infrastructure as the technological aspects of BIM (i.e. software, hardware, network, ...). We also know that human resources relates to the personnel roles and responsibilities, and the level of knowledge, skill, and experience that they posses, in using BIM technologies. The training and educational programs of an organization to improve BIM competency of personnel will be evaluated in this category. In the proposed maturity model, KPAs are also categorized according to their general and specific BIM capabilities. Since a ‘BIM Use’ is about specific application of BIM in a doing a task in a project, KPAs of ‘BIM Uses’ are considered as specific BIM capabilities. But KPAs of “Project management”, “Infrastructure” and “Human resources” don’t reflect any specific BIM application and are defined, in the proposed maturity model, to be part of a ‘General BIM capability’ category.

3.1.3 Roadmaps and practices

A Roadmap is defined “… as a set of linked practices that can often cover many levels of maturity” (April 2005). Each KPA contains a number of roadmaps. Practices are defined within the roadmaps. “In a given
roadmap, the sequencing of the practices is organized based on the sequencing of the pre-requisites required to move from an initial beginner's implementation of a process up to its mastery. Practices required to initiate the implementation process are positioned at the initial level (e.g. level 1), while more sophisticated practices are ordered progressively up to level 5." (April, 2005). In the proposed BIM platform maturity model, the practices are mapped from current BIM maturity models (Succar, 2010a,b; Succar et al., 2012; Sebastian and Van Berlo, 2010; Computer Integrated Construction Research Program, 2012; BIM Indiana University, 2012; NIBS, 2007, 2012) and other relevant resources. Finally, the practices that represent capabilities with the same topic, construct a roadmap. BIM experts meet to discuss the position and the rationale of each practice in the maturity levels, and possible improvements. Based on the obtained feedback, an iterative development of the proposed maturity model (iterative model development/improvement and experts’ feedback) is carried out by the researchers.

3.2 Proposed maturity scale

As many maturity models use five-level scale of maturity (see Succar et al., 2012, p. 134), our model also proposes a five-level scale. We adopted the maturity scale of BIM Planning guide for facility owners (CIC, 2012), which used BIM maturity level definitions inspired from the Capability Maturity Model Integration (CMMI) for Services (Forrester et al., 2011) (Figure 1). Each KPA can be assessed by a maturity scale of five level (levels 0-5). Reaching a maturity level requires the achievement of all practices of that level.

<table>
<thead>
<tr>
<th>Maturity Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0) Non-Existing</td>
<td>At this maturity level, a process has not yet been incorporated into current business processes and does not yet have established goals and objectives.</td>
</tr>
<tr>
<td>(1) Initial</td>
<td>At this maturity level, a process produces results in which the specific goals are satisfied, however, they are usually ad hoc and chaotic. There is no stable environment to support processes with the ability to repeat such and possible abandonment in time of crisis.</td>
</tr>
<tr>
<td>(2) Managed</td>
<td>At this maturity level, a process is planned and executed in accordance with policy; employs skilled people having adequate resources to produce controlled outputs; involves relevant stakeholders; is monitored, controlled, and reviewed; and is evaluated for adherence to its process description.</td>
</tr>
<tr>
<td>(3) Defined</td>
<td>At this Maturity level, a process is tailored to the organization’s standard processes according to the organization’s guidelines; has a maintained process description; and contributes process related experiences to the organizational process assets.</td>
</tr>
<tr>
<td>(4) Quantitatively Managed</td>
<td>At this maturity level, a process is managed using statistical and other quantitative techniques to build an understanding of the performance or predicted performance of processes in comparison to the project’s or work group’s quality and process performance objectives, and identifying corrective action that may need to be taken.</td>
</tr>
<tr>
<td>(5) Optimizing</td>
<td>At this maturity level, a process is continually improved through incremental and innovative processes and technological improvements based on a quantitative understanding of its business objectives and performance needs and tied to the overall organizational performance.</td>
</tr>
</tbody>
</table>

Figure 1: BIM Maturity levels (CIC, 2012)

However, a BIM maturity assessment measurement is inspired from ISO15504 recommendation in four categories: N,P,L and F. The S3" (April, 2005) and many other maturity models conform to this ISO recommendation that defines partial maturity of a practice, when it is not fully achieved or not achieved (ISO/IEC15504):

N: Not reached – 0 to 15%

P: Partially reached – 15%-50%

L: Mostly reached – 51%-85%

F: Fully reached – 85%-100%
3.3 Evaluation process of proposed BIM platform model

To make it easy to assess the BIM maturity level of a participant, an assessment tool can calculate the threshold rating, and a BIM entry level to be eligible to participate in a construction project. The applicants must be eligible in BIM and show their maturity certificate to apply in a construction project bidding. A certified BIM maturity assessor (i.e. an assessment body) would issue the certificate using a class 1 assessment process (this will be presented in another paper). The BIM maturity assessment could take place at any time independently from projects. Based on the type of firm, i.e. architect, engineer, contractor, the KPAs and questions of a questionnaire are filtered and adapted by the assessor to be included in assessment of that firm. For example, within a project an engineer may not be evaluated in KPA of ‘Design reviews’, because the client doesn’t expect the engineer to perform ‘Design reviews’ in that project. The independent assessor would plan the assessment and then distribute a questionnaire to the interested firms. The results of their questionnaire will be evaluated based on their specialty. The questions ask the firms if they have the practice in their organization. As shown in section 3.2, based on utilization level in the firm, a respondent can choose an answer from four options of “Not reached”, “Partially reached”, “Mostly reached”, and “Fully reached”. For a Class 1 assessment, a minimum of four process instances shall be identified for each process within the scope of the assessment. To achieve a maturity level, all practices of that level must be “fully reached” where process attributes are assessed and validated. Finally, the third party reports the BIM maturity assessment results and can issue a certificate.

To describe the evaluation process of the proposed model, the first part of this model is presented in the next section. This portion of the proposed model only presents the “3D Coordination” KPA, its roadmaps and practices, and questions that are asked at maturity level of one. The description of the two other mentioned BIM uses, namely ‘Design Authoring’ and ‘Design Review’ are quoted from CIC (2011) in Table 3.

Table 3: ‘Design Authoring’ and ‘Design Review’ BIM Uses description (CIC, 2011)

<table>
<thead>
<tr>
<th>BIM Use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Authoring</td>
<td>A process in which 3D software is used to develop a Building Information Model based on criteria that are important to the translation of the building's design. Two groups of applications are at the core of BIM-based design process: designs authoring tools, and audit and analysis tools. Authoring tools create models while audit and analysis tools study or add to the richness of information in a model. Most of audit and analysis tools can be used for Design Review and Engineering Analysis BIM Uses. Design authoring tools are a first step towards BIM and the key is connecting the 3D model with a powerful database of properties, quantities, means and methods, costs and schedules</td>
</tr>
<tr>
<td>Design Reviews</td>
<td>A process in which stakeholders view a 3D model and provide their feedbacks to validate multiple design aspects. These aspects include evaluating meeting the program, previewing space aesthetics and layout in a virtual environment, and setting criteria such as layout, sightlines, lighting, security, ergonomics, acoustics, textures and colors, etc. This BIM use can be done by using computer software only or with special virtual mock-up facilities, such as CAVE (Computer Assisted Virtual Environment) and immersive lab. Virtual mock-ups can be performed at various levels of detail depending on project needs. An example of this is to create a highly detailed model of a small portion of the building, such as a facade to quickly analyze design alternatives and solve design and constructability issues</td>
</tr>
</tbody>
</table>

4 3D COORDINATION KPA

CIC (2011) describes BIM Use of ‘3D Coordination’ as “a process in which Clash Detection software is used during the coordination process to determine field conflicts by comparing 3D models of building systems. The goal of clash detection is to eliminate the major system conflicts prior to installation”. The
The design team must check collision against architectural, engineering and MEP models of the project. The collision reports must be prepared, and then the project team or responsible members review the collision report and address the issues in the models (BIM Indiana University, 2012, category A.3). This process includes several activities, which must be mapped with their relationships in a detailed process map. The capabilities in a ‘3D Coordination’ process are defined under four roadmaps of ‘Process map’, ‘Information requirements’, ‘creating, transferring, and compiling information’, and ‘collision detection and solving’. These capabilities are explained as follows.

4.1 3D Coordination process map Roadmap

The responsible organization for performing ‘3D Coordination’ must be capable to develop a detailed process map of this BIM Use. The detailed map must contain all necessary activities and connect them properly. The responsible party of each activity must be determined. According to CIC (2011), Eastman et al. (2011), BIM Indiana University (2012), the main activities of 3D Coordination can be concluded as defining information requirements, performing collision detection and solving collision problems. The required capabilities and questions are as follows:

4.1.1 Process map capability in Maturity Level 1

**Practice 1.** The firm is capable to develop a process map in order to identify 3D Coordination activities and their relation, responsible parties, and information requirements (CIC, 2011, p. 20&21).

Explanation: To initiate 3D Coordination in a project, the responsible firm needs to define the process map. The firm must identify the required activities, the relation and dependency of activities, responsible parties for the activities, and the required information and information exchanges for 3D Coordination in the project (CIC, 2011). Without a process map, the firm cannot carry out the process.

**Question 1.** Does your firm develop a process map in order to identify 3D Coordination activities and their relation, responsible parties, and information requirements? (Choose answer from: No, Partially, Mostly, Yes)

4.2 Defining 3D Coordination information requirements Roadmap

Clash check is between specified building systems, i.e. mechanical and structural systems, because model components belong to a specific type of system (Eastman et al., 2011). Clash detection also can be done within one discipline. Therefore, 3D Coordination information requirements define intended building systems for conflict detection, including structural, mechanical, engineering, plumbing systems, and civil systems such as storm water systems, buried electrical systems (e.g. duct banks), rails, sewer systems, etc. After defining the required building systems’ model, the level of detail of models must be defined for each model. The contractor must make sure the suitable Level of Detail (LOD) (Eastman et al., 2011). To define LOD at the beginning of the project, the clash detection information requirements must be considered for future 3D coordination during the project.

4.2.1 Information requirements capability in Maturity Level 1

**Practice 2.** The firm carries out clash check for Architectural, Structural, and Mechanical, Engineering and Plumbing (MEP) building models (Eastman et al, 2011, p. 273; BIM Indiana University, 2012, category B.2).

Explanation: At this maturity level, the firm initiates to do clash check of Architectural, Structural, and Mechanical, Engineering and Plumbing (MEP) building models, against each other and within the disciplines, irregularly. At this level it is expected that the firm be capable of clash check for various building models and even irregular clash check satisfies meeting maturity level 1.

**Question 2.** Does your firm carry out clash check for Architectural, Structural, and Mechanical, Engineering and Plumbing (MEP) building models? (Choose answer from: No, Partially, Mostly, Yes)
4.3 Performing collision detection and solving collision problems Roadmap

The location and schedule for 3D Coordination meetings must be defined. In the meetings, the conflict problems must be addressed. Therefore, a protocol to address collisions is required before beginning coordination process (CIC, 2011). Clashes can be categorized into two groups. A group of them, which are small errors, can be defined as minor clashes. Minor clashes can be ignored in design phase and can be addressed during construction, on the site (Amiri, 2012). However, major clashes must be defined and be addressed during the 3D Coordination meetings.

4.3.1 Clash detection and solving capability in Maturity level 1

Practice 3. The firm defines the schedule and location of clash detection meetings in order to review and discuss on the clash problem and address it (BIM Indiana University, 2012, A.3; Succar, 2010a, p. 90).

Explanation: The organization assigns a responsible person to arrange a meeting to address the problem. In each meeting, the assigned responsible person prepare a collision report and the other involved project members review and discuss on the clash problem and how to address it. There is no protocol to address the clash problems in this level.

Question 3. Does your firm define the schedule and location of clash detection meetings in order to review and discuss on the clash problem and address it?

5 CONCLUSION

Construction clients need a qualifying mechanism to ensure that the participating firms of a project meet minimum BIM requirements. From the perspective of a client, “minimum BIM qualification” can be translated to “minimum capability to use BIM”. This perspective offers a new opportunity for a novel BIM maturity model and its independent certification process. The authors observed that there is a lack, in the current BIM maturity models, to look at BIM through this lens. This research, which is still in progress, focuses on the “BIM Process” and “BIM Resources” domains of the construction industry to address the construction clients concern regarding assessment of minimum BIM capabilities of potential project participants. This research proposed a new BIM platform maturity model presenting a hierarchical architecture, from most general definitions to most specific practices, namely ‘BIM domains’, KPAs, Roadmaps, and practices. The main contribution of the proposed maturity model is to focus the BIM maturity assessment of key ‘BIM Uses’. BIM Uses are considered as KPA in the proposed model, additional to general KPAs, namely ‘BIM project management’, ‘Infrastructure’, and ‘Human resources’. This BIM platform maturity assessment proposal, which is currently a prototype at concept of operation, proposes to set a threshold, a BIM entry level, to be eligible to participate in a construction project involving BIM. The interested firms to be eligible to participate in a construction project bidding, where BIM is required by the client, would need to be certified at certain BIM maturity level beforehand. A recognized third party assessment body would issue the BIM maturity certificate. By employing more BIM-qualified or BIM-certified firms in the construction industry, the industry will advance more rapidly and should gain more competitive advantages. BIM benefits, which bring most value to a project, include ‘Reduced conflicts during construction’, ‘Improved collective understanding of design intent’, ‘Improved overall project quality’, ‘Reduced changes during construction’, ‘Reduced number of RFIs (Requests for Information), ‘Better cost control/predictability’ (McGraw-Hill, 2009).

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CONSTRUCTABILITY: CAPABILITIES, IMPLEMENTATION, AND BARRIERS

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Abstract: Constructability means finding ways to construct effectively. It minimises disputes, cost overrun, and schedule delays. However, constructability program adoption in construction projects differs from one corporation to another, and the level of implementation (measured in two levels: corporate and project level) extends from highly sophisticated to none at all. Despite its benefits, many construction companies are reluctant to fully implement it due to many barriers (e.g. complacency with status quo and lack of expertise for design firms). In order to improve the effectiveness of constructability programs in construction projects, identification and mitigation of constructability program barriers using gap analysis techniques should be done. This paper illustrates research done with a partner company to measure degree of implementation of constructability in the company. We used CII constructability evaluation matrix to evaluate the degree of implementation of constructability program in both corporate and project levels. ASCE survey and two case studies of existing projects were also used to provide a clear picture of current practices of constructability in the company. The analysis showed that the company constructability program ranged from informal to formal and the percentages of implementation of the program in planning and execution phases were 63% and 67%, respectively. We introduced recommendations for the six missing concepts in the partner company practice.

1 INTRODUCTION

Construction projects are unique in terms of their goals and values, and different projects with different natures normally encumber systematically applying the same construction, communication, procurement or contracting methods. Defining projects major elements such as overall project plan, planning and design, construction schedule, cost estimate, and major construction method is a normal procedure applied by any construction company. The integration and optimization of project major elements enhance project objectives for achieving owner’s expectations in terms of schedule, cost and quality of the final product, and normally it is done by including expert knowledge in the project. Implementing constructability concepts is one way to achieve maximum inclusion of construction expert knowledge in any construction project.

Construction Industry Institute (1986) defined constructability as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve overall project objective," and in 1991, presented by the Construction Management Committee, ASCE divided constructability into two terminologies: constructability and constructability program. The ASCE defined
constructability as “the capability of being constructed” and defined constructability program as “the application of a disciplined, systematic optimization of construction related aspects of a project during the planning, design, procurement, construction, test, and start up phases by knowledgeable, experienced construction personnel who are part of a project team. The program’s purpose is to enhance the project’s overall objectives.”

Constructability programs are not fully implemented in projects due to many reasons (e.g. lack of communication between project participants starting from the conceptual design stage). Type of project, contract type, availability of experienced construction personnel and many other barriers affect the implementation of constructability programs in construction projects. For example, in public services projects, design bid built type of contracts are used. This type of project limits the involvement of contractors in the conceptual design phase of any project and normally it is mitigated by adding design services as part of the contract. Lack of understanding of the benefits of applying constructability programs is another example of barriers. Understanding benefits of applying constructability concepts on construction projects can motivate project parties on applying formal, explicit constructability knowledge bases. For example, it was found that the owner saving on project cost and schedule when applying constructability was 4.3% and 7.5%, respectively (Russell, et al., 1992b). Delivering these research outputs to project participants or stakeholders can enhance the adoption of constructability programs in construction projects.

The level of implementation of constructability programs varies from highly sophisticated program to none at all. These levels of implementation of constructability programs are controlled by barriers which limit the effectiveness of constructability concepts in the construction industry. The existence of constructability barriers extends from corporate to project levels and its mitigating process involves a three-phase cycle: identification, mitigation and review (O’Connor & Miller, 1995). Conducting surveys administered to projects parties is one way to show the gap between the formal constructability program and what is actually implemented in reality. For example, ASCE, represented by Construction Institute’s Constructability Committee, conducted a survey to address the current state of constructability best practices in the architecture, engineering and construction industry (Pocock, et al., 2006).

This paper will illustrate the gap analysis of constructability program implementation in a construction company located in Alberta. We used two approaches to study the gap: reviewing historical projects and surveys. These two approaches complement each other as the first method focuses on project level, the later focuses on corporate level. The paper also proposes a recommendation for the partner company to further enhance their constructability program implementation.

2 LITERATURE REVIEW

Based on the definition of constructability program by ASCE, the optimum use of construction program concepts in any project can be achieved by the involvement of construction personnel in the project team starting from the conceptual design stage. This point depends on the understanding of constructability program capabilities by all project parties, which can result in a corporate commitment for applying such a program. The level of implementation of constructability is controlled by many barriers such as complacency with the status quo and lack of expertise for design firms, and overcoming such barriers is important to create a solid constructability program structure. The following section discusses capabilities, implementation and barriers of constructability program.

2.1 Capabilities

Implementing constructability leads to more owner satisfaction and contractor profit. Jergeas and Put (2001) introduced an example of implementing constructability profit: Trans Canada saved 40% in building a compressor station compared to historical similar projects when they applied constructability concepts. Another example on constructability program capability was presented by Russell, et al. (1992b). He found that the owner saving in project cost and schedule when applying constructability was 4.3% and 7.5%, respectively.
2.2 Implementations

The implementation of constructability programs varies from one corporation to another. The level of implementation or existence of constructability program extends from extremely sophisticated, excellent programs to none at all (Construction Management Committee of ASCE Construc, 1991). CII also concluded that constructability program implementation in the construction industry lacks structure and is progressing slowly (1993). This section provides description of the implementation of constructability programs in the construction industry.

2.2.1 Constructability methods

According to Raviv, et al. (2012), constructability methods can be grouped under seven family categories according to different approaches or methods of implementation:

- Formal corporate policy statement
- Checklists covering corporate procedures, lessons learned, and technical issues
- Organization measures
- Contractual measures
- System modeling and analysis methods
- Reviews
- Advanced technology methods like building information technology (BIM)

Raviv, et al. (2012) found that a construction engineer with full authority and responsibility for constructability is the best, most effective way to achieve constructability, while contract incentive clauses, brainstorming, owner’s involvement, and formal company constructability procedures are the least effective methods. Criticizing this point, the author disagrees with Raviv. The effectiveness of mentioned factors is almost of the same weight. Indeed, the integration of all these factors can produce a solid constructability program structure.

2.2.2 Constructability knowledge transfer

Typically, contractors have more expertise in constructability than engineers; therefore, transferring contractors’ expertise to engineers during the design process will increase efficiency. However, the right information must be available for engineers at the right time. Unfortunately, transferring expertise is done on an ad hoc basis. O’Connor and Miller (1994) introduced the Conceptual Product/Process Matrix Model (CPPMM) which can be used to organize constructability knowledge based on appropriate timing and level of details (Pulaski & Horman, 2005). CPPMM is a kind of matrix, where the vertical axis represents level of details and the horizontal axis represents project phase. According to the current project phase, the relevant information will be introduced. For example, during steel structure design, the model might suggest using shop welding instead of bolting in site. Pulaski and Horman (2005) introduced a case study on using CPPMM in a Pentagon renovation project.

2.2.3 Constructability in design firms

Constructability starts from the design stage; engineers must bear in mind how the contractors will execute the job, otherwise schedule delays and claims are inevitable. A new contracting systems like design-build push design companies to implement constructability as a procedure in the design process. According to Arditi, et al. (2002), many design firms have a formal (explicit) constructability program that is launched as early as the conceptual planning stage of the project. They reviewed constructability implementation during the design phase in a construction project. They focused on existence of constructability programs, timing implementation, and factors that improve or hinder constructability implementation. Arditi, et al. (2002) showed that peer reviews and feedback systems are the most prevalent tools used to achieve high levels of constructability.
2.3 Constructability Implementation Barriers

Constructability tries to improve construction companies’ performance; however, implementing it faces many barriers. A barrier to constructability can be defined as any significant inhibitor that prevents effective implementation of the constructability program (O'Connor & Miller, 1994). O'Connor and Miller (1994) categorized barriers into general, owner, designer, constructor, organized labor, vendor, code authority, and researcher barriers. These barriers affect corporate and project level.

Jergeas and Put (2001) designed a survey to identify constructability barriers in Alberta; they found a large gap in the following constructability concepts:

- Up-front involvement of construction personnel during design stage. This is mainly due to using the traditional contract (design-bid-build), especially in the public sector.
- Construction efficiency, which can be achieved by modularization and pre-fabrication. However, modularization is specific to certain projects.
- Using innovative construction methods.

Goodrum, et al. (2003) discussed the implementation of constructability on highway construction projects. They surveyed 19 state transportation agencies to identify implementation barriers. Lack of time, lack of available manpower, lack of available experience, and contractor reluctance were the main stated barriers.

2.3.1 Barrier mitigation

O'Connor and Miller (1995) suggested identifying barriers then mitigating or overcoming these barriers using barrier breaker tactics. Construction Industry Institute (CII) introduced a list of barrier breakers (O'Connor & Miller, 1995); this includes seven steps to mitigate complacency with status quo:

- Designate a strong program champion
- Report constructability program benefits regularly
- Make constructability the responsibility of younger, more energetic individuals, who more frequently confront the status quo
- Establish funded programs that promote creativity and intelligent risk-taking
- Establish monetary awards for rewarding innovation and intelligent risk-taking
- Conduct training programs in shifting paradigms, promoting creativity, and promoting critical thinking
- Screen out personnel who regularly support the status quo

3 GAP ANALYSIS

We performed a gap analysis of constructability program implementation in a construction company located in Alberta. Identifying the constructability gap is a crucial step to reaching a full constructability implementation. We used two approaches to study the gap: reviewing historical projects and surveys. These two approaches complement each other as the first method focuses on project level, the later focuses on corporate level.

3.1 Methodology

The data used in this study were obtained by two means: 1) reviewing historical projects and 2) surveying a construction manager working with the partner company (a construction company in Alberta). The survey covers two project case studies, which have been built by the partner company. The survey contains two parts: constructability program evaluation matrix, provided by CII, and a survey questionnaire prepared by ASCE Construction Institute’s Constructability Committee (1991). The constructability program evaluation matrix is further divided into two sections: corporate constructability evaluation matrix and project constructability evaluation matrix, as shown in Figure 1. The corporate constructability evaluation matrix shows 13 parameters identified by CII for assessing the level of implementation of the constructability program at the corporate level. The level of implementation is
classified into five levels; level 1 represents no program implementation and level 5 represents comprehensive formal program. In project constructability evaluation matrix, 10 parameters were identified to assess the implementation of the constructability program at the project level and the classifications of implementation levels are the same as for the corporate level. This survey allows the determination of areas where improvement of constructability program is required and also identifies areas where the constructability program is successful.

The second part of the survey is used to provide a clear picture of current practices of constructability in the construction company, which is achieved by describing the following points (ASCE, 1991):

- Project phases at which constructability efforts usually begin.
- Constructability methods used during design and construction.
- Who requires constructability and who performs it.
- The major benefits of constructability and problems it could prevent.
- The major obstacles to implementing constructability.
- Progress in constructability practice and where improvement is needed.

![Constructability Survey Structure](image)

**Figure 1 Constructability Survey Structure**

### 3.2 Case Study

The gap analysis is done on two projects that have been built recently by the partner company. The first project (Project A) involves replacing four existing cyclones and associated ancillary equipment in the Raw Meal Preparation Area with two larger cyclones. The scope of the project included civil, structural, and mechanical works. The partner company tried to include constructability concepts in the project, especially in the early design phase. These attempts included:

- Brainstorming to identify stakeholders’ expectation and opportunities.
- Inspecting “lessons learned” from previous projects.
- Assessing safety considerations like site congestion and critical rigging and lifting.

The Generator Replacement – Evaporator Modernization Project (Project B) for Pulp and Paper Companies is the second case study we considered in the constructability gap analysis. In this project, the partner company applied constructability concepts in different project phases, as follows:
• Conceptual design phase:
  • Optimize layout and routing by assessing equipment locations to minimize handling and reduce crane requirements.
  • Set up an effective communication plan to minimize the impact of delays for all project stakeholders.

• Design and procurement phases:
  • Assess severe winter conditions in the design phase (e.g. use domed tents).
  • Consider three different design options to see which one is better from the constructability prospective.
  • Discuss vessels’ design with constructability personnel.

3.3 Result

By reviewing constructability concepts in the company’s historical projects and surveying, we were able to assess how constructability concepts have been implemented in the partner company. Analysis of Part A of the survey shows that constructability implementation in the company lies between informal and formal program. Table 1 summarizes the results of constructability implementation in the partner company. We included 13 CII constructability principles (Jergeas & Put, 2001) with the corresponding degree of implementation. We used a scale from 1 to 5 for degree of implementation, where 5 means fully implemented and 1 means missing concept, in the partner company practice.

These 13 concepts can be grouped into two general categories: 1) planning phase and 2) executing phase. Figure 2 and Figure 3 show percentage of implementation for each group separately. These figures show that the partner company used concepts like constructability in early project planning and considering adverse weather; however, they are behind in using modularization, preassembly and standardized elements.

Table 1 Constructability concepts and degree of implementation (5 means fully implemented and 1 means missing concept).

<table>
<thead>
<tr>
<th>Concept</th>
<th>Value</th>
<th>Concept</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constructability program integration</td>
<td>4</td>
<td>Design and procurement schedules are construction sensitive</td>
<td>3</td>
</tr>
<tr>
<td>Constructability in early project planning</td>
<td>5</td>
<td>Designs consider constructability issues</td>
<td>4</td>
</tr>
<tr>
<td>Constructability in contracting strategy</td>
<td>2</td>
<td>Standardized design elements</td>
<td>4</td>
</tr>
<tr>
<td>Modularization and preassembly</td>
<td>1</td>
<td>Considering adverse weather</td>
<td>4</td>
</tr>
<tr>
<td>Site layouts promote efficient construction</td>
<td>5</td>
<td>Design facilities turnover and start-up</td>
<td>3</td>
</tr>
<tr>
<td>Constructability team</td>
<td>1</td>
<td>Innovative construction methods</td>
<td>4</td>
</tr>
<tr>
<td>Advanced information technologies (3D modeling)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4 RECOMMENDATION

This section discusses the missing constructability concepts in the partner company and tries to fully implement them.
4.1  **Constructability in Contracting Strategy**

The ultimate use of constructability program concepts in construction is affected by the selection of the type of contract. For example, in design-build and cost reimbursable contracts, the owner and contractor teams work together, while in design-bid-build contracts, the owner and contractor teams work individually, which results in less integration of construction experience in the design stage. The construction management committee of ASCE summarized the factors affecting the selection of the type contract as the following (1991):
• Owner’s corporate policy on contracting.
• Availability of in-house experienced personnel.
• Time available to get the project designed and constructed.
• Desire of owner to control elements of project.
• Importance of cost to owner.
• Amount of risk owner wants to contract out.
• Availability of contractors.
• Local construction climate.
• Experience or confidence in contractor or design builder.

Constructability concepts can be formulated in the contracting strategy by the following points:

1. Including the help of experienced construction personnel in choosing the right contract for the right project for the owner.
2. Adding design services as part of fixed price contracts.
3. Achieving mutual trust with the owner to maintain the use of cost reimbursable type of contracts in the future.
4. Documenting success stories when using constructability programs and delivering them to owners.

4.2 Constructability Team

Constructability process involves the integration of construction knowledge and experience prior to the beginning of the actual design. This process is achieved by the formation of a constructability team that includes construction experts. The application of constructability team in the construction industry differs based on the motivation and the attitude of project participants on applying constructability programs in their projects. For example, the owner is required to expand his front-end planning and invest more time and money in forming a constructability team to better address the interrelationship between construction method, material, equipment, and construction trades. In the contractors’ point of view, constructability teams are always formed while tendering and prior to construction to break down the project to allocate required labor, equipment, materials, etc. for the project. The maximum effectiveness of constructability programs in terms of forming constructability teams can be achieved when constructability teams of the owner and the contractor work together in harmony. This concept can be achieved by considering the following points:

1. Consider forming constructability teams as part of the project roadmap.
2. Establish formal commitment to the idea of constructability.
3. Highlight the importance of early involvement of constructability.
4. Establish constructability specialist’s position in the company.

4.3 Standardized Design Elements

Projects are unique and different projects have different design elements. It is difficult to standardize design elements that can work in any project because the design is controlled by the design firm. However, it is possible to standardize the design elements for big projects with repetitive features such as high rise buildings and residential compounds; therefore, constructability in the form of standardized design elements can be applied in only certain types of projects. Maximizing the use of standardized design elements can be achieved by the following points:

1. Deliver the fact of saving time and money by using standardized design elements to the owner.
2. Enforce the use of standardized design elements in projects of repetitive nature.
3. Provide in-house training in BIM technology.

4.4 Modularization and Preassembly

Prefabrication and preassembly have doubled in the last 15 years (Haas, et al., 2000). However, some companies fail to implement this concept due to barriers like “it is specific for certain projects” (Jergeas & Put, 2001). However, modularization and preassembly are very effective to overcome severe weather and uncontrolled quality on site. It improves productivity and reduces project duration. The following guidelines will help in implementing this concept:

1. Form constructability team early and make sure they are involved in design stage.
2. Use BIM technology.
3. Realize that using modularization and preassembly will be very useful for schedule-driven projects.
4. Perform further analysis for modularization and preassembly cost benefit.

4.5 Design and Procurement Schedules are Construction Sensitive

Construction sensitive schedules are defined by CII as ones that consider project completion date and the requirements of the construction phase to optimize the project cost and schedule (Rusell, et al., 2004). This concept tries to balance the time allocation for each activity in the schedule. To avoid this concept’s barriers:

1. Develop a detailed schedule in the design phase.
2. From the early start, assign considerable time allocation for planning, design, procurement, and construction (Rusell, et al., 2004).
3. Avoid unnecessary changes to the main schedule.
4. Make sure late procurement will not affect the schedule.

4.6 Design Facilities Turnover and Start-up

This concept ensures integrating facilities turnover and start-up in the design stage. This is an important concept to avoid facilities start-up problems and design/construction changes. In order to utilize this concept:

1. Contractors should be involved in the design stage with owners and designers.
2. Prefer new contracts (e.g. design-build) over traditional ones (design-bid-build).

5 CONCLUSION

This paper discusses constructability concepts implementation in the partner company, starting from the gap analysis. The study concluded that use of constructability concepts by the company lies between informal and formal constructability program classification. The degree of implementation of constructability concepts was further divided into two phases: planning and execution phases. It was found that the degree of implementation of constructability concepts in both phases were 63% and 67%, respectively. We found that there are six concepts that need more work within the partner company. Three of them are related to planning phase while the other three are related to execution phase. This paper states specific recommendations for each concept in order to mitigate their barriers and implement them smoothly.
References

Haas, C. et al., 2000. PREFABRICATION AND PREASSEMBLY TRENDS AND EFFECTS ON THE CONSTRUCTION WORKFORCE, Austin, Texas: Center for Construction Industry Studies, University of Texas.
DEMOGRAPHIC INFLUENCES ON CONSTRUCTION CRAFT SHORTAGES IN THE U.S. AND CANADA

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Abstract: The United States and Canadian construction markets are facing a shortfall of skilled craft workers in the face of increasing labor demands. There are initial indications that the shortages are already having a significant impact on project performance in the industrial construction sectors. While there are many demographic aspects of the shortage, the authors focus on the shift in aging of the United States and Canadian construction workforce and the effects this is having on the availability of craft workers, especially on highly skilled craft trades such as pipefitters and electricians. Also, the authors examine immigration policy and its influence on the qualifications of the construction workforce. The authors use multiple US and Canadian data sources to examine the trends on both sides of the border, including the US Bureau of Labor Statistics’ Current Population Survey, Statistic Canada, and the Build Force Canada datasets. The findings show that while both the US and Canadian construction markets are experiencing an aging workforce, the aging of the US workforce is occurring at a much faster rate.

1 INTRODUCTION

Construction is one of the largest economic industries in the United States and Canada. In 2010, construction accounted for 3.5% of the U.S.’s Gross Domestic Product (GDP) (CPWR 2013), and for 6% of Canada’s Gross Domestic Product (GDP) (Statistic Canada 2014). Construction in 2012 employed approximately 9 million workers in the United States (Dong et al. 2014), whereas Canada employed 1.3 million (Statistics Canada 2014).

The Bureau of Labor Statistics (BLS) estimates that the US construction industry will be the fastest growing industry over the next decade, which will create an estimated 1.6 million jobs (Glavin 2013; Gonzales 2013). The growth of construction projects will increase the demand for skilled craft workers, (Wilder 2013; Shelar 2013). Industrial construction on the Gulf Coast has contributed 1,100 projects and $44 billion in revenue, effectively increasing hours worked from 99.7 million to a projection of more than 121 million by 2016. Likewise, Canada has a vast number of oil and gas projects that are on an upward trend (Wilder 2013), although the authors note current dramatic fluctuations in oil prices will likely significantly temper the demand for workers. According to the Construction Sector Council of Canada, the Canadian construction industry will need 319,000 new workers to replace retiring workers and to also fill new job openings—219,000 and 100,000 respectively between 2012 and 2020. The Construction Sector Council estimated that graduates of vocational schools could fill almost half of these jobs, but the other industries like manufacturing and migrant workers will have to fill the remaining jobs (Komarnicki 2012).
Because of the high demands for construction, companies are losing money from the lack of skilled craft workers. According to Stephen E. Sandherr, the Associated General Contractor’s (AGC) Chief Executive Officer, 74% of construction companies in the U.S. are having difficulties finding workers to fill job openings (Gonzales 2013)—specifically in the Gulf Coast region (Wilder 2013). The Bank of Canada’s Business Outlook Survey in 2012 claimed that 29% of Canadian firms face labor shortages, an increase from 2009 and 2010 (Komarnicki 2012).

The skill shortages in the construction industry are not new, and are a cyclic problem (Castaneda et. al. 2005). A shortage of skilled, qualified craft professionals has been an unfortunate recurring trend in the US and Canadian construction industries for the past three decades. In the early 1980’s, the Business Roundtable predicted that a shortage of skilled craft workers would hamper the growth of both open shop and union construction sectors by the late 1980s (BRT 1983). The prediction was confirmed by a 1996 Business Roundtable study that found that 60% of its surveyed members were experiencing a shortage of skilled craft workers; 75% of the respondents indicated that the shortage had worsened in the five years prior to the study (BRT 1997). The shortage of craft workers apparently has further worsened in recent years. In 2001, the Construction Users Roundtable (CURT) conducted a survey in which 82% of the respondents reported shortages on their projects. In addition, 78% of the same respondents indicated that the shortage had worsened in the three years prior to the study (CURT 2001). In 2007, that number had risen to 86% (Sawyer and Rubin 2007).

Higher skilled trades in construction (e.g. electricians and pipefitters) are experiencing greater shortages in comparison to lower skilled trades (e.g. laborers and roofers). Electricians, pipefitters, welders, boilermakers, millwrights, and ironworkers are among the skilled crafts with the greatest demands among construction industry trades in the U.S. (Wilder 2013; Shelar 2013; Gonzales 2013). Yet electricians will be the trade in demand in Canada between 2011 and 2020, as predicted by the Canadian Occupational Projection System (COPS). While COPS believes there will be a higher demand for electricians, this timeframe could also experience a surplus of carpenters, plumbers, pipefitters, and gasfitters. Nevertheless, a surplus in some regions may hide skill shortages in other regions (Komarnicki 2012).

1.1 Reasons for the Shortage

Many agree that the skills shortage issue is multifaceted (Watson 2007; Healy et. al. 2011). Two reasons for long-term shortages are a lack of training and an inability to attract new talent. There are also reasons for short-term shortages, such as an increasing demand within the workforce and the retirement of the Baby Boomer generation of workers (born between 1946 and 1965). A significant reason for the craft worker shortage is the aging, “greying,” population. In 2010, 39% (3.5 million) of the U.S. construction workforce were Baby Boomers, many of whom had already reached the normal retirement age which varies from age 65 to age 67 (SSB 2014; GOC 2014b; CPWR 2013). Just a decade earlier, 49% of the construction workforce were Baby Boomers (4.6 million) (CPWR 2007). The average age of the U.S. construction workers was 40.2 years in 2010. In comparison, union workers are on average five years older than non-union workers. In 2010, union workers average age was 42.4 years and non-union workers average age was 37.7 years (CPWR 2013). Shigeru Fujita (2014), believes the Baby Boomers’ retirement is a main contributor to the workforce shortage, which started around 2010 and became much more problematic at the beginning of 2012. However, 30 % of the total decline in the participation rate, which was measured from the beginning of the great recession up to the end of 2011, is due to discounted workers, who stop looking for employment. R.E. Parker, president of Repcon, Inc., a mechanical contractor based in Corpus Christi, Texas said “Due to the aging of the ‘baby-boomer’ workforce and the tremendous amount of construction planned for the next several years, our current labor shortages are going to become a crisis” (Wilder 2013). However, the major contributor to the construction workforce shortages as a result of baby boomer retirements is a continuance of two actions within the workforce during the last couple of decades. First, more and more existing workers have been leaving the construction industry for other industries, especially during the great recession. Second, there has been a lack of new workers entering the construction industry (Druker and White, 1996). While the current rapid decline in oil prices has diminished the demand for oil service projects, especially in the upstream, it is also having a positive effect of increasing craft demand for construction projects in other
sectors designed to take advantage of cheap energy prices, such as projects related to manufacturing. Table 1 is a list of reasons of construction workforce shortages from previous studies.

Table 1: Reason for Construction Workforce Shortages from Previous Studies

<table>
<thead>
<tr>
<th>Reason of Construction Workforce Shortages</th>
<th>Reference (Previous Studies)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aging of the workforce</td>
<td>Watson 2007; Komarnicki 2012; Gonzales 2013; Wilder 2013; Fujita 2014</td>
</tr>
<tr>
<td>Increase the demand of craft workers</td>
<td>Watson 2007; Healy et. al. 2011; Shah and Burke 2005; Haskel and Martin 1993; Komarnicki 2012; Glavin 2013; Wilder 2013; Shelar 2013</td>
</tr>
<tr>
<td>Changing in skill requirements (i.e. new technology)</td>
<td>Watson 2007; Haskel and Martin 1993</td>
</tr>
<tr>
<td>Poor education/Poor training</td>
<td>Watson 2007; Healy et. al. 2011; Haskel and Martin 1993; Castaneda et. al. 2005</td>
</tr>
<tr>
<td>Not meeting the employer expectation</td>
<td>Watson 2007</td>
</tr>
<tr>
<td>Poor market information</td>
<td>Shah and Burke 2005</td>
</tr>
<tr>
<td>Decrease the number of the new entrants</td>
<td>Druker and White 1996</td>
</tr>
<tr>
<td>Poor wages</td>
<td>Watson 2007; Shah and Burke 2005; Haskel and Martin 1993; Castaneda et. al. 2005; Healy et. al. 2011; CII 2000</td>
</tr>
<tr>
<td>Poor industry image</td>
<td>Shah and Burke 2005; Castaneda et. al. 2005</td>
</tr>
<tr>
<td>Poor working condition</td>
<td>Shah and Burke 2005; Castaneda et. al. 2005; CII 2000</td>
</tr>
<tr>
<td>Geographic location of business/job</td>
<td>Healy et. al. 2011; Shah and Burke 2005</td>
</tr>
<tr>
<td>Lack of job security/Poor treatment/Poor safety</td>
<td>CII 2000</td>
</tr>
<tr>
<td>Lack of a worker-oriented career path</td>
<td>Castaneda et. al. 2005</td>
</tr>
</tbody>
</table>

1.2 Research Objectives

The main objective of this study is to understand the influence of demographics on the construction industry's workforce availability, focusing on the shift in aging of the United States and Canada. In addition, the study examines the influence of immigration policy on the educational attainment of construction craft in both the U.S. and Canada.

2 RESEARCH METHODOLOGY

The authors use multiple US and Canadian data sources to examine the trends on both sides of the border, including the US Bureau of Labor Statistics’ Current Population Survey (CPS), Statistic Canada, and the Build Force Canada datasets. This study includes only craft workers in the construction industry, filtering out manager, superintendents, foreman workers, inspectors, and engineers.

3 RESULTS OF ANALYSIS

3.1 Average Age

3.2 Construction Industries vs. All Other Industries [United States]
An increase in the average age of construction craft workers is one of the reasons for the shortages. Craft workers in the construction industry are younger than craft workers in all other industries. From 1994 to 2006, the aging rate for the construction industry was 0.092 and the aging rate for all other industries was 0.260, Figure 1. However, the aging rate for the construction industry has increased almost four times (4.4 times) from 2007 to 2014 and became 0.405, while the aging rate for all other industries has decreased by 0.7 times to became 0.185. Yet, the average age for all industries is older than the average age for construction industry. In 2014, the average age for all industries is 42.9 while the average age for construction industry is 40.8.

3.2.1 Average Age at Trades Level [United States]

The authors observed the average age among four high skilled trades, including carpenters, electricians, pipelayers-plumbers-pipefitters-steamfitters, and construction equipment operators [except crane], Figure 2. In general, the average age in each these trades is above the average in all skilled trades in construction. The equipment operators’ trade has older workers than other trades, and the carpenters’ trade age has increased sharply since 2006.

3.2.2 Construction Industry’s Average Age [United States vs. Canada]

The writers compared the U.S. construction industry's average age with the Canadian construction industry's average age. The Canadian dataset is relatively limited in that it did not go back earlier than the year 2006. In 2006, the average age in Canada was 39.5 and in the U.S. it was 37.4. However, the U.S. working age increased in 2014 to 40.8 years on average, while the Canadian average age for construction workers stayed almost the same, at 39.8 years, Figure 3. Therefore, the overall outcome summary from this analysis is that the US construction industry is aging at an alarmingly rate, which puts it at risk, especially during the current high demand period.

3.2.3 Age Distribution

The writers examined the age distribution in 2007, just before the great recession, and compared it with the age distribution in 2013. For all craft workers, the average age in 2007 was 37.4 and in 2013 it increased to 41. As shown in Figure 4, the percentage of young workers in 2007 was higher than the
percentage in 2013, but the percentage of the workers who were 70 years old or older was almost the same at years 2007 and 2013. Therefore, the construction industry lost more craft workers than it gained over this six year period. On the other hand, the authors used Statistics Canada to observe the age distribution for the Canadian side. Instead of including each worker’s raw age, Statistics Canada reports data on age classified by groups. In order to examine the age distribution on a similar time scale, the probability distribution for Canadian construction workers was examined for 2006 and 2011, Figure 5. In 2006, the first mode was the age group from 20 to 24 years, and the second mode was the age group from 40 to 44 years. And in 2011, the first mode was the age group from 25 to 29 years, and the second mode was the age group from 20 to 24 years. Therefore, the Canadian construction workers in 2011 were younger than construction workers in 2006.

Figure 4: U.S. All Craft Workers [2007 vs. 2013]  
(Data Source: Current Population Survey)

Figure 5: Canadian All Craft Workers [2006 vs. 2011]  
(Data Source: Statistics Canada)

In a further detailed analyses, the authors examined the age distribution for the electricians and pipelayers-plumbers-pipefitters-steamfitters trades in the U.S., since they represent the industrial construction trades that are currently in high demand. For US electricians, the average age in 2007 was 38.7 and in 2013 it increased to 41.4. As shown in Figure 6, the percentage of young workers in 2007 was higher than the percentage in 2013. However, the percentage of the workers who were 70 years old and older was higher in 2007 than 2013. Therefore over this time frame, the U.S. construction industry lost more electricians than the average loss of all craft workers. For the pipelayers-plumbers-pipefitters-steamfitters trade, the average age in 2007 was 39.7, and it increased to 41.5 in 2013. As shown in Figure 7, the percentage of young workers in 2007 was higher than the percentage in 2013. However, the percentage of the workers who were 70 years old and older was almost the same at years 2007 and 2013.

Figure 6: Electricians [2007 vs. 2013]  
(Data Source: Current Population Survey)

Figure 7: Pipefitters [2007 vs. 2013]  
(Data Source: Current Population Survey)
3.3 Immigration

There are other differences between the Canadian and the U.S. construction workforces. For example, the majority of white workers in the United States are U.S. citizens, while a large number of the white workers in Canada are not Canadian citizens, but rather from Europe and the U.S. However, the Canadian government utilizes a Temporary Foreign Worker Program (TFWP) that “allows Canadian employers to hire foreign nationals to fill temporary labor and skill shortages when qualified Canadian citizens or permanent residents are not available” (GOC 2014a). The workers in this program have flexibility to become permanent residents if their skills are needed (GOC 2014a). The U.S. H-2B Visa, which is equivalent to Canadian TFWP program, is not flexible (Wilson 2013). Therefore, the authors looked at the immigration in the both countries differently. In Canada, the authors looked at the workforce population by their citizenship (Canadian by birth, Canadian by naturalization, and not a Canadian citizen) to study immigration, which is equal to the “not a Canadian citizen” category. In the U.S., the authors focused only on the Hispanic population, since this has been a historically faster growing demographic population in the U.S. construction industry, while other populations have been shrinking (Goodrum 2004).

3.3.1 Canadian Citizenship [Construction vs. All Other Industries]

The authors examined the Canadian construction workforce by their citizenship. Almost 80% of craft workers are Canadian by birth. In 2011, the percentage of the workers who were not a Canadian citizen was almost similar in construction and all other industries with the rate of 4.5%, Figure 8. However, the construction industry has a lower percentage of Canadian citizens by naturalization. In 2011, the percentage of naturalized citizens in the construction industry was 11.13%, while the percentage in all other industries was 15.6%.

![Figure 8: Canadian Citizenship vs. All Other Industries](Data Source: Statistics Canada)

![Figure 9: High School Graduates or Higher](Data Source: Statistics Canada)

3.3.2 High School Graduates or Higher in Construction Industry [By Canadian Citizenship]

The writers took an additional step and observed the educational level of Canadian construction craft workers by citizenship. The educational level varies by citizenship type for the year 2001 and years before, Figure 9. In 1991, the percentage of construction workers who had at least a high school diploma was 55.9% for those who were “Not a Canadian citizen”; 59.9% for those who were “Canadian by naturalization”; and 63.3% for those who were “Canadian by birth”. However, the rate of high school graduates increased for all citizen types. In 2011, the craft workers who had at least a high school diploma were around 80% for both citizens and non-citizens, which is in many ways in stark contrast to the high school graduation rates among Hispanic and non-Hispanic construction workers in the U.S. (Figure 13).
One of apparent influences of the increasing educational level of foreign workers in Canada was the weight applied to an immigrant's educational attainment through the old immigration entry system. The education category constituted around 25% of the old weighting system. The Canadian government focused more on educated (talented) foreign workers, Figure 10. However, the weighting system changed in 2015 to an express entry system, which places significantly more weight on having a job offer (50%), and decreases the weight related to educational attainment to only 10%. The influence of the new weighting system on the educational attainment among immigrant workers in the Canadian construction industry is yet to be seen.

3.3.3 Hispanic Workforce in the United States [Construction vs. All Other Industries]

The authors also looked at the rate of Hispanic employment in the U.S. and found that the rate has grown significantly over time for construction and all other industries, Figure 11. However, the Hispanic population rate was lower for the construction industry in the mid-90s, and it has grown very fast since the beginning of 2000s. In 2014, the Hispanic population rate was 26.9% in the construction industry, and 17.4% in all other industries, while it was 9.9% in 1994, in both construction and all other industries.

3.3.4 U.S. Construction Hispanic workers at Trades Level

The writers examined the employment rate of the Hispanic population among specific U.S. construction trades. The highest employment rates of Hispanic workers within specific construction trades were typically related to the residential sector, Figure 12. In fact, most of these trades did not require an education background (high school degree or higher) (BLS 2014). Less than 20% of Hispanic workers were in higher skilled trades (which are below the all craft trade's average) that require unique training or certification (e.g. electrical and pipefitter).
3.3.5 High School Graduates or Higher in the U.S. Construction Industry [Hispanic vs. Non-Hispanic]

The researchers studied the educational level among U.S. Hispanic craft workers and compared it with non-Hispanic craft workers. The sampled Non-Hispanic workers reported having higher educational levels, measured by high school graduation rates, as compared to the sampled Hispanic workers, with an approximate gap of 37% in 2014, Figure 13. In 1994, 42.1% of Hispanic workers had a high school degree, while 77.4% of non-Hispanic workers had the same degree. In 2014, the rate of educated Hispanic workers increased to 50.3%, while the rate of non-Hispanic educated workers also increased to 87.3%.

4 DISCUSSION

The aging of the workforce indicates that the retirement of baby boomers is having a significant impact on the current workforce shortage. The entire workforce’s average age has increased over the time, but the age of the U.S. construction industry grew very fast in recent years, almost four times faster than in the previous decade. Age distribution results show that the construction industry in the U.S. is losing more workers than it gains, especially electricians and pipefitters. Losing experienced skilled workers will create a gap, since skilled trades require unique training and certification, which for new workers takes time usually measured in years. Therefore, most of the highly skilled trade workers in the U.S., including electricians, and pipefitters, are older than the average craft trade workers in the construction industry. However, the average age of Canadian construction workers was also been growing steadily. However, the average Canadian construction worker in 2014 was still younger than the U.S. construction worker. Moreover, the Canadian age distribution shows that more young workers entered the construction industry in recent years.

It appears that Canadian immigration policy, which has placed a significant weight on an applicant’s educational attainments, has influenced the overall educational level of the Canadian construction workforce. The educational attainment of Canadian foreign-born workers was nearly equal to that of Canadian natural born worker. As part of a growing immigrant workforce in the U.S., the same cannot be said for the U.S. Hispanic construction workforce when compared to the non-Hispanic workforce. A significant educational gap between Hispanic and non-Hispanic construction workers exists in the U.S. This gap limits the abilities of the Hispanic workforce to enter into higher skilled and higher pay construction jobs. In a time when the U.S. construction market is experiencing severe workforce shortages among higher skilled jobs, structural changes in the education and training of the Hispanic workforce is needed.

5 CONCLUSION

Using the previously mentioned data sets (CPS, Statistics Canada, and Build Force Canada), this research primarily examines the influence of demographics on skilled workforce shortages, comparing the U.S. construction industry with Canadian construction industry. Additionally, the authors focused on the trades that are more related to the industrial projects. The following findings were identified:

- There is a “greying” of the workforce, especially in the U.S., and the rate is increasing. All other industries craft workers in the U.S. are older than the construction craft workers. However, in the last decade, the rate of aging among U.S. construction workers is almost four times higher than the growing rate from the previous decade.
• High Skilled trades in the U.S. (i.e. electricians, and pipefitters) are older than the construction industry average age.
• The construction industry in the U.S. is losing more craft workers than it is attracting.
• The Canadian construction foreign workers percentage has not increased over time, but their level of education has increased sharply.
• The percentage of Hispanic craft workers in the U.S. has increased sharply over the time while their level of education has not.

The analysis showed that the aging of the construction workforce plays a significant role in the current craft shortage, especially in the U.S. Outside of revamping a U.S. immigration policy that considers the educational attainment of foreign born workers, the U.S. needs to critically examine how to improve the educational attainment of Hispanic construction workers both for the personal benefit of the individual worker and the industry’s needs.

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References


INTEGRATING 3D CAD AND COST ESTIMATING AT THE CONCEPTUAL DESIGN STAGE OF BRIDGE PROJECTS

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Abstract: Bridge Information Modeling (BrIM), as a concept, has been introduced to enhance the procedures of the whole phases of a bridge life-cycle starting with concept and design, through construction and operation, and ending with maintenance and rehabilitation. Integrating BrIM and design tools would help improve the methods used in designing and constructing bridge projects at early stages taking into considerations their cost and time constraints. The main objective of this research is to develop an integrated model that helps owners, designers and construction managers visualize bridge projects in a 3D mode and accordingly automate the process of generating preliminary cost estimates during the conceptual design stage. To achieve the abovementioned objective, a proposed methodology will be applied where all the aspects needed to develop an efficiently integrated model are realized. Thus, this paper describes the proposed methodology that incorporates three modules, which will be the core of the integrated model. These modules are: a knowledge based system module, which is used to generate conceptual dimensions and parameters depending on algorithmic and heuristic knowledge gathered from codes, guidelines and design experts; a conceptual cost estimation module, which is used to generate conceptual cost estimate based on the results of the first module; and a 3D visualization module, which is integrated with the previous modules where users will visualize the proposed bridge in 3D based on the results of the knowledge based module. The integrated model will be validated through an actual case project to test its workability and output.

1 INTRODUCTION & LITERATURE REVIEW

Significant advancement and Development in automation and communication technologies occurred in recent years, but bridge engineering and its construction management did not fully adapt and integrate these developments (Chen and Shirole, 2008). According to Chen and Shirole; (2008), Bridge Information Modeling (BrIM) has weighty potential efficiencies and reasonable advantages to be gained by developing integrated approaches. The concept is the same as Building Information Modeling (BIM) but it is closely related with an axis for road or railway design (Katz, 2008). Bridge Information Modeling (BrIM) widely is becoming an effective tool in the bridge engineering and construction industry. Bridge Information Modeling (BrIM) methodology is being used increasingly in the design and construction of complex and large bridges, also (BrIM) aspects such as visualization, detailing, bridge operations management and project delivery are being used in infrastructure projects through the use of AASHTO Ware (Shirole et al. 2009). Integrated approaches of BrIM aspects will not only result in costs reduction, faster delivery and improvement of quality, but also will pave the way towards different project delivery models such as design/build delivery model. However, lots of engineers and researchers are still unaware of the economic benefits of utilizing such technologies in cost estimation at the conceptual design phase.
of bridge projects (Shirole et al. 2009). Many researchers studied and applied BrIM on stages of bridge projects such as on the detailed design, construction and maintenance. However, BrIM aspects were not implemented at the conceptual stage of a bridge project. This research proposes a methodology to integrate part of the BrIM, which is the 3D CAD, with cost estimation at the conceptual design stage of bridge projects.

Integrated design and construction of bridges was addressed in many studies and pieces of research, which gave manufacturing industries excellent results and provided improvements. Lee et al (2012) developed 3D models for specific construction methods used in prefabrication of concrete bridges. The proposed model was needed to enable engineers to make cost-effective decisions. Also, the model ensured adequate collaboration between CAD systems that is not available in 2D drawings, because 2D drawings need additional effort to correct constructability problems due to insufficient information delivery between different engineers. Lee’s 3D proposed models not only increase the efficiency of collaboration between different engineers but are also useful for communication between project parties. The CATIA-V5 CAD engine was used in their model to support the 3D geometry models. Their model was based on digital mock-up (DMU) computer-based information technology. The model was validated by utilizing a precast concrete box girder bridge construction project by a general contractor. Concrete segment components were modeled and assembled, where the DMU technology improved the quality of the concrete segments and reduced their time and construction cost. Bill of Materials (BOM) conducted to provide information concerning the product parts and the correlation between the parts. The huge sophistication and complexity of construction and fabrication of the reinforced concrete structure was accelerated using this technology. A lot of researchers have been studying and discussing the operation of construction equipment using computer-aided design software and modern technologies for very complex and complicated bridge projects. Park, et al (2009) applied 3D CAD for effective derrick crane operations in a case project concerning cable-stayed bridge construction. In this case project, a 3D CAD model was applied during the operation stage, wherein it showed, in detail, the movement of the equipment and materials throughout the construction operation. The operation stage requires more in-depth knowledge of the whole construction operation. The case study presented the application of a 3D CAD model to show the operation of a derrick crane in constructing the Cheongpoong Grand Bridge which is a cable-stayed bridge. The derrick crane was the major piece of equipment used in the project. However, analyzing the safety of using the derrick crane in installing objects was crucial. Thus, analysis of the crane operations was conducted using the 3D CAD model. The entire path of the crane, when in motion, was visualized during the envelope analysis before the physical construction starts. Using a 3D CAD model in the case project led the authors to conclude that this technique can prevent reworks, while improving the productivity of bridge construction.

Technology developments that have occurred during recent decades have encouraged many researchers to develop modern methods to improve productivity in different fields of construction. Modern technology and bridge information modeling (BrIM) were used in many bridge projects during both the project and operational stages. Other researchers are currently looking at the application of BrIM project tasks such as planning, scheduling, safety, construction operations and maintenance. Most BrIM applications have been implemented on projects after their design stage where the related information and data are available. However, applying and using the BrIM concept during the project conceptual stage has not captured the attention of researchers. Applying the concept during this stage will lead to developing effective and powerful applications and models that will save time and cost. However, this research will focus on integrating the 3D CAD part of BrIM with conceptual cost estimating; thus, the conceptual design stage is the focus of the research study.

According to Miles et al (1994), the conceptual design area has been resistant to the introduction of computer systems. However, developers were enabled by the development of the KBS to provide systems that undertake conceptual design needs. According to the definition of the KBS, it consists of two main parts: the knowledge and the interface engine. Two types of knowledge are used in the KBS: algorithmic and heuristic. The algorithmic knowledge represents equations based on Newtonian physics, while the heuristic knowledge represents rules of thumb which are based on experience. On the other hand, the interface engine presents the knowledge via logical statements and IF-THEN rules. Manos et al (2011) proposed a methodology for implementing KBS for the preliminary design of the seismic isolation
of bridges. The proposed methodology is based on the current design provisions of Eurocode 8, but is complemented by additional criteria, set according to expert judgment, laboratory testing and recent research findings, while using a combined cost/performance criterion to select from a database of available bearing products on the international market. The methodology is also implemented in software whose efficiency is validated through parametric numerical analyses as well as by using the case of a real bridge. Miles and Moore (1989) proposed another example of implementing KBS for conceptual design. They proposed implementing KBS for conceptual design of road bridges. They developed a system which is intended for inexperienced young civil engineers and aims to assist young civil engineers in gaining more understanding of conceptual bridge design process. Miles and Moore (1989) suggested to include graphics and to build more interaction with other computer system such as CAD systems and intelligent databases.

2 METHODOLOGY

The proposed methodology that integrates bridge information modelling and cost estimation for bridges at the conceptual design stage requires following the steps used to design the bridge at the conceptual stage. This can be achieved by identifying all the necessary bridge-related parameters and information needed for the conceptual design. The integrated model consists of the following three main modules (1) knowledge-based system; (2) cost estimation module; and (3) 3D visualization module. The knowledge-based system is used to generate preliminary dimensions/parameters, and to recommend bridge type alternatives. The cost estimation module consists of a comprehensive cost database that is used to generate cost estimates for the selected alternatives. The visualization module utilizes three-dimensional (3D) drawings in modeling bridges.

2.1 Knowledge Based System

The main purpose of utilizing the Knowledge-Based System (KBS) is to generate preliminary dimensions and parameters which can be used in the conceptual cost estimating module. The main procedure of the KBS involves three steps, (1) user's input variables; (2) knowledge base analysis; (3) KBS output variables. The first step requires the user to identify objective variables rather than subjective variables. The reason behind this is that objective evaluation criteria require objective feedback or measures, which are available to both experienced and inexperienced designers. On the other hand, subjective criteria require subjective feedback or experience judgment, which can be available only for the experienced designer. The objective variables, which should be identified by the user, are bridge length, road type, required number of lanes, location and overpass object information. The second step is to use the user's input variables in consulting the system's stored knowledge base. Two types of knowledge are to be consulted, algorithmic knowledge and heuristic knowledge. The algorithmic knowledge is based on highway geometric design guidelines, navigational waterway guidelines and bridge structural design code, while the heuristic knowledge is based on rules of thumb gathered from bridge design experts and engineers. The knowledge base is consulted and restored though the interface IF-THEN rules. Finally, the third step is to present the output variables to the user, and to provide flexibility to the user in case any changes are desired. These variables are bridge cross-sectional dimensions, element dimensions and span arrangements. These variables are then used in the process of bridge type selection, will be used later in the conceptual cost estimating module and visualization module. Figure 2.1 illustrates the process flow of the knowledge-based system.

2.1.1 Knowledge Base

Transportation Association of Canada Geometric Design Guideline 1999 (TAC 1999) is used by designers in Canada as a source of a highway geometric design guideline. The purpose of using this guideline is to get assistance in generating conceptual road features and dimensions considering all the highway design factors such as mobility, environmental impacts, safety, capital cost, aesthetics, maintenance cost and vehicle operational cost. Sample of the road features and dimensions are lane width, left shoulder width, right shoulder width, median width, bike path width, transit lane width, pedestrian path width and parapet width. This guideline assists designers in applying the design domain concept by providing numerical guidance, in the form of tables and graphs. In addition, it provides a
commentary on the nature of the design domain and quantitative evaluation data of safety performance. After gathering all this information, logical relationships and IF-THEN rules are ready to be created.

The Navigable Waters Protection Act (NWPA), established by Transport Canada, is responsible for protecting the public right of navigation in all navigable waters in Canada. Any company or government agency that proposes to construct or repair any work within the limits of navigable waterway must obtain approval through the NWPA (TAC 1999). A document developed by the Transport Canada Navigational Waterways Protection Division (TC NWPD) in 2006 is used as a guideline in determining minimum navigational clearances. This guideline insures the provision of minimum required navigational clearances that allow safe passage under bridges and culvert structures for all types of vessels. If the bridge crosses a navigational waterway, it is important to know the minimum required navigational clearances in order to be able to identify bridge span arrangements. After gathering all this information, logical relationships and IF-THEN rules are ready to be created.

Little structural design information is available at the conceptual design stage. In addition, there is no specific formula or unique solution the designers have to follow -- structural design is based mainly on the designer's experience and knowledge. Thus, collecting information from bridge design experts is the only source for developing the structural design knowledge base. The research authors decided to interview two bridge design experts to elicit information and knowledge for developing the structural design knowledge base. The reason for selecting multiple experts in developing the knowledge base is that it has been found that interviewing multiple experts is highly beneficial and is recommended for knowledge base development (Moore, 1991). Interviewing multiple experts has been found to provide less chance of missing vital information, and to reduce the length of the overall knowledge elicitation process. Care is taken in choosing experts who have long experience in bridge design. Also, the authors were careful to select experts who are currently practicing bridge design to insure that their expertise will be relevant and useful; otherwise, there is a risk of their knowledge becoming out of date. The meeting involved an interview with the expert, in which the research was explained in full, ensuring the expert understood the intended capabilities of the proposed model, the degree of co-operation which would be necessary, and the format which the model would take. Providing an indication of the type of knowledge that would be required, allowed the problem-solving methodology employed by the experts to be quantified. heuristic information concerning bridge components was collected and gathered by interviewing two bridge design experts. The information was gathered through asking the experts some questions about the type and preliminary dimensions for all the bridge components, such as the choice of bridge deck, decisions concerning the supporting structure, the number of spans, and type of material for the bridge components. The collected information is stored in an Excel spreadsheet for later use in the conceptual cost estimating module. This can assist the designer or user to generate preliminary dimensions for the bridge components.

Figure 2. 1 Knowledge-Based System Process Flow
2.1.2 Bridge Type Selection

It is necessary to select the bridge type prior to starting the process of developing conceptual cost estimating of the bridge project. Due to the lack of information and data at the conceptual design phase the selection process is somehow difficult. The design experts interviewed recommended depending on existing bridges in selecting the bridge type. Historical data of all existing bridges in Ontario was collected from the Ministry of Transportation of Ontario (MTO). The data contains information about 2784 bridges in Ontario. The information include (1) bridge structural type; (2) bridge sub-structural type; (3) total bridge length; (4) total bridge width; (5) bridge span arrangement; and (6) material. The structural bridge types available in the database are (1) beam/girder; (2) arch; (3) frame; (4) slab; (5) temporary modular; and (6) truss. After collecting the data, a validation and consolidation process is applied to remove any repetitive or incomplete information. The data is presented in an Excel workbook. The data was divided into Excel workbooks based on the bridge span number. Each Excel workbook contains sheets that represent bridge types.

The criterion of selecting bridge type is based on comparing the user's input variables with the variables of an existing bridge, and selecting a bridge type that matches the user's input variables. As shown previously in Figure 2.1, the output variables of the knowledge base system are used as input variables for the bridge type selection process. These variables are (1) bridge length, (2) largest span length, (3) bridge width and (4) number of spans. In addition, the user is required to specify a value of Closeness Factor (K), which is a factor used in quantifying the similarity between the proposed bridge variables with existing bridge variables. Based on the number of spans, the existing bridge Excel spreadsheet is selected to be used in selecting the bridge type. The variables of bridge length, bridge width and largest span length are used to calculate the closeness weights. Closeness Weights, which are the ratios between the input variables and the existing bridge variables, are then to be calculated using the following equations:

\[ [1] \text{Closeness Weight of Bridge Width} = \frac{W_0}{W_{in}} \]

\[ [2] \text{Closeness Weight of Bridge Length} = \frac{L_0}{L_{in}} \]

\[ [3] \text{Closeness Weight of Bridge Span Length} = \frac{S_0}{S_{in}} \]

Where, \( W_0 \) = Width of the proposed bridge  
\( W_{in} \) = Width of the existing bridge \( i_n \)  
\( L_0 \) = Length of the proposed bridge  
\( L_{in} \) = Length of the existing bridge \( i_n \)  
\( S_0 \) = Largest Span length of the proposed bridge  
\( S_{in} \) = Largest Span length of the existing bridge \( i_n \)

The next step is to calculate the adjusted closeness weight, to see how close the proposed variables are to the existing bridge variable. The adjusted closeness weight has a range value between one and zero. Adjusted closeness weight value 1.0 means that the proposed bridge variables exactly match the existing bridge variables, while adjusted closeness weight of value zero represents that the proposed bridge variables do not match the existing bridge variables. The following equation is used to calculate the adjusted closeness weight:

\[ [4] \text{Adjusted closeness weight} = \begin{cases} 
\text{Closeness Weight} \geq 2, & 0 \\
\text{Closeness Weight} \geq 1, & 2 - \text{Closeness Weight} \\
\text{Closeness Weight} < 1, & 1 - \text{Closeness Weight}
\end{cases} \]
All of these steps are then repeated for all the bridge cases within the same Excel sheet. As mentioned above, each Excel sheet represents a bridge type. Once adjusted closeness weights are calculated for all the bridge cases within an Excel sheet, the maximum value of the adjusted closeness weights is found. If the maximum closeness weight is found to be bigger than the closeness factor $K$, then the bridge type is recommended to the user. If the maximum closeness weight is found to be smaller than the closeness factor $K$, then the existing bridge type is rejected. All these calculations are repeated with all the bridge types available in the Existing Bridge Excel workbook. Figure 2.2 shows the process flow of the bridge type selection process.

![Figure 2.2 Bridge Type Selection Process Flow](image)

2.2 Conceptual Cost Estimating Module

It is necessary to define the dimensions and to select the bridge design type before one can estimate the cost. Thus the output of both the knowledge-based system and the bridge type selection process are considered as input variables in the conceptual cost estimation module. Preparing a cost estimate greatly depends on the accuracy of the collected data. Thus, data collection has to be carried out before developing the cost estimating module. Since published cost data is not available for bridges, the only remaining alternative source of cost data is the collected cost data from previously constructed bridge projects. In-house cost data is considered to be the best choice in this case; however, cost data of
previously constructed bridge projects can be used for the research purposes. The cost data collection process was conducted before developing the module. The resources of the collected data were from different previously constructed bridge projects in North America. Using the ASTM (E2103) standards and the collected cost data, a bridge elements and components Excel spreadsheet for each type of bridge is created. These Excel spreadsheets are used to calculate the estimated conceptual cost for the project by entering the dimensions and parameters obtained from the KBS. It is important to adjust the cost of previous similar projects for time and location so that they are suitable for the proposed project. Thus, inflation and location adjustments were implemented on the gathered data. Once the cost adjustments are applied, conceptual cost estimating reports can be generated. Three different types of reports are to be generated, which are: (1) detailed cost estimating report, (2) sub-classification cost estimating report, and (3) summary cost estimating report. The purpose of generating three types of reports is to explain the cost allocation clearly by generating a cost estimate for each work group such as, superstructure, substructure, and site work, etc. Figure 2.3 illustrates the data flow of the conceptual cost estimating module.

![Image of data flow diagram]

Figure 2.3 Conceptual Cost Estimating Module and 3D Visualization Module Data Flow

2.3 Visualization Module

The purpose of the visualization module is to visualize the information of each bridge element and to present it in a 3D model. It is important that the generated 3D model contain visual properties that allow the user to identify the texture and color of the material in order to visualize the realistic aesthetics of the bridge. To do that, AutoCAD is utilized as a visualization tool, because its capabilities suit the purpose of the module. AutoCAD has the ability to exchange information with many applications with high efficiency in performing data recall. In addition, AutoCAD has the ability to assign properties such as material type and color to objects. This ability gives the 3D object a realistic visualization, which can assist the user in judging the aesthetics of the bridge elements. Moreover, AutoCAD has the ability to add the effect of lightning on the 3D object to visualize the light and shade effect, which is one of the bridge aesthetics principles. Besides all these abilities, utilizing AutoCAD as a visualization tool will allow the user to orient
the 3D bridge model and visualize it from different views. As shown in Figure 2.1, both the conceptual cost estimating and the visualization modules share the same input variables, which are the output variables of the KBS and the bridge type selection process. Thus, the visualization module can also use the Excel spreadsheets created from combining the cost data and the ASTM standards of bridge element classification. An exchange of information between the two modules is provided. In other words, if any changes or modifications with the generated 3D bridge model result in changes in the Excel spreadsheet, it will lead to changes in the conceptual cost estimation reports. To implement this data exchange, it is important to create a link between the visualization tool, AutoCAD, and the Excel spreadsheets of the model. Figure 2.5 illustrates the data flow of the conceptual cost estimating module.

3 DEVELOPMENT AND VALIDATION

The Knowledge-Based System (KBS) consist of two main components, the knowledge base and the interface. To develop the knowledge base, the following two steps are followed:

- Develop an interface using VB.NET according to the order of the knowledge bases process flow.
- Write programming code for VB.NET by:
  - Converting knowledge base tables and information representation to IF-ELSE rules in the VB.NET language.
  - Representing formulas and equations in the VB.NET language to perform the calculations.

The outputs of the knowledge-based system are used in the bridge type selection excel sheets in order to recommend to the used the suitable bridge types. The user then has to select the desired bridge type. The output variables of both the knowledge-based system and the bridge type selection process are used as input variables for the conceptual cost estimating module. The visualization module shares the same source of data as the conceptual cost estimating module. This source of data is the Excel spreadsheets that store combined information from KBS, bridge type selection, and cost data. Figure 3.1 summarizes the development of the proposed model.

The performance of the model was validated by estimating the cost and generating 3D CAD drawings of an actual project. This performance is measured by comparing the model's results with the actual project values. The actual project was a two-lane concrete slab bridge located on Lakeshore Drive, Ontario, Canada. The comparison between the preliminary dimensions of the actual bridge and those of the model showed exactly the same values. Also, the model's preliminary dimensions were compared with the
values obtained manually from TAC (1999) Highway Geometric Design Guidelines and showed matched values. Regarding the construction cost estimation, both the actual and model's construction cost showed close values with a small difference, which is acceptable because at the conceptual stage there is not enough information known about the project. The generated preliminary dimensions and the estimated cost by the model were in the same range, which proves the feasibility and reliability of the developed model. 3D CAD drawings of the case project were viewed in VB.NET and AutoCAD platforms to provide flexibility in visualization.

4 CONCLUSION AND FUTURE EXPANSION

Bridge Information Modeling (BrIM), as a concept, has been introduced to enhance the procedures of the whole phases of a bridge life-cycle. Integrating BrIM and design tools would help improve the methods used in designing and constructing bridge projects at early stages taking into considerations their cost and time constraints. The main objective of this research is to develop an integrated model that helps owners, designers and construction managers visualize bridge projects in a 3D mode and accordingly automate the process of generating preliminary cost estimates during the conceptual design stage. A proposed methodology is applied where all the aspects needed to develop an efficiently integrated model are realized. The proposed methodology that incorporates three modules, which will be the core of the integrated model, is described. These modules are: a knowledge based system module, which is used to generate conceptual dimensions and parameters depending on algorithmic and heuristic knowledge gathered from codes, guidelines and design experts; a conceptual cost estimation module, which is used to generate conceptual cost estimate based on the results of the first module; and a 3D visualization module, which is integrated with the previous modules where users will visualize the proposed bridge in 3D based on the results of the knowledge based module. The integrated model was validated through an actual case project to test its workability and output. The integrated model performance is measured by comparing the model's results with the actual project values. The comparison between the preliminary dimensions of the actual bridge and those of the model showed exactly the same values. Regarding the construction cost estimation, both the actual and model's construction cost showed close values with a small difference, which is acceptable because at the conceptual stage there is not enough information known about the project. The generated preliminary dimensions and the estimated cost by the model were in the same range.

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ENERGY-BASED SAFETY RISK MANAGEMENT: USING HAZARD ENERGY TO PREDICT INJURY SEVERITY

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Abstract: Worker injuries and fatalities have long been problematic in the construction industry. To address this ongoing concern, recent research has focused on risk-based approaches to proactive safety management. Although the quantity and quality of safety risk data has improved in recent years, available data do not link directly to natural principles and are, therefore, limited in their application and scientific extension. This study offers a new explanation of safety risk using the concept of energy where the underlying proposition is that all hazards are truly defined by the exposure to one or more of ten distinct forms of energy (e.g., gravity, motion, electrical). This concept of safety energy was introduced by William Haddon, was operationalized in a past Construction Industry Institute (CII) research team, and is currently being tested by an active CII research team. The present study aims to link energy transfer to safety risk for the first time. Inspired by natural disaster modeling, the concept of energy is translated to risk by defining the severity of a potential event as the ratio of the magnitude of the energy to the resiliency of the impacted human body part and the pressure exerted on impacted body part. Additionally, the likelihood component of risk is defined by the combination of human, social, technological, and other factors that contribute to the chance that there is an unwanted transfer of energy. To test this proposition, energy-based risk data were extracted from two sources: (1) a random sample of 40 injury reports taken from a larger database containing approximately 7,250 injury reports obtained from 281 private construction organizations and (2) a random sample of National Institute of Occupational Safety and Health Fatality Assessment and Control Evaluation (NIOSH FACE) reports. For each report, a combination of manual and automated content analyses was used to extract the following data: the chief energy source(s) contributing to the incident, the quantity of energy involved, the part of the body affected, and the severity of the outcome. Generalized linear models derived from initial results demonstrate that energy possesses legitimacy in predicting the severity of an injury that will result from a particular hazard, tentatively confirming the proposed theory. This research indicates that energy-based safety risk analysis is a promising line of scientific inquiry with predictive validity that has the potential to increase our understanding of the natural phenomena that contribute to injuries. This research corroborates previous hazard recognition research that introduced the energy principle of hazard classification but challenges the scientific merit of past safety risk data.

1 INTRODUCTION

With an average of more than two fatalities per day, the United States construction industry’s 796 workplace fatalities in 2013 accounted for the highest number of workplace fatalities of any United States industry (Bureau of Labor Statistics, 2014). The construction industry’s disproportionate fatality and serious injury rate has been an ever-present trend which, until the creation of the Occupational Safety
and Health Administration (OSHA) in 1970, was largely viewed as an inherently unavoidable characteristic of the work being performed (Bureau of Labor Statistics, 2014; Cameron et al. 2008; Roudsari and Ghodsi, 2005). Current theory, however, is that workplace safety is an indicator of effective design, planning, training, and work execution (Hallowell et al. 2014). Injuries in the construction industry are extremely costly. In fact, Everett and Frank (1996) estimated that the direct cost of accidents account for 15% of the total cost of a project (Agarwal and Everett, 1997). In addition to the direct costs, indirect costs such as work stoppage, training replacement workers, repairing damaged property, and maintaining insurance coverage have been estimated to be as high as twenty times the magnitude of direct costs (Business Roundtable, 1982). The end result is that the financial impact of workplace fatalities and serious injuries within the construction industry is nearly double that of the all-industry average (Waehrer et al., 2007). Due to the significant humanitarian and financial impacts, improving worker safety within the industry has become an increasingly important priority for construction firms and professionals (Gambatese et al. 2008).

Since the creation of OSHA in 1970, researchers and practitioners have introduced a plethora of safety programs such as project-specific training and safety meetings, frequent worksite inspections, and safety and health orientation. However, the effectiveness of these traditional injury prevention approaches is limited due to their reactive and regulatory-based nature (Hallowell and Gambatese, 2007). Additionally, Esmaeili and Hallowell (2012) found that most traditional strategies have reached saturation in terms of new adoption, suggesting that research and development for construction safety is critical for future improvement. In response to these limitations and trends, researchers have begun to explore risk-based practices as a means for safety innovation. Conventional safety risk management methods assume that work can be decomposed into its constituent parts (Lingard, 2013), ranging from broad safety risk analysis of different construction trades (Baradan and Usmen, 2006) to detailed safety risk analysis of specific construction activities such as concrete formwork placement (Hallowell & Gambatese, 2009). The problem with this approach, as explained by Cooke-Davis, et al. (2007), is that the decomposition of a complex system such as a construction site is of limited value when the work elements are in constant dynamic interaction with one another. As a result, while helpful, conventional safety risk management methods within the construction industry are limited in terms of both their current application and potential for future scientific development.

The purpose and intention of this study is to address the current limitations in safety risk analysis by offering a new energy-based approach to characterizing the potential severity of injuries. The specific goal is to examine the extent to which the quantity and the type of energy predicts the potential outcome of a hazardous work situation. If a link is established, this study could reveal a more fundamental approach to characterizing and measuring safety risk on construction projects.

2 LITERATURE

Applying the concept of energy to explain safety risk requires an understanding of the concepts of both safety risk analysis and safety energy. In order to better illustrate how this study seeks to advance the cause of safety within the construction industry, the relevant literature is reviewed in these two areas.

2.1 Risk Analysis in Safety Management

In a broad sense, risk can simply be defined as the combination of uncertainty, or probability, weighed against the damage that would be incurred. In the context of occupational health and safety, risk is a measure of the likelihood of injury and the associated consequences a hazard present in a given situation (Baradan & Usmen, 2006; Jannadi & Almishari, 2003). In 1984, system safety engineers in the United States military were able to quantify the risk associated with an event as the product of the probability and the severity of an outcome (Quality, 1984). This definition for safety risk, shown in Eq. (1), has remained consistent since its indoctrination and will be the premise for the concept of energy-based safety risk. It should be noted that the probability that a hazard will cause an injury is analogous to the frequency of events within a given period of time. Typically, frequency is expressed in terms of incident rates, whereas the severity is defined in terms of the impact to the work or firm (Hallowell & Gambatese, 2009).

\[
\text{Unit Risk} = (\text{Frequency}) \times (\text{Severity})
\]
Over the past 15 years, several safety risk quantification methods, varying in complexity and application, have been employed utilizing the underlying concept of unit risk analysis. For instance, Everett (1999) quantified the risk of overexertion injuries for various trades by studying the frequency of particular overexertion injuries incurred while performing work tasks. Similarly, Huang and Hinze (2003) were able to quantify the risk of fall accidents using OSHA and Bureau of Labor Statistics (BLS) statistical data. Several additional studies have since contributed to the advancement of safety risk analysis, quantifying risk for such categories as struck-by accidents (Hinze, Huang, & Terry, 2005), fatalities between construction trades (Baradan & Usmen, 2006), and tower crane activities (Shapira & Lyachin, 2009). The commonality among these studies is that the research focused predominantly on analyzing the frequency of event occurrences to quantify risk. The reasons that safety risk quantification research has primarily focused on incident frequency spans two-fold: 1) frequency data is more easily measured and accessible through databases such as the BLS; and 2) the widely used “Safety Triangle” (Heinrich, 1931) derives its basis on the frequency of events. Nonetheless, the severity component in quantifying risk, which, in its truest sense, is equally as important to likelihood when quantifying safety risk, has not received significant attention in construction safety research. The purported concept of energy-based safety risk would address this major deficiency and serve as a means to reliably quantify the severity based on the physical characteristics of the hazard.

In comparison to advances achieved in general risk analysis techniques, the development of safety risk analysis methods has lagged due to two fundamental limitations: 1) there is a limited amount of reliable data sources; 2) the employed methods are restricted in their external applications. Of the data sources available, the primary sources used to quantify safety risk include empirical data from private organizations or companies (Desvignes, 2014; Prades, 2014), government statistics (Baradan & Usmen, 2006; Hinze et al., 2005), and opinion-based data (Brauer, 2005; J. Everett, 1999; Hallowell et al., 2011; Jannadi and Almishari, 2003). All of these data sources have inherent limitations that reduce the validity and reliability of safety risk assessments. Of all methods, empirical data are preferred because they tend to involve less bias. Unfortunately, researcher access to empirical data gathered by private organizations is limited because they often involve proprietary or confidential information. Although statistics made available through governmental agencies like OSHA and the BLS have provided researchers a credible source from which to develop safety risk analysis strategies, the granularity of government statistics limits risk analysis to the trade, work task, or injury classification level. Widely used in safety risk practices, opinion-based data gathered by industry experts has primarily relied on qualitative risk ratings using numerical or linguistic scales (Baradan and Usmen, 2006; Brauer, 2005; Everett, 1999; Shapira and Lyachin, 2009). However, as one might expect, expert opinion data are limited by the personal biases of human raters. For example, Capen (1976) revealed that subjective probability is heavily influenced by individual biases and that people have erroneous judgment in statistical intuition under uncertainty. Since Capen’s (1976) discovery, many other studies have confirmed this debilitating characteristic of expert opinion data (Gustafson, 1998; Kahneman and Tversky, 1982; Sjöberg, 2000). Thus, more robust empirical data must be explored to improve safety risk assessment techniques.

In addition to data source limitations, conventional safety risk management methods are limited in their breadth of application (i.e., external validity). All safety risk researchers assume that the work can be decomposed into its constituent parts in order to address the construction industry’s dynamic and transient nature (Lingard, 2013). Researchers have used a multitude of techniques to decompose and analyze safety risk, ranging from very high level studies looking at methods to evaluate safety risk amongst different construction trades (Baradan and Usmen, 2006; Fung, et al. 2010) and injury classifications (Hinze et al., 2005) to detailed studies looking at specific construction activities and the risk associated with elemental tasks being performed within those activities (Everett, 1999; Hallowell and Gambatese, 2009; Jannadi and Almishari, 2003). However, these risk decomposition techniques are either so overly broad that they have limited application to individual projects or are so specific that any new construction methods or variation upon existing methods requires a laborious research process to collect new data. Very recently, Esmaeili (2012), Desvignes (2014) and Prades (2014) explored attribute level risk analysis, which allows one to evaluate risk independent of specific tasks and environments by focusing on fundamental characteristics (e.g., uneven surfaces, work at height, etc.). The present study introduces the energy-level risk analysis strategy for the first time, building upon the new attribute-level theory.
2.2 Energy-Based Safety

The impetus for an energy-based safety approach is the concept of energy-based hazard recognition (Albert et al., 2014). According to Carter and Smith (2006), construction workers are customarily poor at identifying hazards during construction because of the industry’s diverse, fragmented, and dynamic nature. The inability to identify hazards in turn results in construction workers being exposed to unanticipated dangers or engaging in unsafe work practices without understanding the severity of adverse consequences (Wilson, 1989). Taking inspiration from William Haddon’s work on safety energy, Fleming (2009) sought to improve worker hazard recognition by categorizing hazards based on the primary energy source that could cause the injury (e.g. motion, gravity, electricity, etc.). Fleming’s (2009) principal theory is that all construction accidents originate from a specific energy source that is identifiable prior to work. When an energy source is released outside of the work plan, the unanticipated loss of control over the energy source creates the potential for injury. Principles of energy-based safety were soon implemented with respect to hazard recognition by an expert team sponsored by the Construction Industry Institute (CII), which identified and predefined ten energy sources relevant to construction to serve as cognitive cues (Albert et al., 2014). Using a multiple baseline intervention research method with six construction crews, Albert et al. (2014) demonstrated a significant 31% improvement in hazard recognition skill amongst workers. Unfortunately, existing literature detailing the use of energy in construction safety is very sparse as the concept of energy-based safety within the construction industry remains in its infancy. However, the initial research results indicate that there is significant promise in using the concept of energy to identify and rank safety hazards encountered in the construction industry.

3 POINT OF DEPARTURE

Current safety risk analysis appears to suffer from two primary weaknesses: (1) a lack of scientifically driven empirical data; and (2) risk analysis strategies which are often narrow in scope, thus limiting their effectiveness when applied to the construction industry’s diverse project portfolio. Inspired by energy-based hazard recognition, this study aims to test the null hypothesis that energy has no significant relation to the severity of an injury by offering a new approach to safety risk analysis using the concept of energy to measure the severity of potential hazards, and, by doing so, seeks to introduce natural principals that will allow safety risk analysis to become more universal in its breadth.

4 KEY NEW THEORY

Energy-based safety risk analysis theory draws inspiration from natural disaster modeling which, in essence, predicts the potential impact of a natural disaster by considering the magnitude of the event and the resiliency of the affected area (Johnson, 2004). This same fundamental analytical approach is taken within the context of energy-based safety risk. Specifically, energy is translated into severity of a potential hazard as the ratio of the magnitude of energy to the resiliency of the impacted human body part and the concentration of energy transferred. The probability, in turn is defined by the various action and inaction that results in the unwanted release and/or exposure to the human body. By quantifying the energy found in these potential hazards, energy-based safety risk analysis may result in a standardized approach to evaluate and predict the severity of potential injuries in any environment, which can subsequently utilize current frequency data techniques with the established principals of Eq. (1) to create a more robust safety risk analysis method Energy within Hazards. When evaluating energy-based safety risk, the magnitude of energy present within a specific hazard must first be determined. To illustrate the concept of energy-based safety risk, consider gravitational potential energy (PE), which depends on the mass and vertical position of an object as shown in Eq. (1), where \( m \) = mass; \( g \) = gravitational constant; and \( h \) = vertical position or height above the ground.

\[
PE = mgh
\]

Take, for example, the conditions where both a tape measure and a sledgehammer are dropped on your hand from a height of five feet. Due to their weight differential, intuitively one would expect the sledgehammer to inflict more damage and have a greater potential for breaking bone. Considering
energy, this intuition can be scientifically proven. Specifically, a tape measure, which weighs approximately one pound, would only inflict five foot-pounds of energy while a sledgehammer, weighing approximately 15 lbs., would transfer 75 ft.-lbs. of energy. Clearly, under these parameters, the sledgehammer would pose a much higher risk for severe injury; however, a change to one of the parameters can result in the tape measure having the equivalent potential to inflict injury. For example, if the tape measure were dropped from a height of eight stories it would transfer energy in an amount equivalent to that generated by a sledgehammer dropped from five feet, thus transferring equivalent energy to the hand. Thus, according to this new theory, a sledgehammer at a height of five feet and a tape measure at eight stories possess the same potential to inflict injury. Although the prospect of a tape measure being dropped onto a hand from eight stories may seem remote, the concept is very real. Recently, a worker on a New Jersey construction site was fatally injured as a result of being struck by a tape measure which fell from a height of 50 stories (Santora, 2014). Although at first seeming comparatively harmless, the tape measure, which weighed approximately one pound, inflicted 500 ft.-lbs. of energy on the worker’s head and ultimately led to the worker’s death.

4.1 Energy Transfer through Contact Area

Although calculating the energy provides an objective basis from which to quantify and rank most hazards on a particular construction site, further detail is required within the context of how the energy transfers to the human body. Specifically, when considering the severity of injury associated with a moving object, the contact area, or sharpness, must be taken into account. For example, by minimizing the contact area of a knife blade through sharpening, the pressure exerted by the blade is maximized with the same quantity of applied energy. Once translated to force, the ratio of the quantity of energy and the contact area helps to define the true potential damaging factor: pressure. In order to model how energy is linked to pressure one must first consider the concepts of momentum and impulse. Momentum is defined as the product of an object’s mass and velocity and impulse, in turn, is defined as the change of momentum per unit of time. The equations for momentum \( p \) and impulse \( J \) are shown respectively in Eq. (3) and Eq. (4), where \( m = \text{mass} \); \( v = \text{velocity} \); and \( \Delta v = \text{change in velocity} \).

\[
\begin{align*}
\text{(3)} & \quad p = mv \\
\text{(4)} & \quad J = \Delta p = m(\Delta v)
\end{align*}
\]

It is important to note that the variables used to evaluate momentum and impulse are identical to kinetic energy \((KE)\) as shown in Eq. (4), where \( m = \text{mass} \) and \( v = \text{velocity} \), and which, as a result of conservation of energy, can easily be found using Eq. (1) for potential energy.

\[
\text{(5)} \quad KE = \frac{1}{2}mv^2
\]

The final step in determining the severity of a potential hazard is to ascertain the pressure, defined as force per unit area, exerted by the energy source. By using Newton’s second law of motion, where force is the product of mass and acceleration, and the principals of momentum and impulse, variables used to calculate an object’s energy can be substituted and used to find pressure \((P)\) as shown in Eq. (5), where \( F = \text{force} \); \( A = \text{area} \); \( m = \text{mass} \); \( v = \text{velocity} \); \( a = \text{acceleration} \); \( \Delta v = \text{change in velocity} \); and \( t = \text{time} \).

\[
\text{(6)} \quad P = \frac{F}{A} = \frac{ma}{A} = \frac{m\Delta v}{\Delta t A}
\]

In order to illustrate the relationship between pressure and the severity of a sustained injury, the one-pound tape measure provides a compelling example. It was determined that dropping this tape measure from a height of five feet was relatively harmless, exerting approximately 5 ft.-lbs. of energy. Replacing the tape measure with a concrete chisel of equal mass (1 lb) and dramatic differences in damage would be sustained because of the sharpness of the concrete chisel. Assuming the respective impulse durations and final velocities of the two objects have equivalent values of 0.05 seconds and 17.9 ft/s, the tape measure, landing on its end, would have an estimated contact area of \(2 \text{ in}^2\), thus exerting a pressure of about 5.6 psi. By comparison, the concrete chisel, with an estimated contact area of \(0.01 \text{ in}^2\), would exert a pressure of 1121 psi. Although the concrete chisel and tape measure possess an equivalent
amount of energy, the large disparity in contact area between the objects caused a drastic increase in the
injury suffered by your hand. For this reason, the contact area, or sharpness, of a hazard must be
accounted for in evaluating the potential severity of an outcome.

4.2 Resiliency

Using the analogy of natural disaster modeling, the magnitude of a natural disaster, such as a hurricane,
does not fully predict the magnitude of damage. For example, due to differences in infrastructure, a
hurricane striking the coast of Haiti would presumably inflict more damage than a hurricane striking the
coast of Florida. This concept, referred to as resiliency, also applies in the context of energy-based
safety risk where the extent of injury caused by a particular hazard varies depending upon the resiliency
of a particular body part to the energy transferred or pressure inflicted. For example, if the unfortunate
New Jersey construction worker had been struck by the tape measure in the shoulder rather than his
head, his injury would almost certainly have not been fatal. In summary, the resiliency of the particular
body part involved is a critical factor in predicting the outcome of a hazard event, and thus must also be
taken into account when evaluating safety risk using energy.

4.3 Conceptual Framework for Energy-Based Safety Risk

A conceptual framework has been formulated to evaluate the safety risk for gravity, motion, mechanical,
and electrical energy sources. The rationale for including these energy sources is that they are
associated with the four leading causes of worker fatalities in the construction industry (falls, struck-by,
caught in/between, and electrocution), known as the “fatal four” (Bureau of Labor Statistics, 2014). The
conceptual framework, which is illustrated below in Table 1, builds upon the principles of energy,
pressure, and contact area previously discussed. With the exception of the body part impacted, the
inputs into the conceptual framework are all objectively measurable hazard factors such as mass,
height/speed, sharpness, and voltage of observable physical objects. To simply illustrate relative
magnitudes and mechanisms by which a severity score can be established, one may consider the each
variable on a 1-3 scale, with 1 representing a low quantity and 3 representing a high quantity. The final
component included in an energy-based risk score is the affected body part. Rating the affected body
part is based on the resiliency levels of different body parts and is also scored on a scale of 1 to 3, with 1
representing a less critical body part such as a hand and 3 representing a more critical body part such as
the head. The Severity Score is calculated by Eq. (7), resulting in a range from 1 to 81. It should be
noted that the conceptual framework set forth below is preliminary in nature and, as such, the hazard
factors used the simplistic 1-3 rating scale in addition to being weighted evenly for purposes of illustration
only. As further analysis is performed, the conceptual framework can be readily adjusted in a variety of
ways to provide for a greater degree of precision; for instance, the use of actual, physical values for the
measurable factors in the place of rating scales.

\[ \text{Severity Score} = (\text{Mass}) \times (\text{Height}) \times (\text{Sharpness}) \times (\text{Body Part}) \]

Table 1: Examples of various cases using the energy-based risk analysis method

<table>
<thead>
<tr>
<th>Mass</th>
<th>Height (or Speed)</th>
<th>Sharpness</th>
<th>Criticalness of Body Part</th>
<th>Severity Score (1-81)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Tape Measure Dropped from 5 ft. onto hand</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>Tape Measure Dropped from 50 stories onto head</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>27</td>
<td>Concrete Chisel Dropped from 50 stories onto head</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>81</td>
<td>W-Flange Beam Dropped 50 stories onto head</td>
</tr>
</tbody>
</table>

5 METHODS

The objective of the analysis is to test the proposed theory by investigating the relationship between the
severity of worker injury and the energy present before the injury was sustained. To achieve this
objective, samples of injury reports spanning a three year period were taken from a database consisting of 7,250 injury reports obtained from 281 private construction sources. Reports with sufficient detail to quantify the elements in Table 1 were extracted. Using a system established by Hallowell and Gambatese (2009), the severity of various injury outcomes was classified and assigned a relative rating. The injury classifications, as well as their respective definitions and “relative impact scores”, employed in this system are listed in Table 2.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Definition</th>
<th>Severity Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Aid</td>
<td>Any treatment of minor scratches, cuts, burns, etc. where the worker is able to return to work following first-aid treatment</td>
<td>48</td>
</tr>
<tr>
<td>Medical Case</td>
<td>Any work-related injury or illness requiring medical care or treatment beyond first-aid where the worker is able to return</td>
<td>138</td>
</tr>
<tr>
<td>Lost Work Time</td>
<td>Any work-related injury or illness that prevents the worker from returning to work the following day</td>
<td>256</td>
</tr>
<tr>
<td>Permanent Disability</td>
<td>Any work-related injury or illness that results in permanent aliment</td>
<td>1,024</td>
</tr>
<tr>
<td>Fatality</td>
<td>Any work-related injury or illness that results in death</td>
<td>26,214</td>
</tr>
</tbody>
</table>

*Footnote ~ Average Relative Impact Scores were used for Medical Case and 1st Aid

Despite the relatively large database of text reports from past injuries, the sample size used in the analysis was comparatively limited because fatalities and disabling injuries were (fortunately) rare. To compensate for this limitation, fatality reports were chosen at random from the National Institute for Occupational Safety and Health’s (NIOSH) Fatality Assessment and Control Evaluation (FACE) program. Even so, a lack of injury reports involving the “Permanent Disability” outcome were sparse, and consequently removed from this preliminary analysis on the basis of having an insufficient sample size. Ultimately, the resulting sample size was 40 injury reports, involving 10 injury reports chosen at random for each respective severity level (excluding “Permanent Disability”) in order to maintain consistency for comparison purposes. Once the reports were extracted and compiled, the energy source associated with the hazard involved in each injury report was assigned using either kinetic, potential, or rotational energy techniques. Unfortunately, due to the lack of detail in the injury reports, estimations of object height, speed, and weight were often necessary. To minimize bias, at least two researchers conducted independent assessments.

6 RESULTS AND ANALYSIS

To assess the relationship between accident severity and the magnitude of energy involved in a particular incident, the resulting energy data were compared to the respective severity scores for each injury. By examining the raw distribution of energy contained in the various severity levels, one can see a correlation between the amount of energy involved and the severity level of each outcome (see Figure 1, Figure 2 and Table 3). Because the severity scale and the quantity of energy follow a power distribution, a power regression model was created and confirms a strong correlation, having an $R^2$ value of 0.69. However, although an increase in energy level appears to be positively correlated to the severity of an outcome, there is a wide variability between the various energy levels contained within any specific injury classification. The variability in energy at each severity level relates to the importance of pressure and resiliency as previously discussed. For example, the two injury reports that represented the maximum and minimum amount of energy under the fatality classification involved a 40 ft. crane boom section falling onto a worker and a worker hitting his head after falling 10 ft. off of a ladder, respectively. The crane boom was found to have approximately 40,000 ft.-lbs. of energy, while the worker on the ladder only had 1500 ft.-lbs; however, both incidents were fatal. In addition to the wide variability of energy found within each corresponding severity level, the ranges of energy between corresponding severity levels had significant overlap (see Figure 2). Much like the variability within severity levels, the overlap between severity levels is explained through resiliency and pressure. For instance, the injury report that possessed the highest amount of energy for the 1st Aid severity level and the two lowest energy situations for the
Medical Case and Lost Work Time severity levels possessed nearly an identical amount of energy. The respective outcomes for these 1st Aid, Medical Case, and Lost Work Time injury reports were a 2x4 hitting a worker in the back causing a minor contusion, a worker hit his head on a steel pipe, leaving him temporarily disoriented, and a steel pipe struck a worker's fingers, breaking two fingers. Although these injury reports only varied by 20 ft.-lbs from one another, the three situations possessed very different outcomes due to the factors of resiliency and pressure. Initial results indicate that areas where the energy of severity levels overlap are heavily influenced by resiliency of the human body part affected as well as the pressure exerted on that body part (as indicated on Figure 2, where medical case and lost work-time overlap). Note that there is no overlap between first aid and fatality. These results tentatively confirm the proposed theory, demonstrating that the energy of a hazard has predictive validity in determining the severity of an injury.

| Table 3: Mean, Median, and Standard Deviation |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | $\bar{x}$ (ft.-lzs.) | $\bar{x}$ (ft.-lzs.) | $\bar{x}^2$ (ft.-lzs.) | Min. (ft.-lzs.) | Max. (ft.-lzs.) |
| 1st Aid        | 21               | 18               | 16              | 3.9             | 58.5             |
| Medical Case   | 199              | 109              | 186             | 49              | 585              |
| Lost Work Time | 1093             | 1023             | 919             | 40              | 2407             |
| Fatality       | 10818            | 4403             | 13245           | 1500            | 40000            |

Figure 1: Severity Level vs. Energy (Raw Distribution)  
Figure 2: Severity Level vs. Energy (Raw Value Range)

7 CONCLUSION

To reiterate, the purpose of the research was to test the null hypothesis that energy has no significant relation to the severity of an injury. In order to test the null hypothesis, a theory using the concepts of energy, pressure, and resiliency was introduced and tested using a sample of 40 reports randomly extracted from a database containing 7,250 injury reports obtained from 281 private construction organizations spanning a three year period as well as NIOSH's FACE database. Despite considerable variability in energy data within injury classification levels, statistical and regression analysis indicate that energy may have significant predictive capability in relation to the severity of an injury outcome, thus tentatively confirming the proposed theory. Although the research provides the preliminary evidence of energy’s predictive validity, the study performed possessed limitations. Most notably there was a lack of detailed data for fatal and disabling injuries. The injury reports used for analysis were sufficiently detailed for this analysis. Future researchers, however, could find greater levels of detail by increasing the breadth of the reports analyzed. Furthermore, the study only included three of the ten identifiable energy forms on a construction site (gravity, motion, and mechanical). Supplementary exploration needs to be conducted.
regarding other hazardous energy sources in addition to more detailed research exploring the energy sources used in this study.

The inspiration for assessing whether energy can be useful in predicting the severity of an injury arose mostly from the CII-funded work of Albert et al. (2014), who were recently able to improve deficiencies in worker hazard recognition by using the concept of energy to better identify hazards. The safety risk practices currently employed within the construction industry share flaws similar to those of past hazard recognition techniques in that they lack scientifically driven empirical data and are narrow in scope, thus limiting the effectiveness of these practices when applied to the construction industry's diverse project portfolio. By introducing the concept of energy into safety risk analysis within the construction industry, the goal and intention would be to improve upon these two weaknesses.

According to Lingard (2013), safety risk analysis is based upon decomposing construction activities and hazards in order to quantify risk. The concept of energy builds on this view by breaking down hazards to their most elemental form, thus making energy, when combined with probability data, theoretically translatable to nearly every construction project or activity. The initial research results indicate that energy has significant potential for predicting the severity of an injury. The outcome was that energy-based safety risk analysis shows significant promise in becoming a much improved and more universally accessible technique for safety risk analysis within the construction industry. If developed to its full potential, indications are that use of energy-based safety risk analysis will allow practitioners to more accurately model and respond to hazards as they are introduced and removed from a work environment. The method may also have application to BIM where energy may be calculated during work sequencing and work packaging.

8 REFERENCES


AN INVESTIGATION INTO CURRENT TENDERING PROCESS IN SAUDI CONSTRUCTION PROJECTS

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Abstract: Underachievement in project performance, lengthy delays and financial loss in construction projects in Saudi Arabia has been realised due to the approach of current tendering process. This research aims to investigate the current process adopted for tendering construction projects in Saudi Arabia. The study employs a qualitative study of three organisations utilising semi-structured interviews with managers to gauge clients, contractors and consultants' perspectives on current tendering practice and associated challenges and impacts. Results revealed a number of challenges and impacts facing stakeholders to the adoption of a holistic approach to tender planning process. These include: stakeholders' dissatisfaction, lack of effective strategic plan for tendering system; rigid, inappropriate and bureaucratic tendering process; complicated legalisations used for entering large international construction firms in Saudi construction markets; unscheduled tendering of huge number of projects by both public and private sectors; failed and breakdown projects; low quality of building and expected high expenditure on maintenance and operation. Solutions focus on formulating a strategic planning involved the key factors. The study is one of the few studies that have investigated Saudi tender process from a practical views and dynamic perspective. It reveals not only the challenges and impacts of current situation, but also draws a road map for a better solution.

1 INTRODUCTION

The construction sector plays an important role in the Saudi economy and is closely related to other economic sectors. Additionally, construction is one of the major industrial sectors of the Saudi Arabian economy, worth more than $20 billion accounting for 11.7 per cent of Gross Domestic Product (GDP) in 2011. It is also regarded as an important and reliable indicator of trends and the success of the national economy. The Saudi construction industry has faced several changes since 2006 due to the national dependency on the nearly stable prices of oil revenues. A significant number of construction projects are currently being implemented in both public and private sectors. Despite the high government expenditures on the construction sector, there are concerns about the underachievement of project performance, breakdowns, delays, cost and time overruns, and client dissatisfaction.

The Saudi construction is facing serious challenges in terms of project tendering process. Lack of emphasis on strategic planning to improve the tendering process resulted in some negative impacts such as aborted projects or incomplete tender documents, and lengthy delays that have caused underachievement in project performance and financial loss. Indeed, official government statistics reveal tender inadequacies and shortcomings in over 3000 public projects. Al-Kharashi and Skitmore (2009) agreed with the Ministry of Economic and Planning (MOEP) (2011) report about the most influence on
underachievement performance in Saudi construction projects is the lack of innovative process related to tendering strategy.

Among the required development in construction industry is the need to apply the partnering with international firms. Nevertheless, the globalization of construction, the pressure on resources on one hand as against rising expectations of quality on the other, the need to adopt a long-term perspective to position the economy appropriately and so on, have created a situation where nations and their construction industries need to adopt tendering strategies. However, literature appears that little has been published relating to current tender process in the context of the Saudi construction industry. Specifically, a review of literature revealed that no publications have addressed the challenges, impacts and solutions related to the Saudi construction projects.

2 LITERATURE REVIEW

The construction industry is an important part of the economical backbone in many countries (Ngai et al., 2002), often accounting for between 7-10 percent of the Gross Domestic Product (Voordijk et al., 2000). In many countries the construction industry has, however, attracted criticism for inefficiencies in outcomes such as time and cost overruns, low productivity, poor quality and inadequate customer satisfaction (Chan et al., 2003). In order to achieve successful governance of construction projects a holistic and systemic approach to procurement procedures is crucial (Eriksson and Pesämaa, 2007).

In construction management literature several studies have indicated that procurement systems have significant effects on construction project performance. Noted in this direction are studies of Rasid, Taib, Ahmed, Nasid, Ali and Zainordin (2006) and Hashim (1999). Studies of Ogunsanmi, Iyagbaand Omirin (2003), and Dada (2012) all confirm the use of various types of procurement methods for project delivery in Nigerian construction industry which significantly affect the performance of most projects. The study of Hashim, M.B. (1999) also confirms the effects of procurement methods on performance of construction projects in Malaysia.

The common approach to procurement used in Saudi construction sector is the Design-Bid-Build (DBB). Ibbs et al. (2003) describe DBB as the method in which a project is separated into design and construction phases which means that construction can start when the design is completed. Idoro and Iyagba (2008) state that in the DBB, the project delivery process in both design and construction are separated. However, this method was criticised by a number of researchers especially in Saudi construction. Al-Ghamdi (1999) and Arain (2002) reported that conventional procurement practice in the Saudi construction industry does not involve the contractor in the design conceptual phase. Involvement of a contractor may assist in developing better design and reduce the interface problems with designers (Arain 2002; Adrian 1983; AL-Hazmi 1987). On the other hand, Design build (DB) was described by Chan (2001) as a recent arrangement that is conceived as a solution to the numerous shortcomings in DBB. Moreover, it has been defined as an arrangement whereby a developer contracts a single part or entity to perform both design and construction of a facility or project under a single DB contract (Bennett 1992). Nevertheless, although the general acceptance of the main feature of the method that focuses on the integration between design and construction stages, it observes that the method has variants (Akintoye, 1994 and Turner, 1997).

Practically, there has been a concern with the problems of bidding strategy since the time of Friedman (1956) to explore bidding decisions and establish methods within the modelled bidding decisions. Egan (1988) reported that a competitive tendering must be replaced with long-term relationships based on clear measurement of performance and sustained improvements in quality and efficiency.

In the Saudi construction, projects are usually awarded to the lowest bidder, neglecting other considerations such as technical measures and historical records, such considerations are facing a real challenge. In an early study conducted Aitah (1988), it was found that projects awarded only to the lowest bidder had, in general, a lower performance. Similarly, Alotaibi et al. (2013) identified the current procurement practice used in Saudi construction as one of the critical failure factors that contributes to the underachievement of projects’ performance.
Considering the lowest price or bid as a criterion for selecting a contractor has been criticised by many authors (e.g. Hatush and Skitmore 1998; Stein et al. 2003; Al-Reshaid and Kartam 2005). They collectively argued that the serious problems which arise within the construction phase as a result of accepting the lowest bid can lead to serious overruns of time and cost, serious quality problems and eventually to increased litigation. Many of the research studies criticized the lowest cost tendering process as the main procurement tool and suggested some other criteria to select contractors in order to achieve better performance (Egan 1998, Sebastian 2011, Eriksson and Nilsson 2008, Tikkanen and Kaleva 2011).

Padhi and Mohapatra (2010) claimed that past work performance of contractors is not taken into consideration during the selection procedures and thus, the project will be delivered with poor quality because of the contractor’s poor record of past work performance. Ogunsemi and Aje (2006) highlighted that past performance; contractors’ experience; workmanship quality; tender sum and plant and equipment were the most important criteria for contractors’ prequalification evaluation in Nigeria.

The research studies that aim to assess the holistic strategic plans for tendering construction projects are still limited. Most of the tendering research studies concerned are on evaluating the technical aspects for tendering, evaluating bids and tendering models.

This research aims to investigate the current process adopted for tendering construction projects in Saudi Arabia. But without a better understanding of this phenomenon, it would be hard to address precisely the issue in theory and practices. Hence, an appropriate research strategy and method was required.

3 RESEARCH METHODOLOGY

To achieve the study aim, the research methodology was developed as shown in Figure 1. Consequently, a case study strategy was adopted in this research as an in-depth investigation into the Saudi tendering process to provide an in-depth insight into the current tendering process; and identify challenges and impacts, and forward solutions to address the identified tendering hindrances.

Eight case studies were conducted that used two data collection methods: semi-structured interviews and eight case studies-related documents. For the eight cases, relatively big Saudi companies carrying multiple projects in the housing, industrial and office buildings were considered. From each company three projects were considered. The study of cases was focused on projects already performed or near the end of the completion from which it was possible to obtain required information regarding the procurement process. Three such projects were taken from each company/case totalling 24 projects for eight cases.

Semi-structured interviews were selected as a style of interviewing to give form to the interviews whilst allowing probing questions (Hussey and Hussey 1997; Fellows and Liu 2008). The semi-structured nature of the interview technique enabled researchers to allow the interviewees to elaborate on any topic, but required all predetermined topics to be covered (Love et al. 2002). Therefore, it enables the researcher to probe for further insights and clarification while maintaining some structure in the views collected.

The semi-structured interviews were held with 72 key stakeholders as shown in Table 1 who are involved in the planning and implementation of projects. In each case study project (three projects for each Case Study), 3 representatives were selected, one each from the client, consultant and contractor. Candidates were selected based on multi-criteria: their accumulative experiences in identifying challenges and impacts in such topic, their positions, and their qualifications, involved in tendering committees. Each interview lasted between 90 to 120 minutes to cover the identified issues and to ensure that the necessary information was obtained. The interview sessions were taped, at the interviewee’s discretion, transcribed and coded. The template developed for the interviews includes personal background, current tendering process, challenges, impacts, and suggested solutions which are related to tendering process. A framework analysis technique was used to analyse the interviews as reported by (Ritchie and Spencer...
1994). Furthermore, eight case studies-related documents such as governmental purchases system, invitation documents, tendering documents, project contract documents, prequalification request documents were used and analysed as case studies-related archives to gather the needed information relevant to the eight cases. Qualitative content analysis was used to analyse these documents. During the analysis of data, the factors involving challenges and impacts were not ranked but only identified.

Table 1: Classification of participants

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Position</th>
<th>Experience Year</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7</th>
<th>Case 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td>Project Manager</td>
<td>18</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Consultant</td>
<td>Project Manager</td>
<td>15</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Contractor</td>
<td>Project Manager</td>
<td>14</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

![Research methodology flowchart](image-url)

Figure 1: Research methodology flowchart

4 FINDINGS

The findings obtained from the eight case studies for both the documents and semi-structured interviews were categorised into three groups: current tendering process challenges; impacts of the current tendering process; and suggested solutions.

4.1 Current Tendering Process Challenges

Table 2 below shows a list of challenges that were identified by the interviewees.
Table 2: Current tendering process challenges (respondents’ perspectives)

<table>
<thead>
<tr>
<th>No.</th>
<th>Challenges of Tendering Process</th>
<th>Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bids evaluation and contractor selection depend mainly on lowest price</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>2</td>
<td>Lack of information for contractors' past performance, volume of currently contracted work and their financial situation</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>3</td>
<td>Long tendering duration</td>
<td>contractor</td>
</tr>
<tr>
<td>4</td>
<td>Lack of an effective strategic plan tendering construction projects</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>5</td>
<td>Contractors' classification is not accurate</td>
<td>client</td>
</tr>
<tr>
<td>6</td>
<td>Decline of working in the Saudi markets by large international construction firms</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>7</td>
<td>Using package system for project tenders</td>
<td>consultant &amp; contractor</td>
</tr>
<tr>
<td>8</td>
<td>The huge number of projects offered by both the public and private sectors</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>9</td>
<td>Insufficient details for projects</td>
<td>contractor</td>
</tr>
<tr>
<td>10</td>
<td>Lack of experience of the tendering staff</td>
<td>contractor</td>
</tr>
<tr>
<td>11</td>
<td>Inflexibility/ Bureaucratic process used in the current government purchasing system</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>12</td>
<td>Shortcomings in professional contractors</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>13</td>
<td>Lack of an efficient and comprehensive system for tenders</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>14</td>
<td>Uncertainty of the process used by public sectors</td>
<td>contractor</td>
</tr>
<tr>
<td>15</td>
<td>Difficulties in maintaining the competitiveness through the tendering process</td>
<td>client</td>
</tr>
<tr>
<td>16</td>
<td>Lack of an effective role taken by the Ministry of Planning and Economics</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>17</td>
<td>Non use of FIDIC Standard Forms of Contracts</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
</tbody>
</table>

The respondents agreed that the current tendering process is unsatisfactory and could not lead to a successful outcome for projects. All respondents agreed that the main problem is the lack of an effective strategic plan that contributes towards organising the tendering process. Most of respondents considered the bids evaluation and contractors’ selection based on lowest price as a major challenge. Contractors stressed that the long and slow tendering procedures adopted, especially by governmental sectors as a major challenge. Contractors also considered the use of DBB method as one of the main challenges and called for using Design and Build (DB) method to avoid serious mistakes that could occur during the design process. This was rejected by the consultants and clients who argued that generally contractors lack insufficient skills and relevant experiences. On the other hand, clients disagreed with contractors in relation to slow procedures with regards to awarding the projects, which are considered sensible for identifying the targeted competitors. Consultants and contractors criticised the mechanism adopted for offering very large projects as a single package. Clients concurred with other stakeholders about the adopted mechanism, which in their view is due to end-users’ requirements, as well as economic considerations.

These stakeholders' conflicts would suggest that strategic planning for tendering is impeded by lack of clear collaborative framework. All respondents agreed that the inflexibility and bureaucratic process used in the governmental purchasing system is a significant challenge. In this respect and as a reference to a good practice, the respondents referred to the successful projects implemented by private sectors, which is due to the flexibility and organized process used in tendering projects. Clients and consultants pointed out that despite the shortage of experienced contractors in the Saudi market, there is a complicated legislation used by the government to grant large international firms part of construction contracts.
independently, without using the approach of joint ventures. All respondents considered the lack of a central database or league table used for assessing the contractors' performance is also a critical barrier in the tendering process. Additionally; they identified other challenges, namely lack of references of ruling and issuing the tendering plans, and who should be responsible for managing these processes.

4.2 Impacts of Current Tendering Process

The second classification identified from the findings is an impact of the challenges due to using current tendering process on the projects in the Saudi construction industry as shown in Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Impacts of Current Tendering Process</th>
<th>Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lengthy delays for projects</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>2</td>
<td>Re-tendering for projects several times</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>3</td>
<td>Select of inefficient contractors</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>4</td>
<td>Low quality</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>5</td>
<td>Failed Projects</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>6</td>
<td>Shortages in resources (labours, equipment, materials...etc)</td>
<td>consultant</td>
</tr>
<tr>
<td>7</td>
<td>Increased disputes and claims between contracting parties</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>8</td>
<td>Underachievement in project performance</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>9</td>
<td>Financial loss for owner</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>10</td>
<td>Financial loss for contractor</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>11</td>
<td>Change in project scope</td>
<td>contractor</td>
</tr>
<tr>
<td>12</td>
<td>Failure to achieve the project objectives</td>
<td>client and consultant</td>
</tr>
<tr>
<td>13</td>
<td>Long tendering durations may cause the withdrawal of contractors due to increasing price changes</td>
<td>contractor</td>
</tr>
<tr>
<td>14</td>
<td>Increase in maintenance and operational costs</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>15</td>
<td>Stress on the public services such as water, sanitation, electricity and transportation</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>16</td>
<td>Stress on the government sectors such as Customs</td>
<td>client &amp; consultant</td>
</tr>
</tbody>
</table>

All respondents agreed on a number of direct impacts on the implementation of projects. They emphasised the lengthy completion delays or failed projects. This resulted in retendering a huge number of projects due to insufficient offered bids or withdrawn failed projects. The majority of respondents, particularly clients and consultants argued the financial loss due to failed and retendered projects which finally influences the cycle of the national economy. Contractors discussed the unclear process used for tendering in terms of criteria which affected the fairness of awarding the bids. Consultants and clients criticised the strategy of competition used by contractors in which the contractor could evaluate his capabilities. This resulted in a number of bankrupt contractors which has led to direct impacts on delivering successful projects. This has created several disputes and claims between contractors and clients which often have to be solved in litigation.

Contractors stated that the use of DBB method contributed to mistakes and discrepancies in design documents, delays in producing design documents, unclear and inadequate details in drawings, and the complexity of projects design, insufficient data collection and surveys in the early stages of design resulted from the current tendering process.

A shortage of resources was identified as one of the impacts resulting from the use of the current tendering process. This has placed considerable pressure on achieving the sustainability of natural resources. Respondents discussed the breakdown of many projects due to the shortage of resources as a result of huge demands coming from the construction sector. Moreover, they agreed that the use of the
current tendering process influences the quality of delivered projects due to awarding projects to incapable contractors. Nevertheless, this has occurred because of using the lowest price system. Most of respondents discussed the cost of operation and maintenance which will be affected negatively due to the low quality of project implementation. Public services (water, sanitation, electricity and transportation) have been affected by the tendering process. Furthermore, the process of importing materials from abroad has been affected by the current tendering process, thus resulting in long queues of containers waiting for customs clearance. In addition, labour market prices have been affected by the tendering process and this has resulted in a shortage of labours both skilled and unskilled. Respondents stated that shortage of specified lands owned by clients for tendered projects appeared as a major impact and was a hindrance at the start of projects. They fully agreed that the current situation increases the price of materials and labour and has a direct influence on the cost of the projects execution, for either ongoing or future projects. Additionally, the current situation contributed towards realising the large differences between estimated cost of projects and the final executed cost.

4.3 Suggested Solutions for the Tendering Process

Many solutions and suggestions were delivered by the respondents as shown in Table 4.

<table>
<thead>
<tr>
<th>No</th>
<th>Suggested solutions to enhance the tendering process (respondents’ perspectives)</th>
<th>Stakeholder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Develop an effective system for the evaluation of bids (Not dependant mainly on lowest price)</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>2</td>
<td>Support small and medium local contractors</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>3</td>
<td>Develop programs to improve the performance of local contractors</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>4</td>
<td>Implement projects in stages (avoiding large packaged systems)</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>5</td>
<td>Attract large international construction firms to work in the construction sector in Saudi Arabia</td>
<td>client &amp; consultant</td>
</tr>
<tr>
<td>6</td>
<td>Develop an effective strategic plan for tendering construction projects</td>
<td>client &amp; consultant &amp; contractor</td>
</tr>
<tr>
<td>7</td>
<td>Improve the classification system for contractors</td>
<td>consultant &amp; contractor</td>
</tr>
<tr>
<td>8</td>
<td>Improve the classification system for engineering Offices and contractor</td>
<td>client</td>
</tr>
<tr>
<td>9</td>
<td>Develop a holistic data base for contractors</td>
<td>client</td>
</tr>
<tr>
<td>10</td>
<td>Employing some monetary funds in other investments</td>
<td>client</td>
</tr>
<tr>
<td>11</td>
<td>Lessons learnt should be activated between contractors</td>
<td>consultant &amp; contractor</td>
</tr>
<tr>
<td>12</td>
<td>Adopting innovative procurement techniques (partnering)</td>
<td>client</td>
</tr>
</tbody>
</table>

All respondents suggested that developing a comprehensive strategic plan based on the real needs is necessary. This plan involves developing an effective system for bid evaluation which is not dependant only on the lowest bid price. Additionally, this plan should focus on supporting and encouraging small and medium local contractors. This can be done by aligning local firms with the participation of international firms to improve the performance of construction projects, as well as allowing the transferring of their experiences to the Saudi construction sector. Indeed this will reflect positively on the performance of local contractors.

However, most of contractors disagreed with the participation of international firms and were concerned that it would reduce the opportunity of winning a large number of projects for Saudi builder. Adopting innovative procurement techniques are delivered by client as a best tool for delivering successful projects (partnering). Consultants and clients stated that attracting the international firms is considered as part of strategic plan. At the same time, they focused on the prequalification of those contractors as major criteria for their selection.
Clients suggested that a workable system should be developed to organise and manage the engineering offices and contractors. This could start with establishing a central database containing the required information about consultants and contractors such as: qualifications, classification, past and current performance, financial abilities, skilled staff and available construction equipment. Consultants and clients suggested that the way of tendering projects as a single large package should be avoided because it has been recognised that projects are affected by the failure of other projects implemented by the same contractor. Respondents suggested that rescheduling the tendered projects should be done based on determined criteria to mitigate the current fragmentation, and improve the overall performance of construction sector. The criteria should depend on crucial factors such as high priority projects, project documents’ readiness, site’ readiness and the clients’ capabilities for supervising the projects. Clients suggested that government could place additional monetary funds in other investments rather than the current blending of monetary funds. Respondents agreed that the aforementioned should be involved in an effective strategic plan that should be formulated, implemented and evaluated, to improve the current tendering process.

5 DISCUSSION

The findings reveal that all participating stakeholders were dissatisfied with the current tender process. Additionally, the agreement focused on the serious challenges due to the lack of an effective strategic plan that improves the current tendering process and contributes toward successful implementation. Similarly, Egan (1988) criticised the methodology of using competitive tendering when there was no practical strategic plan adopted by the construction industry. Results also show that the bids evaluation and contractors’ selection based on lowest price are a major challenge. Aitah (1988) pointed out that a lower project performance is considered as the expected outcome of the lowest bid price. It has been argued that the serious problems which arise within the construction phase as a result of accepting the lowest bid can lead to serious overruns of time and cost, serious quality problems and eventually to increased litigation (Hatush and Skitmore 1998; Stein et al. 2003; Al-Reshaid and Kartam 2005). In the context of the Saudi construction, it seems that the lack of a central database for contractors and consultants is regarded as a serious problem.

Impacts of the current tendering process directly affect the overall Saudi construction sector. Retendering huge numbers of projects is a serious challenge of continuing to support the current tendering system. Disputes and claims made by contractors have arisen as a result of delayed and failed projects which resulted in these claims having to go to litigation to be resolved. It was identified that the Saudi construction suffered from a lack of skilled and experienced staff involved in the undertaking of projects (Al-Kharashi and Skitmore 2009). Major mistakes, inadequate design and insufficient data collection and surveys were identified as having a negative impact on the current tendering process. This has resulted in producing low quality buildings and structures and thereby increasing the cost of operation and maintenance of facilities (Assaf and Al-Hejji 2006). Shortage of resources was another issue that affected the performance of Saudi construction projects. The resources of construction materials in Saudi were affected by the current tender system and therefore this affects the sustainability. The need for resources to be concentrated up-front on projects is necessary for any project to deliver greater efficiency and quality.

Solutions delivered by respondents focused on drawing up a strategic plan that contributes towards improving the performance of construction projects and results in leading to the stakeholders’ satisfaction. The inclusion of international construction firms were put forward as a suitable solution to avoid the current challenges which leads to the financial bleeding of the project budget. Rescheduling projects based on proper criteria in parallel with a sound methodology for tendering is a high priority. Establishment of a central database for having information about consultants and contractors is a crucial factor and is a clear priority.
6 CONCLUSIONS

The findings of this research show that there is a common stakeholders’ discontent with regard to the current tendering process, which is adopted in publicly funded projects. A practical strategic planning is necessary to mitigate the negative impacts resulting from the current tendering process, which is based on low bid competitive tendering. This topic will be covered in a further paper. The findings also indicate that the current tendering process is an inappropriate method for the extensive programmes that are implemented in the Saudi construction sector. Furthermore, results highlight the serious problems that may appear in the future when large expenditures are wasted on failed and incomplete projects. Valuable lessons learnt from what is occurring in the Saudi construction sector in terms of challenges and impacts as well as suggested solutions should be activated to achieve sustained improvement. It is recommended that further research should be conducted to validate the identified factors that were derived from this paper through specific case study projects. This further research can be extended to the quantification of the performances of the projects due to current practice of tendering process particularly with respect to the factors like time loss, delays, cost, quality, failure rate, retendering, litigation cases etc. Based on an in-depth investigation that takes into consideration the strengths, weaknesses, opportunity and threats (SWOT) to produce solid and robust a strategic plan for tendering to be implemented in the Saudi construction projects. This plan should involve the key factors mentioned by respondents such as (effective system for bid evaluation, rescheduling the tendered projects, extend the invitation to international firms and activate lessons learnt as an improvement tool). A central database centre of contractors and consultants is an essential need to overcome part of that problem facing the Saudi tendering processes.

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BIM OBSTACLES IN INDUSTRIAL PROJECTS: A CONTRACTOR PERSPECTIVE

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Abstract: Using BIM technology is well established in construction projects, especially in industrial projects where a maze of pipes and modules have to be installed in congested work areas under tight time schedule. BIM offers potential benefits (e.g. visualization, collaboration, alignment …etc.) that can be key for complex project success; however, these benefits have not been fully implemented in industrial projects. The authors worked last two years closely with a construction company -which specialized in oil and gas projects- trying to discover ways to maximize utilization of knowledge embedded in BIM models. Though the partner company has used BIM for long time, we noticed many obstacles that hinder reaping the full benefits of BIM for construction planning and control. These obstacles are related to the ability to extend a model by adding new attributes and to link the model to data from external sources (e.g. cost or schedule control information systems). This paper discusses these obstacles, illustrates implemented short-term solutions to work around and mitigate these obstacles, and finally concludes by proposing using semantic web as a long-term solution to overcome these obstacles and clear the path for gaining all potential benefits during industrial projects construction.

1 INTRODUCTION

Industrial projects are one of the first projects to use BIM technology; this is largely due to project complexity and size, as these two factors determine the degree of information technology usage in the project (Thomas, Macken, & Lee, 2001). However, the degree of usage varies based on company policy and employee expertise. (Jung & Joo, 2011) categorized BIM usage into passive and active utilization, passive usage encompass engineering analyses like safety and scheduling; while active usage works on extracting embedded knowledge in BIM.

BIM builds a virtual model that can be investigated and tested before constructing the real project. It offers many benefits for construction projects like saving cost and time (Cooperative Research Center for Construction Innovation, 2007), (Azhar, 2011), and (Gilligan & Kunz, 2007). However, not all benefits are fully gained as some benefits are more popular than others; for example, clash detection and space utilization are more common than automating shop drawings for fabrication (Gilligan & Kunz, 2007).

Although BIM has potential benefits, there are some unsolved issues. These issues can be grouped into contractual (e.g. model ownership) and technical level (e.g. interoperability) (Azhar, 2011). This paper represents a case study regarding BIM utilization in industrial projects. It tracks developing the model in engineering firms and shows the consequences of their decisions on the contractors.
The paper starts by a brief introduction about technologies used or proposed to enhance BIM utilization, then, it discusses current practice and issues found in the partner company’s current practice. Afterwards it presents short-term solutions that have been developed to mitigate these issues. Finally, we conclude by our vision for using semantic web technology as a long-term solution for these issues.

2 CURRENT PRACTICE AND ISSUES

Industrial project model usually consists of multiple sub-models (e.g. structural, mechanical, electrical model, etc.), each model is designed separately and then all models are compiled by engineering firm into one model to review and detect any clashes. After that, the engineering firm issues the model for the contractor as one model. Figure 1 shows IDEF0 diagram for this process.

Engineering firms that work with the partner company use two proprietary software applications (NavisWorks® and SmartPlant®). Based on their preferences, the engineering firm will determine which software they will use and the contractor has to comply with this choice; this adds overhead cost on the contractor including purchasing the two software and training its employees.

![Figure 1: IDEF0 for issuing BIM model for the contractor.](image)

During our work with the model, we observed the following issues:

1. **BIM ownership (contractual level)**: The contractor receives only the compiled model for reviewing and visualization. However, the contractor cannot add to the model and, therefore, any operational attributes have to be saved in a separate database,

2. **Lack of standards (contractual level)**: The same item might be labelled “I beam”, “I-Beam”, or “I Beam column” based on the engineering firm convention. In addition, some items do not have essential attributes (e.g. item type),

3. **Model limitation (technical level)**: The contractor cannot calculate quantity take-off accurately as only boundary volume of the item is available, and
4. **Interoperability (technical level):** It is a tedious task to transfer data between different systems or software. This task requires using intermediate format and it is very prone to error and missing data.

3 **SHORT-TERM SOLUTION**

In order to overcome the previously stated issues, a complete change in the process has to be done. However, this is not always feasible and it will take time to accomplish. Hence, we proposed some short-term solution to work around these issues temporarily while working on a longer-term solution. While developing this solution, we take into consideration two points: 1) **We will try not to change current practice.** In other words, changing the contractual relationship between contractor, owner, and engineering firm to facilitate more effective exchange of BIM details is outside the scope of this work; and 2) **our solution should clarify limitations of the current practice to proof the need for long-term solution.** This section will describe two of our quick solutions that have been implemented in the company.

3.1 **Filter by discipline**

As we stated earlier, the partner company receives multiple BIM models from different engineering designers compiled as one model (Figure 2). With the lack of standards and conventions between the designers, the company found it hard to filter model items based on trade (e.g. extract all concrete piles, or all pipes). A coordinator has to visually inspect model items and add them to different display set based on their type. This is a daunting work that takes days to complete, and it becomes more problematic in case of fast tracking projects where new models come sometimes every week.

![Figure 2: This BIM model lacks essential attributes to filter by trade. This model contains more than 700,000 model items.](image)

By investigating four models for four different projects that has been done in the last ten years, we found that although there is no explicit attribute that indicates the item trade, well-defined rules can be used to extract trade’s items. For example, in one of the projects we found that almost 30% of the pipes have an attribute called “Source file” that ends with “dgn”, different rules can be found for the rest of the pipes. Therefore, we decided to define a “Filter” structure that contains attributes for one rule. Figure 3 shows an example of a filter that captures the previously stated rule. It contains seven attributes as follows:
1. Criteria ID: to intersect multiple filters as shown later;
2. Condition ID: because filters are stored in SQL database, it was required as a part of the primary key;
3. Category: the trade name to apply the rule;
4. Category display name: this points to the tab name in Navisworks (Figure 3), although this attribute is not essential, we preferred to use it as it reduces the process time significantly;
5. Property display name: the property name as in Figure 3;
6. Condition: either equals, not equals, contains, not contains; and
7. Property value: the value we are looking for as in Figure 3.

![Figure 3: An example of a rule.](image)

Table 1 shows the set of rules used to extract all items for four trades (namely; concrete, pipe, steel, and piles). It took three trials to get all items by refining the rules to capture these items. These rules are stored in SQL server database and a .NET plug-in reads the rules and applies them on the 3D model.

As shown in Table 1, some trades require one rule while others require more than one. This clearly will depend on the project. However, we designed our tool to compile multiple rules using intersection and union to accommodate any complex filtering case. The general formula for intersection and union is:

\[
\text{Trade} = (\text{Filter 1 AND Filter 2 AND \ldots\ldots Filter N}) \text{ OR (Filter N+1 AND Filter N+2 AND \ldots\ldots Filter M}) \text{ OR \ldots}
\]

For example:

\[
\text{Concrete} = (\text{color is green and source file contains “dgn”}) \text{ OR (Color is blue and Material is “C50”)}
\]

If more than one filter have the same criteria ID then they will be combined using intersection (AND operator) to form a filter block, then filter blocks will be combined together using OR operator. For example, there are four rules for pipes in Table 1, the first two have a criteria Id of “2” while the other two rules have a criteria Id of “3”. This means the result of the first two filters will be intersected together to form the first block then the results of the other two filters will intersected together to form the second block then the two blocks will be merged using union operation as in Figure 4.

Using the plug-in to apply these rules finds all items in the four trades, the plug-in will label each item with its trade so it can be retrieved later; in addition, a display set is created for each trade as in Figure 5.

### 3.2 Work areas

With complex project that covers large area and consists of millions of components, it is always a good practice to partition it to small work areas. The partner company partitions their project according to two criteria: “Work packages” and “work areas”. Work package represents a set of items that have to be installed together and costs 500 to 1000 man-hours (i.e. one rotation), while work area represents a set of
items that reside inside an imaginary 3D box. These two breakdown criteria are independent of each other, so one pipe might span multiple work area (because of its length) while it belongs to one work package.

Because of model ownership issues and software limitation, work area boundary boxes cannot be directly applied on the model. Therefore, we developed a plug-in using .NET technology that reads boundary boxes coordinates from database (Figure 6) and create a display set that contains all items inside any boundary box. This enables the user to isolate one or more work areas easily as in Figure 7. Moreover, these display sets can be accessed by people on site using handheld devices to check a virtual prototype of their required task.

Table 1: Set of rules required to capture four trades in the project.

<table>
<thead>
<tr>
<th>Criteria Id</th>
<th>Condition Id</th>
<th>Category display name</th>
<th>Property display name</th>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Concrete PDS</td>
<td>Material</td>
<td>Contains</td>
<td>Concrete</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Pipe Item</td>
<td>Material</td>
<td>Equals</td>
<td>Colour 66</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Pipe Item</td>
<td>Source File</td>
<td>Contains</td>
<td>Dgn</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Pipe Item</td>
<td>Material</td>
<td>Equals</td>
<td>Colour 115</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Pipe Item</td>
<td>Source File</td>
<td>Contains</td>
<td>Dgn</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Steel PDS</td>
<td>Material</td>
<td>Contains</td>
<td>Steel</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>Steel Item</td>
<td>Material</td>
<td>Equals</td>
<td>Colour 166</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Pile PDS</td>
<td>Material</td>
<td>Contains</td>
<td>Steel</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>Pile PDS</td>
<td>Material</td>
<td>Equals</td>
<td>Colour 161</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>Tray PDS</td>
<td>OL_type</td>
<td>Contains</td>
<td>Tray</td>
</tr>
</tbody>
</table>

Figure 4: Applying filters to find all pipes in the model. First each rule is applied individually, then they are combined using AND operator to form Filter blocks that grouped using OR operator to find items by trade.
Figure 5: A display set will be created for each trade and each item will be labeled.

Figure 6: Work Area boundary box is defined in a separate database.

Figure 7: The plug-in will create display set for each work area, so it can be filtered easily.

4 LONG-TERM SOLUTION

4.1 Overview

The aforementioned solution overcomes the obstacles but it shows many limitations that can be overcome only by changing the current process. These limitations can be stated as following:

- Manual inspection of the model to find filtering rules;
• Rules can filter steel items, but it cannot identify their classes;
• Need for customized configuration for each project (impossible to automate); and
• Any non-graphical data (e.g. work area boundary box and scaffold log) have to be stored in a separate database, which requires management and sometimes causes discrepancies.

A more effective solution will require a complete change in the process to streamline the flow of data from engineering firms to construction and allow linking multiple data sources flawlessly. The first step, in our opinion, is using layered system approach. Layered system separates data layer from the application, which will eliminate interoperability issue and any software limitation while providing one source for all kind of data.

The structure of the data layer should be chosen carefully as it has a direct impact on all aspects of the system. Here, we suggest using semantic web technology; many scholars (e.g. Jung and Joo 2011) have mentioned its potentials in BIM future to facilitate data exchange and information integration.

Our long-term solution (Figure 8) consists of two main steps: creating the data layer and using it to automate some tasks (e.g. schedule generation). The first step will require developing ontology for the data layer, which stores all attributes related to BIM model items, and another component will use shape recognition techniques to recognize unlabelled items and 3D legacy CAD models.

After defining the data layer, many applications can be developed to automate different task. We selected three applications (partial models, schedule generation, and scaffold discovery) that we thought would be most useful for a contractor. The following two sections give a brief introduction to shape recognition and semantic web technology as they apply to the proposed long-term solution.

4.2 Shape recognition

Since the mid-1970s, Computer Aided Design (CAD) starts to replace traditional paper drawing as it provides more quality, facilitates editing, increases productivity. However, CAD systems lacks object oriented concept, which limits the ability to share data between different systems (Anumba, et al., 2008). However, the advent of BIM quickly supersedes CAD systems as BIM seams to address CAD limitations. Yet, there are huge legacy projects, which use CAD models.

On the other hand, the proliferation of 3D objects required new methods to search and query these objects (3D objects retrieval) as traditional text search is insufficient (Funkhouser, et al., 2003). There are many researches regarding 3D object retrievals (see (Cardone, et al., 2003), (Iyer, et al., 2005) and (Tangelder & Veltkamp, 2008)) that have been used to many application like cost estimation in engineering mechanics by comparing the current model with previously done models (Cardone, et al., 2003).

The basic idea behind 3D objects retrieval is finding the shape signature (also called descriptor and shape representation in some references) and compare it the previously stored signatures database. The similarity between two 3D objects is measured by the distance between the two signatures (zero means the two objects are identical).

4.3 Semantic web technology

During the project life cycle, different parties (e.g. architectures, engineers, contractors...etc.) generate a sheer volume of documents and drawings (Rujirayanyong & Shi, 2006). These documents used to be stored in binders; each binder –which represents a project or a cycle - was stored in lockers. Accessing data from these binders requires a huge amount of time and effort to the extent that companies have to hire people just to archive and organize these binders.

With the advent of PCs, binders have been replaced by folders that contains electronic version of all documents and drawings (scanned or CAD drawings). This means faster information retrieval in a cheaper way. However, as governed by old expertise, PCs have been used to store files without paying
much attention to describe their contents. That means user will have multiple files that should be explored manually to find the required information.

(Berners-Lee, et al., 2001) suggest extending the structure of World Wide Web to a computer-readable format that called semantic web. Semantic web will use schema (called ontology) to define the data stored in machines. This will enable machines to interpret the data instead of just storing them. Using this powerful structure, machines can link multiple data sources to generate information automatically.

Semantic web utilizes two profound technologies: eXtensible Markup Language (XML) and the Resources Description Framework (RDF) (Berners-Lee, et al., 2001). XML is very similar to HTML language (that is used for current World Wide Web); however, it gives the user the ability to define his own tags and structured them in any sophisticated way to capture complex data model that cannot be contained in traditional database. Though its flexibility, it is hard for anyone to build on or extract data from existing XML file other than the creator due to its arbitrary structure. On the other hand, RDF specification has been developed by World Wide Web Consortium (W3C); it uses triples (subject, predicate, and object) to express data. RDF provides a standard way to exchange data (Segaran, et al., 2009).

Incorporating these two technologies will offer data model flexibility and yet a standard way to represent data; however, it requires another component that can identify similar concepts from different data sources. For example, how the machine can know that the “mouse” in animal context is similar to “mouse” in mammal context while it is different from “mouse” in hardware context or from the programming language “mouse”, here where ontology comes to play as it uses Uniform Resource Identifier (URI) for different concepts. Therefore, ontologies are an essential tool for merging data from different sources (Deshpande & Kumbhar, 2011), and semantic web success depends on ontology proliferation (Maedche & Staab, 2001).

In construction domain, semantic web applications can be grouped into files’ management and knowledge extraction. As an example of files’ management, (Jiayi & Anumba, 2008) utilized semantic web technology to discover relations between construction project files. In addition, (Wang, et al., 2011) developed ontology to manage construction files contents.

Regarding knowledge extraction, researchers developed ontologies to extract information from 3D models: For estimation purposes, (Lee, et al., 2014) developed an ontology to evaluate multiple work items for tiles. Another ontology is developed by (Zhang & Issa, 2013) to extract partial models from IFC format. However, most of these applications have been verified by simplified case studies rather than real ones.

4.4 Long-term solution summary

The following list summarizes the main points of the proposed solution and states success criteria for each point:

1. **Create ontology to enable error-free exchange of data** that should be able to merge data from different sources (e.g. combine two 3D parametric models). **Success criteria**: Using Quality value (Fröbel, et al., 2011).

2. **Recognize 3D shapes** and convert it to the proposed ontology. There are many techniques to calculate shape signature to recognize 3D items; these techniques vary on their efficiencies and computational power based on the type of 3D object (e.g. 3D solid or 3D surface) and the degree of intricate details. We propose using shape distribution technique (Osada, et al. 2002) because of its robustness and insensitivity to small details (i.e. It will not be largely affected if the item missing some parts). This step will be applied on legacy CAD projects and unidentified items in BIM models. **Success criteria**: a ratio of correctly recognized objects over total number of objects.

3. **Generate partial 3D models based on the proposed ontology**, After constructing and populating our ontology, it can be queried using the semantic query language (SPARQL). It will be used to filter
the model items by trade, work package, work area ...etc. to generate partial models. These models will be very helpful for tradesmen who need a 3D model for only their trades within a specific work area. **Success criteria:** Expert opinion.

4. **Automate entities mapping to a schedule** by mapping every work package (“work package is a detailed plan that contains 500: 1000 hours to be executed during one rotation” (Ryan 2009)) to an activity and create relations based on spatial attributes and traditional sequences between trades. **Success criteria:** Expert opinion.

5. **Scaffold discovery** based on reported progress, the system will discover required scaffold ahead of time so the user can remove this constraint before actually starting the required task. The system should estimate erection man-hours based on historical data. This will be an example of automation in execution phase. **Success criteria:** Expert opinion and scaffold estimation models.

![Diagram](image)

Figure 8: Long-term solution framework: shape recognition algorithms will be used to classify items. These data will be stored on ontology data format that can be queried using SPARQL to generate partial models. It also can facilitate automating schedule generation and scaffold discovery.

5 **CONCLUSION**

This paper discussed a case study related to the use of BIM by a partner company on industrial projects. We identified a number of obstacles regarding implementing BIM technology. In order to overcome these obstacles, a solution that relies on multiple filtering rules is proposed as a short-term solution that can mitigate these obstacles, but has limitations and cannot be generalized. Therefore, we propose a different approach that relies on separation of the data layer from the model and the use semantic web technology to facilitate sharing data between different users and extraction/integration from different information sources. This approach can automate different tasks like generating partial models for trades, schedule generation, and scaffold discovery.
References


INTEGRATING BUILDING INFORMATION MODELING AND CONCEPTUAL DESIGN TOWARDS EFFECTIVE FACILITIES MANAGEMENT: A FRAMEWORK TITLE

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Abstract: The engagement of Facilities Management (FM) during the conceptual design stage of building projects has been recently explored. Incorporating FM during the design stage through the concept of BIM has the potential to minimize the possible waste of project resources (time, money, materials, and sustainability impacts) especially during the operational stage while offering the essential tools to keep buildings running to the required living standards. This paper proposes a framework to develop an integrated conceptual design model towards effective FM. Based on an intense literature review and series of interviews with FM and design professionals, this innovative framework is created to fulfil the following basics attributes: (1) tackling the key factors that affect FM; (2) Identifying the most effective stage of design (conceptual design) to involve facility managers; and (3) Detecting the major aspects that will directly contribute in enhancing the quality of managing, operating and maintaining facilities at the early design stage of a project. The expected results of the integrated BIM-FM model should show the importance of facilities managers’ contribution during the conceptual design stage that leads in reducing the operating and maintenance costs, while providing 3D Integrated Design within Building Information Modeling (BIM) environment by generating list of design alternatives through design simulations. An actual case project is used to test the models’ capability and workability.

1 INTRODUCTION

The use of advanced materials and building technologies in the construction industry has been evolving, particularly in the past three decades. Consequently, complex building systems and supporting services are implemented, which have increased the need to bring the Facility Manager (FM) on board at the early design stage, known as the conceptual design stage (Mohammed & Hassanain, 2010). The International Facility Management Association (IFMA) defined facility management as “a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, processes and technology” (Wang et al., 2013). The data required to operate and maintain any building is usually enormous and requires an advanced integrated platform to fill the existing gap that resides in missing, misleading and misplacing project information (Al-Hussein, 2000). BIM is an integrated process that is used to facilitate the exchange of design and construction information to project participants. It is the act of collecting and of using consistent, reliable and sufficient data to support any desired activity throughout the construction lifecycle (BIMCAN, 2011). All of the building information is translated into a digital format that is represented in the modeling process and it is used to support integrated data exchange in a secure reusable fashion. These models create a platform in which physical and functional features can be explored through visualization, simulation and analysis of the existence of the physical facility/building (BIMCAN, 2011). The use of BIM by facility managers will provide all the necessary information for the building components to keep buildings up to the required living standards, while minimizing possible
wastes of resources (time, money, materials, and sustainability impacts) associated with managing those resources. Furthermore, BIM enables facility managers to obtain access to all life-cycle information of the project, especially during the planning and implementation phases by allowing them to supplement their professional inputs towards a more efficient FM (Sabol, 2008). Moreover, BIM is ideal to categorize, modify, monitor and integrate data gathered from various building systems and components throughout the entire lifespan of the project and to secure facilities’ information and data (i.e., CAD drawings, operation instructions, maintenance manuals and schedule of equipment).

A study completed by BIM-Canada in 2011 indicated that most of the current commercial tools used in BIM focus on the needs of the planning and designing phases of a building project. Currently, other parts of the building lifecycle are being considered by various software developers to add the required tools to support the activities that take place during the construction and operation phases. These tools will offer access to new BIM tool functionality, either through add-on modules or through embedding the new BIM tools’ functionality in their own main applications or through using existing BIM applications and applying their required improvements as add-ons. Add-ons will usually come from third party developers who have access to large vendors’ databases. Although this approach has significant benefits to the user, such as effective workflow and seamless integration between modules, there are also disadvantages, such as the compatibility issues resulting from miscommunication and lack of integration (BIMCAN, 2011).

Mohammed & Hassanain (2010) stated that an increase in the cost of maintenance during the operation of systems and components can result as a consequence of deficiency in design. Currently, as buildings are designed to meet greater building standards, design can have a positive influence during the operating and maintenance stage of buildings. The effects of decisions made during the design stage can have far-reaching effects on future building maintainability (Mohammed & Hassanain, 2010).

In 2012, The British Institute of Facilities Management (BIFM) listed the following consequences of the British government’s role in specifying the use of BIM in all governmental projects effective in the year 2016. These benefits will be spread across the globe as the benefits of BIM concepts and its tools starts to arise. BIM can support the creation and maintenance of facilities in a more efficient way, lower carbon emissions, lower and enhance operation costs, and create more effective and safer places to live and work. However, this is not achieved without the involvement of an integrated project team that includes the FM at the early stages. Moreover, while addressing the barriers to FM engagement, the following is stated (Tranced, 2012): “Databases are absolutely key to the issue of interoperability for different tools, to enable software from different manufacturers to talk to one another.” They also added that, “In the UK the government is targeting level 2 BIM, which accepts a series of architectural, structural and MEP models requiring a tool to pull them together. The UK government cannot spend on any number of interfaces between current BIM applications (Planet FM, Maximo, Revit, Bentley, etc.), and it cannot support proprietary software so it has to have something that’s open. Because, of this, it is adopting the freely available, non-proprietary system called Construction-Operations Building Information Exchange (COBie) as an information exchange mechanism between information models and asset management systems” (Tranced, 2012). This should encourage the use of one of the widely-used BIM applications, which in this paper will be Autodesk Revit.

Becerik-Gerber and Jazizadeh (2011) designed an online survey based on the outcomes of in-depth interviews with FM. The survey distributed to FM professionals to determine the current practices and interests related to the application of BIM in FM. The results, as illustrated in Figure 1, show that the most significant operational functions that FMs are looking to include in BIM are energy management, maintenance, and repair and space management. These results are going to be the basis of the proposed model, since those are the most measurable components that can affect FM during the conceptual design stage of a project.
Furthermore, the participants of that survey were asked to share their comments and thoughts about the difficulties they are facing in implementing BIM in FM. The participants’ responses were categorized as: 1) Unclear and invalidated benefits of BIM in ongoing FM practices (for example, unclear productivity gains, or benefits gained from reduced equipment failure and better-automated building energy usage); 2) The amount of work that has to be done in order to define the FM-specific needs for which a model is necessary and how that model should be prepared to meet these needs; 3) Lack of interoperability between BIM solutions themselves and between BIM solutions and FM systems; 4) Lack of demand for BIM deliverables by owners due to the uncertainty about the potentials of using BIM; 5) Lack of clarity about who will be responsible for project insurance and contracting; 6) Lack of FM standards and working process; and 7) Lack of experience among facility managers in using BIM technology.

The model’s proposed framework will be created in an attempt to fill the gaps identified from the implemented literature review. It will explore the abilities of BIM concepts and the required role that FM should perform as early as possible during the conceptual design stage of building projects. At this stage all the design modifications will result in less impact on time and effort which means cost savings across the entire life cycle of the project. Creating a detailed database for the proposed model will also fill the gap of finding a comprehensive database that can integrate the various disciplines that deal with common projects. The proposed database will contain three main subcategories. The first stores information from the FM historical reports that reflect the experience and case studies that occurred in previous FM projects. The second incorporates the standards and guidelines used to implement FM in a BIM environment along with the systems and vendors’ information available in the market. This innovative framework will consider the following basic attributes: (1) tackling the key factors that affect FM; (2) Identifying the design stage in which the involvement of facility managers will be more effective with respect to time, cost and quality; and (3) Detecting the major aspects that will directly contribute to enhancing the quality of managing, operating and maintaining facilities at the early design stage of a building project.

2 METHODOLOGY

The proposed methodology used to develop the framework starts with identifying the limitations of the existing FM software, followed by clarifying all the aspects of the anticipated model’s components and architecture. An actual case project will then be implemented in a BIM tool to test the capabilities and workability of the developed framework.

2.1 Existing FM Software Limitations

Based on many reports and reviews, ten of the top existing FM software packages were explored and evaluated to find their limitations and capabilities as illustrated in Figure 2. Those ten software providers where chosen according to their customer base popularity, reviews and features provided (Business-Software, 2015).
Many vendors offer various services towards a goal of a more reliable FM practice; the key features selected in Figure 2 were based on the common services required by the FM and the available features of those tools that can be accordingly analyzed. The figure shows that the capabilities of most of the software are common when it comes to delivering a Software as a Service (SaaS) solution or on-premise solution: preventive maintenance, work order management, planning and scheduling, and reporting and analytics features. However, the limitations start to appear in fully applying Computerized Maintenance Management Software, in which the dependence on paperwork will be fully replaced by e-files. Moreover, applying BIM, Space Management was minimal comparing to the other provided features, while the integration of the Conceptual Design Stage was totally missing in all of the software. This increases the need to introduce a comprehensive platform that allow the supplement of professional inputs from facility managers during the conceptual design stage through the BIM concept towards a more efficient FM that will contribute in minimizing the possible waste of project resources (time, money, and materials), enables facility managers to obtain access to all of the life-cycle information of the project and offers the essential tools (i.e. monitoring, scheduling and integrating) to keep buildings running up to the required living standards.

2.2 Model Components

As illustrated in Figure 3 the proposed model consists of four interrelated modules that are developed within the BIM environment based on the most important factors FM required to include with BIM (Figure 1) and the limitations of the existing FM tools (Figure 2). The first module, the Operation & Maintenance Module, consists of different elements such as scheduling, building systems, parts/replacement, operational instructions and cost. This module combines all the FM technical information that can be affected or enhanced during the conceptual design of a project. The second module, Space Management Module, includes three elements which are: usable spaces, move management and non-usable spaces.
The focus of these three elements reflects time and cost savings. The usable spaces cover the utilization, circulation, accessibility, zones, future expansions, and technical requirements, whereas the move management comprises the utilization, circulation, accessibility, zones, future expansions, and special equipment allocation. The non-usable spaces, on the other hand, involve equipment, systems, circulation, accessibility, zones, future expansions, and special equipment allocation. Moreover, the “Life Cycle Costing (LCC) Module” covers the capital costs, expenses, revenue, risk analysis, and forecasting.

Figure 3: Proposed Model Components

The result of these modules is a list of recommendations that will be based on probability studies that will generate various design simulations in the “Knowledge Based Integration Module” to help the owner, architect, and FM team to decide on the best design approach that will result in an effective FM practice. This module includes a Design Decision Support System that will collect all the results of the four modules and throughout the knowledge acquisition database. The Knowledge acquisition databank contains three main databases. The first stores information from the FM historical reports that reflect the experience and case studies that occurred in previous FM projects. The second incorporates the standards and guidelines used to implement FM in the BIM environment along with the systems and vendors’ information available in the market. The FM team will reflect all the owners’ requirements from the FM point of view, and their professional opinion to what specific requirements are needed for this specific project will generate the third database.
2.3 Model Architecture

The proposed model consists of several components and its architecture includes: data input, data analysis, criteria, and output, as illustrated in Figure 4. The data input is divided into three different parts. The first part is related to the project information. It will cover the project type (residential, commercial, hospitality, etc.), project program (users’ information, required spaces for each zone, and their relation), conceptual plans, which should be in a BIM-supporting format. Additionally, site constraints (location, orientation, accessibility, geometry, weather, etc.) will be covered in the project information part, as well as the key issues and guidelines, construction and FM of the project, along with the specified budget to reflect on the sections of building techniques, materials, equipment and the entire LCC of the project. All the data in the first part will be gathered from the owner(s) and the project architect. The second part is the information related to technical standards and also input by the architect of the project. This input will cover all the required equipment specifications, the replacement circulation and special equipment whenever it is needed according to the project type, location, and stage. The third part is related specifically to the maintenance information that will be provided by the FM team. This part will cover the FM item requirements for this specific project, the essential systems data and equipment information. Moreover, the operational instructions, maintenance manuals and schedules will be gathered in this part of the input by the FM team.

![Figure 4: Proposed Model Architecture](image)

The data analysis, in its turn, is divided into four sections. Three of those are: 1) Operation and Maintenance (O&M), 2) Space Management and 3) Life Cycle Cost Analysis (LCCA) has been classified as the data that will have a direct input to the FM practices which can be enhanced in the conceptual design of a project. However, the fourth section will focus on the reliability of the data to generate the required data analysis for such a complicated and multi-input model. The O&M section will involve data for scheduling, building systems, parts and replacement, operational instructions and cost data. However, the space management section will generate data regards the space utilization, zoning classifications,
circulation for both usable and non-usable space, standards required for specific space, building codes and standards, equipment specifications, and accessibility. Moreover, the space management section will include the date for possible future expansions, specific technical requirements, special equipment allocation and time- and cost-saving practices from previous projects. The LCCA will contain data that is related to capital, expenses, revenue, risk analysis, and forecasting. The Reliability section of data analysis will gather the following information: FM in BIM guidelines, functionality, maintenance system, operational systems, specific project requirement, and the data of vendors and system information (availability, cost, location, durability, technical specifications, delivery dates, etc.).

The data analysis will be based on the following criteria: productivity, LCC, and FM in BIM guidelines. In the productivity section the equipment performance rates, systems integration compatibility, zoning flexibility, and safety (of allocating commonly-used zones to hazardous ones) will be examined. It is very important to verify the data input source, which in this model will be either from the project owner, architect, or FM. Knowing the input source will allow categorization of the requirements according to their importance. Moreover, the FM historical report will be filtering the data to provide solutions and insights based on comparing the current data input to comparable historical measurable. However, in the LCC section, the data analysis criteria will be energy consumption, overhead cost, O&M cost, salvage, inflation rates, taxation and other expenses that might be added to the LCC of the project. In the third section of the criteria, the data will be tested to check its validity with regards to FM in BIM Guidelines that consist of Construction-Operations Building Information Exchange (COBie), National BIM Standards, U.S. General Services Administration (GSA) BIM Guideline for FM, and the National BIM Library. Collecting all of those guidelines in one model will generate a comprehensive database that will contribute in savings of costs and time during the FM stage of the project.

The output of the proposed model will be a series of recommended design alternatives and solutions through design simulations. Moreover, FM effectiveness reports, will provide the facility manager with all the information related to the operation, maintenance, and evaluation of the facility in an effective way. Additionally, all the main building systems—LCCA, market availability, recommendations and comparison reports—will be generated along with the 3D integrated design that will allow all the professional inputs from various project parties throughout the entire project life-cycle. The platform of this model is developed using the BIM concept, in which systems integration is achieved by using an existing BIM model at the conceptual design stage and assuring data-updating from all the parties throughout the project life cycle, as described in the validation below.

3 VALIDATION

To validate the developed model, only the space management module will be tested in this study as part of the ongoing overall model validation, by using a sample project (AL Dammam Four Seasons Hotel), which is located in the eastern province of the Kingdom of Saudi Arabia. This project is currently at the conceptual design stage (30% of the design is completed). The authors created a 3D model of that project in the BIM tool, which is Autodesk Revit in this case, where the space management module is added into Revit’s toolbar as a plug-in, as shown in Figure 4.

Once the conceptual design of that case project is done, the user will activate the space management module by clicking on the plug-in, which will generate an alert after analysing the data in the knowledge acquisition database to produce the following information: 1) Suspended scaffold equipment; 2) Data Input; 3) Impact; 4) Alert description; 5) Recommended actions; 6) Read More, which will provide an in-depth LCC, Vendors Information.

Figure 4 shows a list of recommended actions that will contribute in saving costs and energy during the operating stage and the FM practice. In this case the architect did not consider the location of the window-cleaning machine for the project because apparently the focus is on using every possible space in the project to reflect the owner's requirements. This required data is recorded in the model through the FM team. The model will then describe the problem after a process of filtering that will go through the database and according to the set of criteria (productivity, LCC, and FM in BIM guidelines) that are provided in the model architecture.
Figure 4: Model Validation – Move Management Alert

Figure 5: Model Validation – Future Expansion Alert
Figure 5 indicates that one of the owner’s requirements is to expand this space. The model allows the architect to calculate the energy consumption aspect along with ensuring its workability and compatibility with other building systems.

This is ongoing research that is still underway with the attempt to achieve a fully automated process that integrates BIM tools with other applications for scheduling and estimating, as well as data acquisition. The results of the proposed framework prove the importance of facilities managers’ contributions during the conceptual design stage that potentially result in reducing the cost of operation and maintenance.

4 CONCLUSION

This paper described the framework used in developing a model that will be used by the project architect/design team to integrate existing Building Information Modeling tools (Autodesk Revit) with the data that can be gathered and generated by the owner, architect, and FM at the conceptual design stage of a project towards effective facilities management, as has been discussed. As this paper conceptually illustrated testing the capabilities of one of the four proposed modules, the space management module that was chosen for the purpose of this conference paper only, future work will focus on programming this model towards testing its workability and validating it as a plug-in through Autodesk Revit using an actual case project.

References


CULTURE IN CONSTRUCTION ENGINEERING

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Abstract: The idea of culture has become a hot topic in construction engineering research. However, this term is used with many meanings. As such, the objective of this paper is to present a content analysis of the online record of ASCE Journal of Construction Engineering and Management (JCEM). A 2014 keyword search for “culture” in JCEM returned 557 articles. The authors reviewed the abstracts of each paper to categorize them according to the purpose statement: international markets (70 articles), safety (63 articles), and collaborative working arrangements (40 articles) emerged as the most frequent themes of the articles. The identified papers were then downloaded in full text form and imported into QSR NVivo, a qualitative coding software package. These articles were then searched for use of the word culture in conventional content analysis. Definitions of culture were extracted from the articles presenting a wide array of interpretations with respect to culture. Finally, this paper reviews the various theoretical bases for culture used in each category, and makes recommendations for future research in culture and construction based on the findings.

1 INTRODUCTION

Culture can be defined in a variety of ways. It can be used as a verb (to culture as in microbial cells), noun (culture as a group of beliefs or ideas), or adjective (cultural as in cultural traditions). The goal of this paper is to discuss the various meanings of culture in the construction research community. The construction practice is made of people from varying firms, countries, and perspectives trying to work towards common goals. The accomplishment of such goals typically involves a strict schedule and tight budget; this makes team performance vitally important for successful projects. Culture has therefore been a factor in many research analyses. The paper aims to determine how culture is used in construction research through a content analysis of Journal of Construction Engineering and Management (JCEM) research.

2 POINTS OF DEPARTURE

Changing technologies, geographies, and demographics have real impacts on construction projects and organizations (Levitt 2007). Within the past 15 years, culture has come into focus in research; unfortunately culture is not always well mobilized despite being the subject of ongoing research (Fellows 2010). In order to explore how culture has been used in the construction research community, this research identifies definitions of culture in construction and explores how construction research has approached culture research. Future investigations will focus on how culture is being operationalized.
When researchers conduct cultural studies, they assume a philosophical position, which will impact their choice of research methods and therefore results (Gajendran et al. 2012). In this paper, we identify culture as a traveling concept (Bal 2002). Bal's argument is that the transfer of concepts across disciplinary, national, and historic boundaries alters the intended meaning. These changes are what create discussions in interdisciplinary subjects. Culture, with its roots in the social sciences, has crossed over the disciplinary boundary (Murdock 1932). Concept mapping bridges the gap in varying academic disciplines (Neumann and Nünning 2012) and adds clarity to our theory. In support of this goal, this paper maps concept of culture throughout JCEM in order to determine how the idea of culture is being viewed from varying nations, sectors, and firms.

3 RESEARCH METHOD

In order to determine the various uses of the word culture within Construction engineering, a keyword search was performed for the word “culture” in the American Society of Civil Engineer's Journal of Construction Engineering and Management from March 1, 1983 until the present (December 29 2014). This search resulted in 557 articles from 1988 until 2014. 523 of those articles were primary articles. All editor's notes and discussions were excluded from this research. A conventional content analysis in which codes emerged from the data was performed twice: first on the purpose statements within the abstracts of these articles and second on the full text of 172 articles identified in the first analysis.

Content analysis is a proven research technique to study the characteristic meaning of messages (Krippendorff 2012). In this case, technical construction articles from JCEM were analyzed as the messages in order to determine the meaning behind the use of the word culture. Content analysis has several methodological advantages validating its use in this research. First, it is unobtrusive, as in the instrument by which the data was collected does not affect the results. Second, the results are directly taken from the data. Third content analysis does not require a specific format for the data; it takes context into account (which is of particular importance in this study); and fourth it allows for the study of large amounts of data (Krippendorff 2012). This study implemented both conventional content analysis, which is particularly useful in areas where research literature on a phenomenon is limited and a summative content analysis which focuses on interpreting the content (Hsieh and Shannon 2005). In conventional content analysis, categories are derived inductively. Subcategories are combined into larger categories, and definitions of the larger (parent) categories are developed. This approach was used to classify each articles purpose statement. In summative content analysis, searches for a particular word are performed in order to determine how that word is being used. This approach was implemented to find definitions of culture.

In the conventional content analysis, the articles were categorized into categories through an iterative process. International management, safety, and collaborative working arrangements emerged as the top three categories with 40 or more articles each. Descriptions of these categories can be seen in the results section. For this paper, only articles in these three categories were analyzed further. All 172 articles from these categorizes were further subjected to a summative content analysis for the word culture using QSR Nvivo. Within the 172 articles, several were categorized in two of the three categories. For example, the purpose statement in Ozorhon et al. (2008) [Statement: “In this study, the effect of cultural similarity/difference relative to the national and organizational characteristics of partner companies on IJV performance is examined through a questionnaire survey” pg. 361] was coded in collaborative working arrangements and international markets. Eight articles were repeated in both international markets and safety, and two articles were repeated in international market and safety.

4 RESULTS

4.1 Keyword Search

The 523 articles were analyzed and categorized according to the purpose statement given in the abstract. The purpose statement was defined as the statement in which the goals, intent, or purpose of the article was included. If no purpose statement was provided in the abstract, the article was categorized based on
the summarization of findings, also found in the abstract. The abstracts were read three times in order to iteratively categorize the articles. For brevity, table 1 only shows the top three categories and the description of the types of articles the category contains.

Table 1: Article Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Article Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Markets</td>
<td>Export of construction services to a nation outside of the firm’s home nation or comparisons between construction practices of two nations</td>
<td>70</td>
</tr>
<tr>
<td>Safety</td>
<td>Qualities of or related to risk or causes of injury;</td>
<td>62</td>
</tr>
<tr>
<td>Collaborative Working Arrangement</td>
<td>Relationships described between two or more companies in the construction industry which offer the potential for greater market competitiveness including alliances, joint ventures, and partnering</td>
<td>40</td>
</tr>
</tbody>
</table>

As mentioned in the research methods, several articles were listed in two categories as they were equally related to both topics. (Ozorhon et al. 2008) was the only article that was double coded and contained explicit definitions of culture. These definitions are contained within the collaborative working arrangements section although they could also have been presented in international markets.

4.2 International Markets (IM)

Articles related to international markets were distinguished by their mention of work outside of a home country or a comparison of international firms or nations. Seventy of the original 523 related to the international market category. Table 2 below shows the definitions given in the full text.

Table 2: Definitions of Culture

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Culture</td>
<td>&quot;Culture, consisting essentially of people’s collective deep-held values and beliefs, is a critical factor in shaping people’s conceptions of the world around them (Earley and Erez 1997).&quot;</td>
<td>(Chen et al., 2009, pg 478)</td>
</tr>
<tr>
<td>Culture</td>
<td>&quot;Hofstede (1984) defines culture as “the collective programming of the mind which distinguishes the members of one human group from other's. systems of values and values are the building blocks of culture.&quot;&quot;</td>
<td>(Chan and Tse, 2003, pg 376)</td>
</tr>
</tbody>
</table>
| Culture    | "Loosemore (1999) states that "it is now accepted that a culture of a society is its shared values, understandings, assumptions and goals learned from earlier generations. It results in common attitudes, codes of conduct and expectations that guide behavior."
                                                                                                                                                                                                 | (Chan and Tse, 2003, pg 376) |
| Culture    | "Culture describes the social system created by a group of people; it starts from the moment that a few people get together regularly and begin to establish norms and rules through which they will interact and communicate with each other and maintain order; it is about patterns of meaning; it is about shared beliefs, values, perspectives, and worldviews; it is about shared behavior, practices, rules, and rituals; … (Tso 1999)."                                                                 | (Chan and Tse, 2003, pg 376) |
| Culture    | "Culture as the word is understood by every man in the street without elaboration."                                                                                                                                                       | (Chan and Tse, 2003, pg 376) |
| Culture    | "Culture represents a general pattern of values, attitudes and behavior in one nation that distinguishes it from other culture groups."                                                                                                         | (Chua et al, 2003, pg 135) |
| Culture    | "Culture serves as a socially shared knowledge schema giving meaning to incoming stimuli and channeling outgoing reactions (Triandis 1972)."                                                                                                                                                  | (Tsai and Chi, 2009, pg. 957) |
Culture

"Every national culture describes distinct beliefs (what is true), values (what is important), and norms (what is appropriate) that are deeply embedded in people's mind and demonstrated in their behaviors accordingly (Trompenaar 2004)."

(Tsai and Chi, 2009, pg. 957)

Culture

"Kotter and Heskett [1992] think of culture as having two levels, which differ in terms of their visibility and their resistance to change. At the deeper and less visible level, culture refers to values that are shared by the people in a group and that tend to persist over time even when group membership changes. At the more visible level, culture represents the behavior patterns or practices of an organization that new employees are encouraged to follow."

(Ozorovakaja, et al, 2007, pg 901)

Cultural

"Widely shared, socially constructed symbolic representations"

(Javernick-Will and Scott, 2010, pg 547)

Four articles defined the word culture just once. Chan and Tse (2003) present three definitions as they explain how culture lacks true definition in the literature. They conclude by defining culture for their paper as a concept generally "understood by every man" (pg 376). Tsai and Chi (2009) present several definitions of culture shown in Table 2 while explaining the uses of Hofestede's cultural dimensions that the study used to measure cultural characteristics of Taiwanese-Chinese construction professionals. Finally, as previously mentioned Ozohorn et al (2008) also defined culture in international market, but the definitions are in the collaborative working arrangement category.

4.3 Safety

Sixty-two articles described safety in their purpose statements and were therefore analyzed for their use of culture. In this set of articles culture was used in a compound noun (i.e. blame culture, corporate culture etc.) to describe which type of culture to which the author was referring. Seven articles provided the seventeen definitions of culture as seen in Table 4 below. There are six definitions of corporate culture, two for organizational culture, and eight for safety culture.

Table 4: Definitions of Culture

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blame Culture</td>
<td>&quot;A blame culture allocates fault and responsibility to the individual making the error rather than to the system or management process.&quot;</td>
<td>Martin and Lewis, 2014</td>
</tr>
<tr>
<td>Corporate Culture</td>
<td>&quot;Hampden-Turner (1990) define corporate culture as &quot;a pattern of basic assumptions invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration that has worked well enough to be valid and to be taught to new members as the correct way to perceive, think, and feel in relation to these problems.&quot; &quot;</td>
<td>Molenaar et al., 2009, PG 498</td>
</tr>
<tr>
<td>Corporate Culture</td>
<td>Corporate culture refers to the values held by employees of an organization that tend to persist even when membership changes (Kotter and Heskett 1992).</td>
<td>Molenaar et al., 2009, PG 498</td>
</tr>
<tr>
<td>Corporate Culture</td>
<td>&quot;Corporate culture is a collection of uniform and enduring beliefs, customs, traditions, and practices that are shared and continued by the employees of a corporation (Hai 1986).&quot;</td>
<td>Molenaar et al., 2009, PG 498</td>
</tr>
<tr>
<td>Corporate Culture</td>
<td>&quot;These shared beliefs define the fundamental characteristics of an organization and create an attitude that distinguishes one organization from all others (Maloney and Federle 1990)&quot;</td>
<td>Molenaar et al., 2009, PG 498</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
<td>Source</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Corporate Culture</td>
<td>&quot;It is the unique configuration of norms and behaviors that characterize the manner in which employees combine to accomplish tasks (Graves 1986).&quot;</td>
<td>Molenaar et al., 2009, PG 498</td>
</tr>
<tr>
<td>Corporate Culture</td>
<td>&quot;Corporate culture is defined as the beliefs, values, and behaviors that are consistent throughout all members of the corporation. These beliefs, values, and behaviors must be consistent throughout upper management, middle management, and field employees.&quot;</td>
<td>Molenaar et al., 2009, PG 498</td>
</tr>
<tr>
<td>Organizational Culture</td>
<td>&quot;Organizational culture can be thought of as &quot;the interaction between the organization and individuals&quot; (Choudhry et al. 2007) containing both formalized structure and direction from the top down (Zohar 2005)&quot;</td>
<td>Gilkey et al., 2012, PG 1044</td>
</tr>
<tr>
<td>Organizational Culture</td>
<td>&quot;Organizational culture”—a concept often used to describe shared corpora values that affect and influence members' attitudes and behaviors.&quot;</td>
<td>Mohammed 2003, PG 81</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;The safety culture of an organization is the product of individual and group values, attitudes, perceptions, competencies, and patterns of behavior [Health and Safety Commission (HSC) 1993].&quot;</td>
<td>Martin and Lewis, 2014</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;Safety culture is a set of prevailing indicators, beliefs, and values that the organization owns in safety&quot;</td>
<td>Fang et al., 2006 PG 574</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;According to Mohamed (2003), safety culture is a top-down organizational attribute approach to addressing safety management.&quot;</td>
<td>Chen and Jin, 2013, PG 806</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;The National Occupational Research Agenda (NORA)...defined safety culture as the organizational principles, norms, commitments, and values related to the operation of safety and health. Safety culture determines the relative importance of safety and other workplace goals (NORA 2008)&quot;</td>
<td>Chen and Jin, 2013, PG 806</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;The corporate atmosphere or culture in which safety is understood to be, and is accepted as, the number one priority (Cullen 1990).&quot;</td>
<td>Mohammed 2003, PG 81</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;fundamental to an organization's ability to manage safety-related aspects of its operations (Glendon and Stanton 2000).&quot;</td>
<td>Mohammed 2003, PG 81</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;Safety culture is a subfacet of organizational culture, which affects workers' attitudes and behavior in relation to an organization's on-going safety performance.&quot;</td>
<td>Mohammed 2003, PG 81</td>
</tr>
<tr>
<td>Safety Culture</td>
<td>&quot;Mohamed (2003) suggested that safety culture is concerned with the determinants for the ability to manage safety (top-down organizational attribute approach); whereas, safety climate is concerned with the workers' perceptions of the role safety plays in the workplace (bottom-up perceptual approach).&quot;</td>
<td>Choudhry et al. 2009, PG 891</td>
</tr>
</tbody>
</table>

As seen in the table, blame culture, corporate culture, organizational culture, and safety culture make up the four terms used in the safety articles. Although all subsets of culture, each of these terms implies a slight narrowing from the broad term of culture. Four articles provided more than one definition of these culture related terms. Molenaar et al. (2009) provided all the definitions of corporate culture in an attempt to explain how it relates to safety and references Molenaar et al. (2002), published outside of JECM and therefore out of the scope of this paper, for further definitions of corporate culture. Martin and Lewis (2003) defined both safety culture and blame culture. They differentiated between safety climate and culture, as they wanted to understand the key drivers of risk taking behaviours on construction sites before attempting to measure safety climate. Similarly, Chen and Jin (2013) offered two definitions of safety culture in an attempt to describe the difference between safety climate and culture before they conducted a study measuring safety culture. Finally, Mohammed (2003) referenced by Chen and Jin (2013) provided one definition of organizational culture and three definitions of safety culture. Mohammed (2003) sees safety culture as a subset of organizational culture; therefore he defined organizational culture and then safety culture in the article's literature review before recommending the use of a scorecard approach to measuring what he calls organizational safety culture.
4.4 Collaborative Working Arrangements (CWA)

For purposes of this article, collaborative working arrangements are defined as relationships established between two or more firms in the construction industry, which together attempt to create a more competitive team to complete a project. Examples are relational contracting, alliances, joint ventures, and partnering. From the original 523 articles, 40 related directly to collaborative working groups. Of these 40 articles, only four defined a term containing the word culture as shown in Table 6.

### Table 6: Definitions of Culture in CWG Articles

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural Distance</td>
<td>&quot;Individual’s perception and understanding of the differences between the individual’s culture and a foreign culture that forms the basis of cultural distance (Evans et al. 2000; O'Grady and Lane 1996).&quot;</td>
<td>Ozorhon et al., 2008, pg 364</td>
</tr>
<tr>
<td>Cultural Distance</td>
<td>&quot;the distance between the home market of an IJV [International Joint Venture] partner and a foreign market where the IJV is operating&quot;</td>
<td>Ozorhon et al., 2008, pg 364</td>
</tr>
<tr>
<td>Culture</td>
<td>&quot;A set of shared experiences, understandings, and meanings among members of a group, an organization, a community, or a nation (Hofstede and Hofstede 2005; Mead 1998).&quot;</td>
<td>Ozorhon et al., 2008, pg 361</td>
</tr>
<tr>
<td>Culture</td>
<td>&quot;Culture is also that complex whole which includes knowledge, beliefs, arts, morals, customs, and any other capabilities and habits acquired by men and women as members of a society&quot; (Pheng and Leong 2000)</td>
<td>Ozorhon et al., 2008, pg 361</td>
</tr>
<tr>
<td>Culture</td>
<td>&quot;According to Barkema et al. (1997), culture is a complex phenomenon and embodies a host of values, beliefs, and norms, many of which are subtle, intangible, and difficult to measure&quot;</td>
<td>Ozorhon et al., 2008, pg 364</td>
</tr>
<tr>
<td>Culture</td>
<td>&quot;Weber sees culture as an autonomous producer of social structure and networks. Elements of culture can be material artifacts or immaterial values, norms, symbols, language, and knowledge. Culture is meaning making in everyday life... (Lewis 2002).&quot;</td>
<td>Girmscheid, and Brokmann, 2010, pg 354</td>
</tr>
<tr>
<td>Culture</td>
<td>&quot;The business traditions, processes, and attitudes that an organization uses in pursuit and performance of its work.&quot;</td>
<td>Sillars and Kangari, 2004, pg 507</td>
</tr>
<tr>
<td>Organizational Culture</td>
<td>Hofstede and Hofstede (2005) define organizational culture as &quot;the collective programming of the mind which distinguishes the members of one human group from another.&quot;</td>
<td>Ozorhon et al., 2008, pg 362</td>
</tr>
<tr>
<td>Organizational Culture</td>
<td>Organizational culture refers to a pattern of shared basic assumptions about the environment, human nature, social relationships, and reality that employees have learned as they addressed and resolved problems of external adaptation and internal integration (Schein 1992)</td>
<td>Ozorhon et al., 2008, pg 362-363</td>
</tr>
<tr>
<td>Organizational Culture</td>
<td>Organizational culture refers to the set of values, beliefs, understandings, and ways of thinking that are common to the members of an organization or corporation (Daft 2001)</td>
<td>Ho et al., 2009, pg 521</td>
</tr>
</tbody>
</table>

Of particular note in Table 6 is the number of definitions that come from Ozorhorn et al. (2008). The purpose of this study was to measure the cultural effect on international joint venture performance. Both national and organizational realms of culture were operationalized through Hofstede and Hofstede’s (2005) framework.

5 DISCUSSION

Thirty-seven definitions were found in 17 of the 172 articles studied, meaning only 10% of the articles contained in this detailed search contained a definition of culture. All 37 definitions were unique; there is no single understanding of culture in construction research. Unique here does not imply that every one of the 37 definitions is radically different from the other; however, it means that no two definitions have the
same combination of ideas. For example, Molenaar et al. (2009) combines the concept of a set of values in a group and persistence over time as the defining components of corporate culture; where as the working definition of culture for this same article adds such ideas must also be spread out throughout the entire organization in order to be considered culture. No other definition combined these two components. The definitions contained two general themes. In 38% of the articles, culture was thought to be a set of values, beliefs or ideas held by a particular group of people; however, 54% went beyond that idea and thought that these values were translated into behaviours and actions taken by certain groups. Just 8% saw culture as just the actions take by a group of people.

As was mentioned after each table of definitions, articles frequently include several definitions in order to properly convey a point (Mohamed 2003; Molenaar, et al 2009; E. Chan and Tse 2003). This range of definitions offered the audience a range of perspectives about how people have sought to define aspects of culture. The unique nature of these definitions can cause variation in the measurement of culture as a variable which should be considered in future research. Behaviour and actions are inherently easier to measure because they are observable; conversely, values and beliefs have to be measured or quantified indirectly. In our data set, this is most commonly been done through questionnaires. Both observations and questionnaires have their advantages and disadvantages as well as their own biases. When interpreting results from studies related to culture it is important to notice this distinction in order to realize the generalizability of the previous data as the field moves forward. For example, Molenaar (2009) defined corporate culture as including beliefs and behaviours consistent through time and throughout the organization. The resulting study then measured both belief and behaviour in a longitudinal study at every level of the company. Molenaar (2009) conducted a survey that resulted in a structural equation model which provides guidance for future researchers who intend to define culture in a similar fashion.

Another foundational difference seen in the definitions was the inclusion of time. Four definitions included time culture included maintenance over time (Molenaar et al. 2009; E. Chan and Tse 2003). While those two articles only represent 1% of all the articles, time was considered in several other studies within this paper’s scope. For some, safety culture developed very slowly (Huang and Hinze 2008; Kleiner et al. 2008; Patel and Jha 2015), while for others project culture in partnering could be developed rapidly (A. Chan et al. 2004). Definitions of culture without time imply cross-sectional studies of an environment are suitable to make evaluations of culture; however, these few definitions with time might require a longitudinal study in order to get a full view of culture. As for all research, specific research questions will define the appropriate theoretical grounding.

Another distinction made in the definitions of culture was the organizers of culture. 74% of the definitions made a reference to who governed a certain culture. Thirty-five percent of those articles argued that culture was controlled by an organization while 65 percent argued that the members or employees guided the culture. This was particularly apparent in the definitions of safety culture. Chen and Jin (2013), Choudhry (2013), Fang et al (2006), Mohammed (2003) reference safety culture as a product of the organization; where as the remaining two safety definitions (Martin and Lewis (2014) and Mohammed’s definition from Cullen (1990) see safety culture as the product of the employees. This distinction is important to note because of the impact it has on the types of beliefs and behaviours a group takes on. A culture imposed by a single source (like upper management of an organization) can heavily influence the resulting culture, which in the case of safety could save lives; however, this influence could allow for certain values to be ignored such as communication. A culture founded in beliefs from the employees can be much more comprehensive by allowing employees to contribute their views to company; however, priorities of each belief could vary among employees causing conflicts when different priorities oppose. From a construction research perspective, where the culture is founded substantially influences who to survey and what questions to ask, as was noted by Gilkey et al. (2012) and Chen and Jin (2013).

Sixty-one percent of the definitions originated from a source outside the field of engineering and construction, meaning there were only seven definitions, which referenced a source in construction. In fact 39% of the definitions came from engineering and construction, 33% came from business and management and finally 28% came from the social sciences. The field was determined by the journal in which the reference was published or author’s background. For multiple authors the definition was counted once for each author. The ideas of Bal (2002) and Neumann and Nünning (2012) offer a viable
explanation for the large variability that was seen in the definitions of culture. The concept of culture is changing as it is converted into a usable concept for construction engineering. As conceptual misinterpretations can lead to inaccurate interpretation of results, our results emphasize the need for careful and explicitly given definitions as construction researchers mobilize the idea of culture.

6 CONCLUSIONS AND FUTURE RESEARCH

This paper presented a conventional content analysis of 523 articles in the JCEM produced by ASCE and a more detailed summative content analysis for 172 articles relating to the same category. Thirty-seven unique definitions were found, suggesting that culture is not uniformly defined in construction research. Fifty-four percent of the definitions contained beliefs and behaviours as part of the definitions, and 11% of the definitions included time (i.e. the amount of time the beliefs and behaviours have persisted). Finally, culture was seen as the product of the organization by 35% of the definitions and as a product of the people by 65%. All three of these variances in the definitions effect the way in which culture in construction is researched, particularly the measurement of culture (surveys or observations) and research design (longitudinal or cross-sectional, and target population). Finally, the definitions of culture referenced literature in engineering/construction, business/management, and social sciences approximately equally which may explain some of the variation in the definitions. In conclusion, these results show definitions of culture travelling across disciplinary boundaries to create a set of definitions which researchers should carefully consider. More research is needed to determine if larger trends exist in defining of culture. Further analysis into the effect of a definition of culture on the methods and results of a study would provide valuable insight into how the definitions should be chosen and standardized across construction research. Expansion of the current content analysis to search for definitions of culture in all 523 articles as well as adding more academic construction journals would also add valuable knowledge.

Acknowledgements

We would like to thank the University of Washington for providing us with the resources to conduct this research. In particular we would like to thank the Valle Scholarship Program without which this work would not have been possible.

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BENEFITS OF INTEGRATING BIM AND GIS IN CONSTRUCTION MANAGEMENT AND CONTROL

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Abstract: Generally, a tremendous amount of waste and debris are generated by the demolition of existing buildings. Construction managers and site engineers are encountering difficulties in accurately calculating the volume of these materials, which have big influence on the duration and cost of projects. This paper describes the methodology used in developing a model that integrates Building Information Modeling (BIM) and Geographic Information System (GIS) to facilitate demolition waste management and control for megaprojects. The suggested model aims at facilitating the processes of estimating the quantities of waste by calculating the travel distance between the site, storages, and landfills and related time, as well as computing the number of trucks required for loading and hauling the waste from and to multiple sites. The main goal of this study is to demonstrate how this integrated model will provide construction managers with a comprehensive tool that could substantially benefit them in comparison to solely utilizing BIM. This paper will demonstrate how the model works and explain how it has the edge over using BIM only. The suggested BIM-GIS model will contribute to more green and efficient construction management. A hypothetical case project is given to test the workability of the model.

1 INTRODUCTION

BIM and GIS are powerful platforms widely used in the construction industry due to their various individual features and capabilities; however, each platform lacks important features the other platform offers. For instance, GIS provides topological (georeferenced) data, which allows for 3D analysis, spatial analysis, and queries such as calculating the distance between two different points, calculating routes, and defining the optimal location (Irizarry and Karan, 2012). BIM, on the other hand, is incapable of such analysis, but it provides a detailed database of object-oriented parametric information for the building and represents it in a 3D model, a feature that GIS is lacking (El-Mekawy, 2010). Research efforts conducted on leveraging the integration between BIM and GIS in the construction management process are rather scarce in comparison with ones that are carried on utilizing BIM only. Thus, this paper attempts to highlight various areas in which such integration is useful for construction managers and practitioners. Furthermore, the paper will underline some of the advantages of using the BIM-GIS model in managing the waste generated from the demolition of an urban development (a megaproject), plus controlling and monitoring some of the processes involved.

2 LITERATURE REVIEW

Poon et al (2001) pointed out that demolition (D) waste is estimated to be 10% to 20% higher in weight than waste generated from new construction (C). Llatas (2011) emphasized that as requirements for C&D
waste quantification become more and more accurate, concise and detailed, it is believed that computer-aided estimation has good development prospects. Wu et al. (2014) argued that one advantage of giving a detailed classification of construction waste is that the chances of recovery of waste may be increased. As a result of the urgent need for such tools, efforts to use BIM technology in construction management have increased. Cheng and Ma (2013) developed a model to improve C&D waste sorting and quantification and estimation processes by leveraging BIM tools. Jalali (2007) considered that the estimation results could provide fundamental data for practitioners to evaluate the true size of the waste and hence, make the adequate decision for their minimization and sustainable management. Wu et al. (2014) believed that the waste generation rates derived from different projects can assist in providing information for benchmarking the effectiveness of different management practices. The optimal technologies and work procedure can be selected by comparing the waste generation rates. Furthermore, studies on the integration of BIM and GIS in the construction management field are few in general. Irizarry, et al. (2013) developed a BIM-GIS integrated model to improve the visual monitoring of construction supply chain management. Liu and Issa (2012) emphasized on the importance of 3D visualization for pipeline maintenance and how it overcomes the shorting in 2D illustration. El Meouche, et al. (2013) investigated multiple approaches to integrating BIM and GIS but did not propose a model or a solution to a particular construction management problem. Isikdag, et al. (2008) suggested a BIM-GIS model for the support of the site selection and fire response management processes. Irizarry and Karan (2012) utilized BIM-GIS integration to optimize the location of tower cranes on construction sites. Other research work, such as (El-Mekawy, 2010); (Berlo and laat, 2011) and others, worked on the interoperability issues between BIM and GIS; and how to unify both domains at the semantic level to make communication and the data transfer between the two platforms easier and more efficient. Borrmann (2010) developed a spatial query language for 3D building models using tools and concepts from GIS on BIM. The query language is meant to enable inquiring about walls located in certain story, if a certain room is equipped with heating system tools, determining the columns that intersect with a certain slab, defining the fire extinguishers positioned within a given distance from a certain building component such as a window or a column, etc.

It is evident, based on the above literature review, that the research work done on BIM-GIS integration in recent years has not suggested a solution for demolition waste management for megaprojects (urban development), even though it is an important area with much room for optimization of the current practices and numerous issues to solve. It also can be concluded that there is an urgent need to use computers and technology in construction management and to explore how this will benefit professionals. This study will establish how integrating a spatial analysis capability, in GIS, is rather beneficial and will add greatly to the typical construction management practice of just using BIM tools. Hence, the suggested model aims to facilitate the processes of waste estimation, sorting, and removal, on an urban scale, by leveraging the capabilities of both BIM and GIS and it provides this to the users in a single unified place. The model includes two main modules, a management module and a monitoring and control module, as shown in Figure 2. Each module has subdivisions, two of which are under the monitoring and control module, which are work progress and sustainable demolition practice implementation. The management module includes three subdivisions, which are waste estimation, waste sorting, and resources management. Later in this document, each subdivision will be explained in detail to show how the module works and what privileges it provides over using BIM only.

3 METHODOLOGY AND DEVELOPMENT

Data transition, query and analysis between BIM and GIS are further problematic due to interoperability issues between both platforms at a semantic level, among other issues (El-Mekawy, 2010). Thus, this paper is going to demonstrate a methodology, based on a literature review of Isikdag, et al. (2008) and El Meouche, et al. (2013), for integration between the two platforms, leveraging the GIS analytical and query tools to perform some tasks on the imported BIM file. The two programs used in this paper are ArcGIS 10.2.2 by ESRI (as a GIS tool) and Autodesk Revit 2015 (as a BIM tool). The methodology used to develop the integrated BIM-GIS model process flow is shown in Figure 1. Section 3.2 illustrates the main modules encompassed by the model and explains how it works, presenting the capabilities and
advantages of the model comparing to solely using BIM. A hypothetical case project, in Section 4, will be used to test the workability and capability of the proposed model.

3.1 Model Development

First, the Revit file of the urban development is exported as an IFC2x3 file. The BIM file's coordinates should match the real world coordinates of the city or the region where the urban development is located, to allow for the drafted buildings to be set in the right place after the importing process. Once the file is imported into the GIS, all the families (objects) included in the design will be categorized and put in groups (feature classes), based on the type of that class. For instance, all doors will be put together in one feature class named IFCDoors, and the same goes for windows, walls, floors, ceilings, etc. Some IFC components such as doors and windows contain a mix of materials: aluminum, steel, glass, wood, plastic, etc. As this paper is part of an ongoing research project, the current model does not automatically separate those materials or distinguish between their condition (reusable, recyclable, and total loss). After that, the imported BIM (IFC) file is georeferenced by allocating the proper projection system. If the urban development BIM (IFC) file is going to be imported on an already existing transportation network and topography layers (triangulated irregular network, known as TIN), it has to have the same projection system as them in order for all layers to work properly. It should be noted that using a multiuser Geodatabase (.gdb) file is preferable when dealing with cases such as urban development or megaprojects, as it allows what is called "versioning" which enables data to be shared and used by different users simultaneously and allows nullable fields in the attribute table associated with the geometric features imported into GIS (ESRI, 2009). Afterwards, the user defines the work zones. Depending on the nature and requirements of their work, these zones could be digitized (drafted) manually using a GIS sketch tool or also imported if they are already drafted in the BIM file. Each zone should be given a unique name to avoid the issues of conflict and to ease the analysis processes. The zone allocation could be based on a variety of characteristics defined by the main contractor. Next, two major fields should be created, within the GIS, in the attribute table of each component or feature class (door, window, etc.) in order to facilitate the waste estimation, sorting, categorizing, and quantification processes. These fields are: "condition", with the following attributes, reusable (onsite and non-onsite), recyclable and total loss and, if applicable, “classification” (Inert or Non-inert). Accordingly, each building component should be categorized and allocated one unique attribute from the aforementioned attributes. The proposed BIM-GIS model should be successful in estimating the demolition waste generated, sorting the waste according to material condition (reusable, recyclable, and total loss), material type or element (steel, wood, concrete, glass, plastic etc.) and estimating the number of trucks needed for loading and removing the waste. The material condition attributes (reusable, recyclable, and total loss) are to be put manually in the model based on experience from previous projects and/or data collected on materials and building components. Those attributes could be updated later based on a field survey of the actual buildings. The attributes could be entered manually into the BIM (IFC) model and then exported to the GIS or entered into the GIS directly. It must be emphasized that the output data acquired is only as good and as reliable as the input data is.
3.2 Model Components (Modules)

Figure 2 provides a detailed explanation of the model's components and its associated modules. In each module, there are subdivisions that represent the main operations involved in the demolition-waste management and control that the BIM-GIS model is capable of processing efficiently and in a timely manner.

![Diagram of BIM-GIS Module Components]

Figure 2: Explanation for the modules (components) of the BIM-GIS model

4 CASE STUDY

The case study provided in this document is hypothetical and meant to confirm the workability of the presented BIM-GIS model and aims at validating it, considering its efficiency for the purpose of C&D waste management and control. It encompasses twelve simple and similar buildings that are equally distributed over three different work sites. Each building includes 4 windows, 4 doors, ceilings, walls, stairs and railings with an approximate area of 2,000 ft². Land use (residential, commercial, and industrial) is assigned to the work zones (work sites) instead of lots on which the buildings are. This is because it will be hard for the reviewers to tell the difference at such a scale (urban scale) when reading this document. Also, the low number and simple structure of the buildings is meant to be as this case study is meant to test the workability of the model, which can be done sufficiently with the provided data. A true waste treatment facility, close to the project area as shown by Google maps, was selected and drafted in GIS as the destination point to which the demolition waste is going to be transported. The model is used to estimate the demolition waste, sort the materials and calculate the number of trucks required to remove the waste generated.

![Image of BIM (IFC) urban development into Arcscene]

Figure 3: Imported BIM (IFC) urban development into Arcscene.
5 THE BIM-GIS MODEL VALIDATION

5.1 Management

5.1.1 Waste Estimation

The waste estimation process in this model could be conducted in various ways. First, the fields required for the demolition-waste estimation process (material condition, total waste per material and land use), are created. All the required parameters and measurements for all the materials available in the building already exist in the imported BIM (IFC) file. Accordingly, the volume for all the materials is calculated by utilizing Equation 1. Then all the condition attributes, reusable (onsite or on other site), recyclable or total loss, are assigned to every single material. These different condition data could be determined first, based on standards or experience and then calibrated during the process of the demolition for more precision. After the previous steps, the utilizer could easily retrieve the information about the estimated waste volume in any required way. For instance, the user could use the model to estimate the total waste of a certain building, work zone (as in this case study), or for the entire project. This could be done by the “select by location” function in ArcMap’s (GIS) main menu. Also, the waste could be calculated for a certain type or condition of the materials one wants to inquire about, such as concrete, wood, steel, glass, etc., or reusable (onsite or other site), recyclable, or total loss. This also could be done by first “select the location”, as previously mentioned, of the wanted materials and then by the “select by attribute” function available in the ArcMap’s main menu. Equation 3 is used in the model for estimating the total loss that will be calculated after estimating the total waste, reusable and recyclable waste volume generated as illustrated in Figure 4. Even though BIM is capable of inquiring about materials according to their conditions, the proposed BIM-GIS model is evidently advantageous in terms of estimating the waste for targeted location exploiting the spatial relationships between objects. The model could also estimate the waste generated from a certain building located within a certain radius or within a certain distance from a street or another building. Furthermore, the model can include the waste index values discussed in (Cheng and Ma, 2013), such as the Global Index method introduced by (Jalali, 2007) and the waste index presented in (Poon et al., 2001). Cheng and Ma (2013) explained the waste index as the amount (in unit of volume or weight) of construction waste generated per m$^2$ of Gross Floor Area (GFA) and the global index as a more detailed method that allocates certain changes or increased percentages to every kind of building material. For example, concrete, steel, wood, glass, cement, and masonry have a value of 1.1, 1.02, 1.05, 1.05, 1.1, and 1.1 respectively. This could be easily done by creating a field named “increase factor” and assigning the values to the building materials, then, calculating the material adjusted volumes by using Equation 2. The previous step could be applied to any adjusting factors needed to be calculated even if it is related to the land use or project type, such as private residential, public residential, or commercial buildings. GIS also enables associating the attributes of one layer such as “land use” with all the building components by using a feature called “Spatial join.” This is one of the multiple features that GIS boasts, which the BIM tool lacks and thus could not run such process with the same efficiency if at all. Finally, maps, using BIM-GIS model, could be produced for determining the locations of the components need to be demolished with associated attributes and estimation to provide the workers or practitioners with a target volume to consider while demolition of the building or part of it. Also, a detailed description for the component could be printed out using the layout tool in GIS. Figure 5 shows how the model can estimate the waste volume for single building component.


Figure 4: Waste volume calculations generated by the BIM-GIS model.

Figure 5: Calculation of the waste volume for a single component (doors) in three different zones.
5.1.2 Waste Sorting

The BIM-GIS model helps in performing a variety of data manipulation, enquiry and analysis. The model allows users to run customizable sorting for the demolition-waste generated by placing it under three main categories; these are: by condition, material type and component. Each category is then subdivided into different attributes depending on the category as shown in Figure 6.

Each component in the building should get one unique attribute from the attributes given in this subcategory; these are: reusable (onsite or other site) and recyclable. Total loss could be subdivided into inert and non-inert material if needed. As stated by (Zhang et al., 2012) common inert materials include but are not limited to: "reinforced concrete, asphalt, cement plaster, mortar, aggregate sand, bricks, rocks, rubbles, and soil." Common non-inert materials include but are not limited to: "wood, metal, plastic, and other organic materials." Each sorting attribute, recyclable for instance, could then be exported using the GIS export option into a new separate layer (feature class) that could be used separately for further analysis and statistics. The model offers users with an abundance of analysis and statistics capabilities that are only possible by integrating BIM with GIS. Thanks to its feature of relating space (location) to geometry, the user can run analyses or ask questions such as "how much is the volume of recyclable materials generated in this zone?" and compare them to the other zones. This could help in identifying or studying the type of buildings that generate more recyclable, reusable or total loss materials and sorting them according to different attributes such as the age of the building, the structural system, etc. (This type of query is not part of this paper; therefore, its results were not included).

The BIM-GIS model also helps users to perform statistics on the types of materials in the demolition-waste estimate. For instance, the user can inquire about the amount of steel that would be generated in a particular building or zone. This sort of analysis and estimation is beneficial for the workers to help them plan and prepare their demolition operation. Also, by using the export feature class option within ArcMap, the users could isolate any material of interest in a separate layer to further analyze and perform more statistics and analysis as needed. By adding the cost of the different waste materials generated, the user could estimate how much money, as return on investment in some cases, could be gained in this case. This, again, can be estimated on the different project's scales previously discussed.

The model will provide subcontractors with necessary information such as the number of doors or windows in the building or area that needs to be demolished. Also it enables the operator to run such statistics in different levels or scales. The user can inquire for information about multiple buildings, a certain work zone, for the whole project area or even according to land use. This feature is unavailable for BIM users, as spatial data analysis, which BIM lacks, is required in order to get this type of information.
Furthermore, detailed specifications and drawings can be printed out for the workers to recognize the specified components along with maps showing exactly where they are in the building.

Resource Management:

Cheng and Ma (2013) calculated the number of trucks, as many studies did, by dividing the volume of waste estimated by the truck capacity. The suggested model can instantly calculate the distance and travel time between the waste location and the target destination as well as the number of trucks required for the process of removing the waste as demonstrated in Figures 7 and 8. However, this is not accurate enough, as the distance between the waste location and its final destination ought to be taken into consideration in order to get the appropriate number of trucks based on trip frequency as shown in Equation 4. Some other pieces of information, along with the round trip time, should be included before using that equation, which are the truck loading time, unloading time, time needed to check the load, and wash-up time. These parameters, with the round-trip time, are part of the “Total round-trip time (min).” Using this approach, no trucks will be waiting for the other trucks to finish loading nor will there be any idle time waiting for trucks to come back and start the loading process. To test the workability of this method, we can take the volume of the recyclable materials shown in Figure 8 that have a volume of 785.68 m³ as an example. The number of trucks is estimated to be 112 considering a 7 m³ truck capacity. This is a huge number, of course, considering the estimated volume. To calculate the number of trucks for the same volume of waste first, values of the different parameters included in the equation are assumed as: unloading time = 10min, loading time = 10min, checking time = 5min and washing time = 5min. The total in this case will be 30min and the travel time between the site and the recycling facility, as shown in Figure 7, is around 22min, which will make the approximate overall time to be 74min. Using Equation 4 the estimated number of truck will be 74/7=10.57 trucks, which is rounded up to 11 trucks. It is obvious that the difference between both numbers is substantially big, therefore the smaller number (11 trucks) is selected and this number can be adjusted based on the work productivity on site. The estimated number of trucks will increase as the trip time increases, which means that locating closer facilities is essential for this process, a spatial problem that the integrated model could solve instantly. This method (total round trip time) is used when the number of trucks does not exceed the number of loads estimated; therefore, both numbers have to be acquired and compared.

[4]: Total round-trip time (min) ÷ unloading time (min) = Number of trucks needed.
5.2 Control and Monitoring

5.2.1 Work Progress and Application of Sustainable Demolition Practice Onsite:

The subcontractors’ progress and efficiency in applying the best practices in demolition and sustainable waste management could easily be monitored with the developed model. Once the total waste is estimated, a certain percentage (5-8%) could be considered to cover potential error, then whoever is responsible for record-keeping can easily identify if a percentage of waste (recyclable or reusable) generated is far less than estimated, and can track down the reasons that led to this shortage. This could, again, be performed on the different scales (building, block or zone, and the entire project) as discussed previously in this document. On the other hand, the workers should be notified of the amounts expected from them to maintain the minimum level of applying the sustainable practices in the task performed, as mentioned previously in the literature review. The developed model is a useful tool to perform the tasks required from them adequately. Also, the model provides a useful tool in terms of establishing and calibrating benchmarking for the different types of waste generated as it can record the rate of the waste generated based on material condition, type, and component and compare among the results.

6 CONCLUSION

A BIM-GIS model is demonstrated in this paper, providing outstanding capabilities for facilitating some of the most demanding and experience-dependent processes in planning, management and control during the demolition phase of megaprojects. These procedures involve waste-sorting, estimation, and estimating the number of trucks required for loading, hauling, and removing the demolition waste. The model was validated and proven to be beneficial when it was tested using a hypothetical, but realistic, case study and capable of performing all the aforementioned tasks successfully and sufficiently. The model has even been proven to be able to go far beyond the scope and tasks discussed in this paper, which will lead to more research and testing in order to improve the model in the future. The analytical comparison between the capabilities of the proposed BIM-GIS model, versus using BIM tools solely,
emphasizes the benefits of the combination of spatial data and the object-oriented data of buildings in the construction management field. This paper is part of an ongoing research that seeks to improve the current model in terms of applications in construction management in general and the demolition phase and urban planning, management and control in specific. In addition, future work will focus on increasing the automation and integration procedures between GIS and BIM to further facilitate the use of the model and to maximize its benefits. Finally, there is no doubt that integrating BIM and GIS will enrich the current construction management and control tools used in the industry by adding a vast variety of new functions, all performed in one single place.

References


INTEGRATING BUILDING INFORMATION MODELING (BIM) WITH SUSTAINABLE UNIVERSAL DESIGN STRATEGIES TO EVALUATE THE COSTS AND BENEFITS OF BUILDING PROJECTS

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Abstract: Building Information Modeling (BIM) is a well-known innovative approach in project design and construction. The use of BIM enables designers to control project cost from the early stage of its life cycle. The cost impact resulted from the construction of sustainable building is one of the main resources that designers should consider when designing such type of facilities. As the North American population is aging Universal Design requirements (design that accommodate the needs of human regardless of their ages and abilities) should be considered in conjunction with the sustainable design criteria to achieve sustainable universal design (SUD). The aim of this research is to investigate the benefits and costs associated with adopting the concept of sustainable universal design applied for building projects. Therefore, this paper proposes a methodology to develop a model that integrates BIM tools with SUD requirements and strategies (i.e. Energy, material, and indoor air quality and barrier free environment) and to evaluate the associated benefits and costs of proposed buildings at their conceptual design stage. The proposed model consists of three main modules. First, a database module, which is mainly devoted to illustrate items necessary toward SUD approach including: hand rails, entrance slope with its associated material and lighting shapes and specification. All of the mentioned items will be in accordance with the standards (i.e. Canadian National Building Code (CNBC), LEED, international standards). Second, a 3D design module will describe the design components and system used in the different areas in the 3D conceptual design (i.e. living room, toilet, and kitchen). Finally, a cost benefit analysis module that will evaluate the initial cost of each designated area that complies with the needs of aging people who have chronic health conditions, where the total cost and benefits is calculated accordingly. The effective development of the integrated model will help owners, designers, and developers to evaluate the cost and benefits of adopting sustainable universal buildings. An actual case project is used to test the workability, capability and performance of the proposed model.

1 INTRODUCTION

The sustainable approach is widely adopted in today’s construction industry. This notable adaptation of the sustainable approach emphasise its importance based on the economic, environmental and social improvement constraints. Kim and Emily (2007) consider that the visible and measured outcomes from some sustainably designed projects include increased occupant satisfaction, reduced construction and operation-related waste costs, reduced water use, and improved energy performance. While the adaptation of sustainable design (SD) approach in the construction industry is growing, the nation’s population is aging as well; therefore, more design strategies should be considered to overcome this issue. Recent studies devoted to guide designers in providing safe and functional facilities for inhabitants
who like to age in their living place (Demirbilek and Demirkan, 2004). Universal design (UD) is one of the innovative approaches that have been considered in the construction industry. It has been implemented to help disabled individuals to maintain their daily activities (Hunter et al., 2011). Although, implementing sustainable strategies in buildings (new/existing) showed better economical trend over the long run, its initial associated cost is doubtable. The results of a survey conducted in 2007 by the World Business Council for Sustainable Development found that the costs of sustainable buildings are “overestimated” for an additional cost of 17 percent added to the cost of conventional building which is considered more than triple the actual cost of 5 percent (Hoffman and Henn, 2008). Certainly, it is beneficial for owners, developers, and designers to accurately calculate the cost associated with the construction of Sustainable Universal (SU) buildings at the early stage of the project’s life. In order to evaluate such a cost, designers tend to examine and analyse multiple design criteria at the conceptual stage of projects (e.g. materials, technologies, spaces). Those criteria directly affect the principles, measures and costs of sustainable universal design (SUD). Building Information Modeling (BIM) is an innovative approach that allows designers to control project cost starting from the early stage of its life cycle. It helps designers to visualize their design and their associated materials and technologies before the building physically exists (Bryde, Broquetas, and Volm, 2013). This paper proposes a methodology to integrate BIM with the SUD principles and requirements in order to evaluate the benefits and costs of adopting such type of design over buildings anticipated life.

2 LITERATURE REVIEW

The primary objective at the early stage of building projects is to design and evaluate their budget and performance. Critical decisions concerning the profitability and performance can be made at that stage (König, 1995). Bogenstätter and Bogensta (2010) indicate that the conceptual phase of project’s life play an essential role toward sustainable buildings. They suggest that in order to integrate life cycle cost (LCC) and ecological requirements into the conceptual design, building specifications and knowledge about the characteristic values of LCC should be known at that stage. On the other hand, considering the concept of universal design affects the building cost, performance, and occupant’s wellbeing as well. Therefore, designers are expected to involve the universal design strategies at the early stage of designing buildings; this in return will reduce costs, improve designs, and solve usability problems during the design process (Afacan and Erbug, 2009).

Green building certification systems provide a guidance to design and operate buildings; it allows to document progress, compare buildings, and record design and operations outcomes and/or strategies (Wang and Fowler, 2012). One of the well-known designs, construction and operation rating system is the Leadership in Energy and Environmental Design (LEED), which was developed in 1994 under the U.S. Green Building Council. LEED is designed to rate new and existing commercial and institutional buildings based on the energy and environmental principles. Sets of criteria are included in the LEED system, where each criterion has its own required points; based on the accumulated points, a building would be awarded either certified, silver, gold, or platinum certification (Dhawade and Harle, 2014). Unlike the sustainable design, universal design has no specific guidance to design and operate buildings. However, many international standards were developed to support the usability of products. When reflecting the concept of universal design to the aging and people with disabilities, there is a wide number of established written documents, which are standards, references and/or norms to guide the design process such as ANSI 1986; BSI 1979; Fair Housing Act Design Manual 1996 (Demirkan and Olguntürk, 2014). Canadian National Building Code is one of the barrier free guidelines; it is a legal document that sets the minimum requirements for design and construction. It first introduced the accessibility requirements in 1965 and continued until 2010. During that period accessibility was mentioned in a several sets of requirements based on the national demand (Jrade and Valdez, 2012).

Researchers highlighted the need of knowledge when doing the integration between different computational tools applied at the conceptual design stage of building projects (König,1995). Building Information Modeling (BIM) is used to convert the 2D based drawing information systems (i.e. universal material specification, universal components, sustainable universal guides) into 3D object based information systems (Arayici et al., 2009). Multiple efforts were done in the construction industry to find the effective way to integrate BIM with sustainable design and analysis tools (Zhang and Xiao, 2013).
Achieving this goal have the ability to remove the construction industry’s obstacles, increase its productivity, efficiency, and quality and reach the sustainable development principles (Arayici et al., 2009). This paper proposes a methodology to integrate BIM with the SUD principles and requirements in order to evaluate the benefits and costs of adopting such type of design for buildings over their anticipated life.

3 METHODOLOGY

The proposed methodology is routed on an intense literature review related to the benefits of both sustainable and universal approaches. The literature illustrated factors that affect SUD such as: universal design features, sustainable building parameters, type of green materials, and proper technologies used toward SUD principles and strategies. All the information related to these factors is collected and accordingly the proposed model’s conceptual design process can be started. The process consists of three stages as shown in Figure 1. Starting by data analysis and comparison, passing through selecting the best types of materials and technologies that will be applied in the 3D model, then applying the life cycle cost analysis method and ending by the validation part. Afterwards, the model’s components and architecture are identified.

3.1 Model’s Components and Architecture

The proposed model consists of different components that are interrelated with each other in a way that data and information is shared in an automatic and efficient way. The proposed model incorporates the following three modules: a database module; a sustainable and 3D design module; and a life cycle cost analysis module. Figure 2 illustrates the components of the proposed model.

In order to simplify the development process of the proposed model its architecture is created as shown in Figure 3. The analysis section used to examine the input data and its criteria (i.e. SUD strategies, sustainable materials, and energy performance, Masterformat). The analysis is based on the set objectives of the research; therefore, the analysis takes into consideration occupants’ requirements, building codes and standards (CNBC), and LEED (Leadership in Energy and Environmental Design) system. The output is a list of selected sustainable universal materials, accumulated LEED credit points and certification level, total cost of the selected materials, total cost of the selected technology, net cost of the project, and life cycle cost analysis.
Figure 2: Model’s components

Figure 3: Model’s Architecture
3.2 Module 1: Database Module

The module’s objective is to establish a database necessary to apply the SUD approach. Set of data were collected form the literature, publishers, and suppliers, which include information related to materials and components used in doing sustainable universal design such as 3D design families for windows, walls, and roofs. This data is analysed and evaluated based on SU strategies and their technical specifications, LEED and CNBC. After that the collected data is stored and organized in the database based on the Masterformat Work Breakdown Structure (WBS), besides is the associated costs as shown Figure 4.

![Figure 4: Data collection process of the sustainable universal materials and components.](image)

3.3 Module 2: 3D Design Module

This module incorporates 3D design families that are created in accordance with the sustainable and universal design requirements. These families are made of different green elements and their associated information such as cost, keynotes, specification, description and comments. These elements are created to have them handy whenever designers are doing sustainable universal design for proposed buildings. Once the 3D design is done, the information related to the 3D project components can be exported to an external database using a Database Management System (DBMS) to calculate the project’s life cycle cost as illustrated in Figure 5. LEED accreditation system and UD design standard for each component (i.e. door width, height of handrails, height and width of the kitchen sink) will also be incorporated within the module.

![Figure 5: The process to integrate DBMS with BIM tool](image)
3.4 Module 3: Life Cycle Cost Analysis

This module is developed to evaluate the costs and benefits of adopting SUD; accordingly, a cash flow will be generated for analysis and comparison purposes. The module works based on two systems. The first system is to calculate the cost of the elements used in a 3D design of the proposed project by using BIM tool (i.e., Autodesk Revit). The second system is to extract the total cost obtained from "system 1" to calculate the cost benefits and to generate the cash flow accordingly. Figures 6 and 7 illustrate the module’s process and components.
4 VALIDATION

The developed model should be validated to test its capability and workability; therefore, a one floor case building project is used for that purpose. The project has an area of 8,089 ft². First, 3D sustainable universal design of the case building is created (using BIM tool, which is Autodesk Revit in this case, as shown in Figure 8). Second, the selected materials and components associated with the created 3D design chosen from the database created in module 1. The cost of a similar conventional building was obtained from RSMeans© Cost Data in order to compare it with the cost of the created 3D SU design.

![Figure 8: 3D sustainable universal model](image)

4.1 3D Model Design

The families created in accordance with sustainable and universal design requirements are implemented into the 3D designed model of the case building. They are imported with their associated information (cost, keynotes, assembly code, specification and description), which are stored in the database of module 1. The process of customizing BIM families is done by duplicating the existing family and adding the necessary parameters as illustrated in Figure 9.
4.2 Cost Benefits

This section presents the final result of the LCCA module that recognises the selected design elements by their keynotes. Therefore, after exporting the information of the 3D SU design model of the case building, the costs of these elements are automatically extracted from the external database based on their associated keynotes. Accordingly, the cash flow is generated for analysis and comparison as shown in Figures 10 and 11.

![Figure 9: Snapshot of customizing BIM families](image)

![Figure 10: Conventional building’s cash flow](image)
5 CONCLUSION

The paper emphasised the importance of considering sustainable universal design strategies at the early stage of designing buildings. The paper was developed in order to integrate BIM with SUD principles in order to evaluate the costs and benefits of adopting this type of building projects. Outputs of the developed model consist of a list of the selected SU materials and components, their associated LEED accreditation level; list of the associated universal design standards and suggestion; and a LCCA report presented in the form of cash flow that is automatically generated. Having such a model helps designers, owners, and developers evaluate and compare the benefits of adopting the construction of sustainable universal design buildings.

6 REFERENCES


A NOVEL FRAMEWORK FOR BIM ENABLED FACILITY ENERGY MANAGEMENT – A CONCEPT PAPER

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Abstract: Building Information Modeling (BIM) enabled facility management has gained increased interest both in academia and industry. Previous research has shown the importance of having dynamic BIMs that can react and interact with real-time data obtained from building sensors. The other sought benefits of BIM such as improving workforce efficiency, proactive maintenance planning and improving maintenance records, which would lead to reduced energy and water consumption, are also acknowledged both by the academic community and the industry practitioners. However, BIM implementation for facility energy management activities, specifically for energy use monitoring, has not yet been explored, and one of the main reasons pertain to not having standards for BIM to be effectively used for facility energy management tasks. This paper provides a comprehensive literature review on BIM implementation and BIM requirements for facility management and facility energy management related tasks. Also, it proposes a conceptual framework that enables to achieve dynamic BIM for building energy use monitoring activities. The proposed framework connects BIM database with building energy management systems, while enabling BIM to act as a central data repository and a visualization tool to achieve energy use monitoring related tasks. Finally, it summarises the challenges to achieve dynamic BIM, and concludes with the expected benefits of implementing dynamic BIM for building energy management as well as recommendations for future research.

1 INTRODUCTION

Energy Management is one of the most important tasks among Facility Management (FM) responsibilities. Building Energy Management Systems (BEMS) are used to operate, control and monitor energy use in buildings. BEMS are also used to manage buildings’ environment and to control their heating, cooling and lighting systems. However, many of BEMS capabilities, such as automated data sharing, are not yet fully achieved.

There is a growing interest in the Construction Industry in using Building Information modeling (BIM) throughout buildings’ life cycle including Facilities Management (FM) practices. BIM implementation for FM applications, including energy management tasks, is considered an emerging field. Many benefits of implementing BIM in FM are sought during later phases of buildings’ life cycle. Those benefits include the ability to extract and analyze data for various needs that could support and improve decision making process, thus improve the energy performance during Operation and Maintenance (O&M) phase.

In this paper, a novel framework is introduced, where BIM is used as central data repository for operating buildings and managing their energy performance. This framework aims to achieve a dynamic BIM that
can act and react with BEMS and provide feedback to operators and building energy managers. This framework is part of a larger study that will be implemented for educational buildings in order to test its performance.

The paper is organized as follows; the next section gives background on current building operation and energy management practices including BEMSs. Section 3 then reviews current BIM uses and presents a novel framework for using BIM during building operations and maintenance phase. Section 4 focuses on the challenges that this framework would face and proposes solutions for each identified challenge. Section 5 draws conclusions and discusses future research needs.

2 CURRENT BUILDING ENERGY MANAGEMENT PRACTICES

Energy management is considered the top priority among the functional responsibilities in FM, followed by maintenance and repair (Sadeghifam et al. 2013; Underwood and Isikdag 2011; Yao 2013; Yiu 2007). Currently, tools such as Building Automation Systems (BAS) and BEMS are used to manage buildings' environment and control their heating, cooling and lighting systems, i.e. to perform building energy management tasks. Those systems are defined as a collection of microcomputer systems consist of Direct Digital Control (DDC) controllers and their control devices, which operate under supervisory control equipment or software collectively. Their abilities include sharing data with individual controllers for coordination and optimization, linking control processes, and performing operation tasks and reports (Doty and Turner 2009). BEMS are considered an essential source of information for building energy performance assessment that is used to optimize building energy performance as well as to fix any problems in building systems. However, many of BEMS capabilities, such as automated data sharing, are not yet achieved, and the current BEMS practices lack continuous data flow throughout facility life cycle (O’Sullivan et al. 2004) (Figure 1). Furthermore, data to the O&M phase is input manually, which results sometimes in inaccurate and incomplete information (Kelly 2013) that would require facility managers to re-enter the missing data they need to operate BEMS and guarantee optimal energy performance.

2.1 Design
- 2D drawings documents
- 3D models, lack sufficient specification
- Energy performance simulation

2.2 Construction
- As-built 2D drawings, 3D models
- Equipment testing and commissioning
- Minimum to no update on the energy performance simulation

2.3 Maintenance
- Re-entry of BEMS information
- Energy performance recording
- Minimum role of as-built drawings for O&M

Figure 1: Energy management related data flow throughout building life cycle

Continuous feedback from BEMS during O&M is considered essential to maintain the planned operational and energy performances of buildings. In addition to imprecise commissioning and BEMS malfunctioning, not providing real-time data to BEMS are considered as the main reasons for buildings’ performance deterioration. BEMS enable building energy performance monitoring, and help achieve energy savings of
up to 40% (Claridge et al. 1994; Herzog and LaVine 1992; Salsbury and Diamond 2000). However, they are becoming more complex and difficult to operate for an average operator (Hyvärinen and Kärki 1996).

BEMS records and stores building energy use data collected from sensors (e.g., temperature, CO2, zone airflow, daylight levels, occupancy levels, etc.) as well as data from fault detection and diagnosis sensors (e.g. air handler units controls, HVAC systems, valves controls and fans controls). Those sensors are numbered and organized based on their location in the building, and presented in list format. Sensor outputs, energy performance metrics (i.e. energy consumption), and other building performance metrics are presented in 2D histograms, tables and lists of tasks or in similar formats (Figure 2). Furthermore, maintenance records and other facility documents are kept in separate systems, not in BEMS, plus all these software have their own data structure that are not compatible with each other (Wang et al. 2013). As a result, when BEMS shows a problem for one of the building elements, facility energy managers and maintenance personnel need to obtain further information associated with that particular element. This requires them to check other systems such as building maintenance and warranty records. Finally, after gathering all necessary data, the problematic element needs to be located within the building, which maybe a tedious task, especially if the element is located in an area congested with other building elements such as pipes, ducts etc.

Figure 2: BEMS user interface

Overall, this makes it cumbersome to evaluate energy performance of an entire facility by gathering data from separate systems (Pietruschka et al. 2010; Yao 2013). Furthermore, it limits the possibility to react to any changes or possible problems in the system on time. It also prevents from developing a proactive maintenance strategy, which may increase energy losses due to system defects. For example, it is estimated that about 30% of the energy in commercial buildings is wasted because of degraded and poorly maintained equipment (Granderson et al. 2011).

3 A NOVEL DYNAMIC BIM FRAMEWORK FOR BUILDING ENERGY MANAGEMENT

There is a growing interest in the Construction Industry in using (BIM) throughout buildings’ life cycle including FM practices. BIM supports a collaborative approach throughout the project's life cycle phases and engages multiple stakeholders in the project including architects, engineers, contractors and the facility managers. Furthermore, BIM eliminates tedious and error prone data entry process, which leads to decrease/eliminate loss of project/facility information during project lifecycle (Figure 3) (Eastman et al. 2011).
BIM implementation for FM applications, including building energy management, is considered an emerging field that lacks real case studies (Kelly 2013). However, most benefits of implementing BIM in FM are sought during later phases of buildings’ life cycle, such as the ability to extract and analyze data for various needs that could support and improve decision making process (Azhar 2011). Furthermore, BIM in FM applications can help increase the efficiency of work order executions by providing faster access to data and by improving the process of locating various facility elements with its user friendly 3D interface (Kelly 2013). In addition, BIM implementation in FM and BEMS would help eliminate redundancy in data re-entry since BIM would act as a central data repository (Figure 4) that supports all activities throughout the buildings’ life cycle from design to maintenance and operations (Fallon and Palmer 2007).

Figure 3: Documentation loss of value during project lifecycle (Eastman et al. 2011)

Figure 4: BIM as Data repository in buildings’ life cycle
3.1 Dynamic BIM framework

BIM implementation for energy management activities has been limited to green retrofit modeling and design simulations. This maybe a result of unforeseen productivity gains that can be realized from reduced equipment failure as well as the productivity increases that maybe realized through an integrated platform (Becerik-Gerber et al. 2011). A suggested step forward would be to integrate energy use data with BIM database for building energy use monitoring (Muthumanickam et al. 2014) in order to achieve a dynamic BIM (Figure 5). Having dynamic BIM models that reflect actual as-built conditions and contain real time building information gained increased interest lately (Akanmu et al. 2013). A dynamic BIM model has the potential to provide improved documentation, minimize the cost of facility operations and maintenance, serve as a useful reference for future projects, and improve proactive maintenance planning (Chen et al. 2014; Teicholz 2013). This, overall, would lead to reduced energy consumption as a result of having well maintained, efficient mechanical equipment.

This paper proposes a novel framework that utilises dynamic BIM models containing real time building information obtained from sensors and BEMS to improve facility energy management activities (Figure 6). This framework aims to integrate BIM with BEMS systems using a programming application to enable industry foundation classes (IFC)-based BIM files read and update their database based on the BEMS live feed. Visualization of BEMS data in user friendly 3D BIM interface would enable facility energy managers to take timely actions about the problematic building elements, i.e. proactive maintenance, which would translate into energy savings.

In order to achieve the proposed framework, two programming applications will be developed; the first one is to link the BIM database with energy sensor output data, through BEMS, thus to visualize real-time energy use as color coded 3D models and to link it to each model element, where building maintenance and records of warranties and other information are stored. This would allow comparing the collected data with historical energy consumption data, the design or manufacturer claimed data and maintenance records simultaneously, which would help discovering any over consumption or flaws in the system in an efficient and timely manner. The second programming application will be developed to link BIM database with energy analysis programs, where energy consumption can be analyzed and over consumption can be detected.
Consequently, this should enable energy managers to detect any over consumption immediately, which would help them determine the reasons behind it faster. This would improve proactive maintenance plans and actions as it enables detecting defective or faulty equipment in a faster manner, so that they can be replaced immediately without causing more energy losses.

4 DYNAMIC BIM CHALLENGES

In order for BIM to be used in facility and energy management practices it needs to be dynamic; and that is, reflecting actual conditions of a facility and presenting real time building information. However, achieving “dynamic” BIM is faced by a number of challenges, which can be grouped into three main categories: (1) lack of guidelines for the necessary information required for BIMs to be used in building energy management related tasks; (2) inaccuracy and/or incompleteness of as-built BIMs; (3) interoperability issues between BEMS and BIM authoring tools (Laine et al. 2007). In this paper, a framework that connects BIM with BEMS is being introduced to help overcome one of these challenges, the interoperability issue.

The first obstacle, the necessary information required for BIMs to be used for building energy management tasks, has been addressed and stated in the literature. Becerik-Gerber et al. (2011) suggested that three types of energy management related FM data should be incorporated into BIM: (a) equipment and systems, (b) attributes and data, (c) portfolios and documents. However, specifications and details of this FM data, such as type of equipment that should be included in the model and attributes and the level of detail of the building model, were not described. Furthermore, the Pennsylvania State University computer integrated construction research program report (2013) suggested that the following items should be identified, documented and included in order to achieve dynamic BIMs: (a) type of building elements to be tracked (b) information display format (c) Level of Detail (LoD) required for each model element (d) properties and attributes of each element.

The second challenge pertains to inaccuracy and/or incompleteness of as-built BIMs. Several researchers suggested that early involvement of FM personnel in design and construction phases would be very beneficial for developing accurate and complete as-built BIMs (Teicholz 2013; Wang et al. 2013). However, such involvement remains limited due to lack of knowledge about BIM implementation for FM tasks (Kelly 2013), lack of specific data requirements (Becerik-Gerber et al. 2011; Kelly 2013), and interoperability issues (BIFM 2012). The issue related to inaccuracy of as-built BIMs (at object level), has been addressed both by researchers and industry practitioners. Several researchers emphasized the importance of having accurate and up-to-date as-built BIMs for FM tasks (Ahmed et al. 2014; Akinci 2015; Bosché et al. 2013; Son et al. 2014). Therefore, developing guidelines and requirements for BIMs to be used for building energy management practices is essential for achieving dynamic BIM and needs broader attention.
The third obstacle, interoperability issue, has been widely expressed both by researchers and industry practitioners. Interoperability enables to manage and communicate electronic data among collaborating firms, between different disciplines in individual companies and between different phases of a project, i.e. design, construction, maintenance and business process systems (Gallaher et al. 2004). Interoperability issues between FM and BEMS programs and protocols are common and well known. Furthermore, there are interoperability issues between BEMS and BIM as well as between various programs that are used for building maintenance, building condition monitoring and document management. Typically, these programs have their own data structure and are not compatible with each other (Wang et al. 2013). The role of BIM for FM and BEMS within current practice is still unclear. However, as shown in Figures 5 and 6, there are possibilities for connecting BIM with various BEMS and other FM software. BIM would act as a central data repository that collects and stores data from various systems, and provide access to this data through a 3D, easy to use, user friendly interface.

5 CONCLUSIONS AND FUTURE RESEARCH

BIM implementation for facility energy management practices has gained increased interest both in academia and in industry in recent years. The current energy management practices have several drawbacks such as lacking automated data sharing, requiring manual data entry during O&M phase, and not facilitating continuous data flow throughout facility life cycle. BIM enabled energy management facilitates extracting and analyzing data for various needs to improve decision making process, which would translate into increased efficiency in work order executions and elimination of redundancy in data entry. Dynamic BIM models could improve documentation, minimize the cost of facility operations and maintenance, serve as a useful reference for future projects, and improve proactive maintenance planning which would lead to reduced energy consumption. Lack of guidelines to prepare BIM for BEMS, inaccuracy or incompleteness of as-built BIMs and interoperability issues between BEMS and BIM authoring tools are the main challenges that prevents from achieving dynamic BIM. In this paper, a conceptual framework that proposes to connect BIM with BEMS was introduced to help overcome the interoperability issue. The proposed conceptual framework will be implemented by developing a programming application to link BIM and BEMS and tested in future research. It is expected that it would help improve current facility energy management practice, and help save energy.

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References


BRIM IMPLEMENTATION FOR DOCUMENTATION OF BRIDGE CONDITION FOR INSPECTION

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Abstract: Bridge condition inspection data provide critical and rich information for assessing structural condition. Currently, the majority of bridge inspection methods use printed checklists, and their interpretation is labor intensive, subject to personal judgment, and prone to error. To realize the full benefits of bridge inspections, there is a need to automate the data management process. This study implements Bridge Information Modeling (BrIM) technology for bridge inspections and compare it to the conventional approach of paper checklists. The environment combines a 3D representation of the infrastructure, and allows the integration of inspection data, such as the presence, type, severity, and localization of damage and previous maintenance decisions. In this paper, we use the acronym BrIM to refer to the database that integrates a 3D bridge model and bridge element condition data. In order to validate our approach, we obtained 2D drawings and previous inspection and maintenance data from two bridges located in Ames, Iowa, and modeled them using Revit. We then synced both models using cloud-based solutions so that we could access them from tablet computers on-site. Then, we tested the BrIM based inspection methodology with Iowa DOT engineers and bridge inspectors, who confirmed that BrIM can be used to automatically query, sort, evaluate and send information to decision makers. Furthermore, we conducted a short survey with several DOT engineers and bridge inspectors regarding with possible expected benefits of using 3D BrIM based solutions for inspections. It is concluded that this methodology will substantially improve bridge assessment and maintenance operations, resulting in reduction of costs associated with bridge assessment, and improvement structural resiliency by enabling more effective maintenance and repair operations.

1 INTRODUCTION

The Federal Highway Administration (FHWA), according to Federal-Aid Highway Act of 1968, requires all states to perform a biennial inspection for each bridge to document its condition. Current bridge inspection and assessment methods rely heavily on a reiterative process of manual data entry and extraction, which are subjective, error prone and time consuming. Data collected during site inspections provides the foundation for maintenance and rehabilitation actions. Bridge Information Modelling (BrIM) is a fairly new technology that is still in its infancy in terms of its adoption in the industry. BrIM technology enables storing all bridge data, including its drawings and models, material specifications, inspection notes and others, in a central database that can be accessed both from the office and the field. This gives an opportunity to adopt BrIM to develop an automated bridge inspection method. BrIM has many proven benefits such as reduced construction duration and cost savings when implemented during design and construction. However, the benefits of adopting it for inspection purposes are still uncertain. In this paper, a novel framework that employs BrIM and cloud computing technologies for bridge inspection and
assessment is introduced. The framework was tested to determine its applicability and impact on bridge inspection. The test/mock inspection was conducted on a bridge located in Ames, Iowa with the collaboration of Iowa DOT personnel to evaluate and compare the current and proposed inspection practices. Furthermore, a survey was conducted among eight other DOTs in order to better understand current and possible future BrIM applications at their institutions. The survey included questions regarding 3D modelling, BrIM applications in general, as well as BrIM adoption for bridge inspections.

This paper is organized as follows: Section 2 provides a literature review on information technology and modelling applications in heavy-civil sectors. Section 3 presents the research methodology by detailing the BrIM based bridge inspection framework and by providing the details of the survey. Section 4 presents the results of the mock inspection and the survey. Section 5 draws conclusions and discusses future research needs.

2 LITERATURE REVIEW

The U.S. economy depends heavily on its road network and bridges. Any failure in maintaining this network can cause substantial economic losses (Elbehairy 2007). In order to keep this network maintained, all states must perform a biennial inspection for each bridge to document its condition. This requirement puts a cumbersome responsibility on state DOTs to manage their assets. As a result, standalone Bridge Management Systems (BMS) (e.g., AASHTOWare PONTIS and VIRTIS) were adopted to satisfy DOTs needs such as: the operational requirements, planning and program management, e.g. load rating, permitting and routing. However, those systems do not satisfy the need to coordinate management tasks of all phases of a bridge life cycle i.e. design, construction, operations and program management (Shirolé 2010). Furthermore, they require re-entry and transformation of data, which is a cumbersome, redundant and error prone process. On the other hand, comprehensive asset management solutions such as BrIM could improve the deployment of services and maintenance resources, reduce maintenance costs and increase the quality of services (Zhang et al. 2009). BrIM benefits are being recognised by DOTs and asset owners (Howard and Björk 2008). While the current BMS do not satisfy the need for a more comprehensive solution covering the entire life cycle of a bridge (Shirolé 2010), BrIM can offer an integrated comprehensive solution for life-cycle bridge management (Chen and Shirolé 2006; Chen and Shirolé 2007; Shirole et al. 2009; Shirolé 2010).

Building Information Modeling (BIM) is an emerging technology that has gained increasing popularity among designers and contractors in the civil, architectural, and construction industries. BIM is the development and use of a 3D digital model to simulate and represent the design, construction and operation of a facility. This model is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, where data appropriate for various users’ needs can be extracted and analysed in order to generate useful information for decision makers in a facility and improve the process of delivering a facility (Eastman et al. 2008; AGC 2006). Despite a variety of definitions, the agreement is reached that BIM is a digital representation of a facility. Also, it is widely accepted that BIM is not only a modeling software, but an integrated design and construction process providing a collaboration and communication platform for various parties throughout the project lifecycle (Carmona and Irwin 2007).

Bridge Information Modeling (BrIM) is the specialization of BIM to bridge projects. Other similar terms in the field include Heavy BIM, Horizontal BIM, Virtual Design and Construction (VDC) and 3D Engineered Models for Construction. Heavy civil construction projects such as bridges have unique characteristics compared to a typical building construction project. Various land contour, changing site conditions over the long span of a project, existing infrastructure segments and traffic coordination during construction are some of those unique characteristics that impact the design and construction of a new project (Cylwik and Dwyer 2012). Previous research has highlighted many benefits that can be obtained from implementing BrIM for bridge maintenance and operations. (Shirolé 2010) summarised the benefits that can be obtained from adopting BrIM in bridge management as follows: 1) satisfied data needs at project level; 2) elimination of repetitive manual transcription of data; 3) improved data quality, reliability and speed of bridge inspection; 4) easy access to bridge safety related data so that it can be extracted and updated in an efficient manner; 5) improved communication between inspectors and bridge engineers by providing
virtual models which would eliminate the need for re-inspections and improve well inform the decision makers; and 6) cost effective bridge life cycle management (Shirole et al. 2009). Possible benefits of BrIM for bridge management are acknowledged both in academia and industry. However, its implementation and possible benefits for managing existing bridges is still unclear (Marzouk and Hisham 2011). This paper aims to create a better understanding of bridge inspection needs and how to meet them using BrIM. A novel framework is created and tested with cooperation of Iowa DOT, and then their feedback in addition to other DOTs was recorded.

3 METHODOLOGY

BrIM can be considered a comprehensive bridge management system as it enables managing bridge information from design through maintenance and operation phases. In this paper, a BrIM based bridge inspection workflow is presented. This workflow involves using a mobile device such as a tablet computer that enables inspectors to access an accurate, up to date 3D information model of the bridge via cloud data storage services. This 3D model contains all bridge elements including their maintenance history at object level. This environment allows entering and storing inspection data such as sketch drawings and measurements. The proposed workflow allows direct access to inspection data from home office. This BrIM based inspection workflow is tested with Iowa DOT inspectors and bridge engineers. In addition, a survey with several DOTs was conducted to evaluate the applicability of the proposed framework.

3.1 BrIM enabled inspection framework

This study has taken an existing bridge located on highway US 30 spanning the Skunk River in Ames, Iowa as a case study. Two dimensional (2D) plans and historical inspection data of the bridge were provided by Iowa DOT to the research team in electronic document format. The research team then combined all this data in an intelligent 3D model, i.e. 3D BrIM.

In the traditional way of inspection, a bridge is divided into three groups i.e. deck, super structure and sub-structure. Usually the inspection team divides the main three groups between the team members and each group is inspected using a separate inspection sheet. The other method is doing a loop by starting with one group to the next until they finish. The condition of each element at the time of inspection is documented to the best judgment of the inspector and according to the measurements that are taken from the damaged area, - e.g. in concrete structures, the inspectors look at the integrity of the bridge, specifically corrosion, spalling, concrete cracks and paint cracks. A crack comparator scale is used to measure the width of the crack. Any crack that is at least 1/16 inch wide should be watched. The depth of the crack is not measured, however if rust was found this is taken as an indication that the crack is deep and further inspection is required. Then, the inspection team draws manual sketches to document the size, severity, depth and location using true dimensions of the problem. Finally, the report and the sketches are taken to the office and re-entered again into the BMS to update the current status of the bridge condition. Then bridge engineers do a comparison with the previous inspection, and actions are taken to fix problems, if any existed.

The 3D BrIM model was built by mimicking the traditional way of bridge inspection. Model elements were divided into similar groups such as deck, super structure, sub-structure, channel and piers in order to mimic the traditional bridge inspection method. Each of those categories is downloaded as a separate model to the tablet application, and they can be merged again easily using the 3D modeling software application in the office. Then, each group is given a specific color, and each element is provided with details that are pinned to that element. Those details include previous inspection information with technical details. The BrIM-enabled inspection framework concept, as shown in Figure 1, consists of three major elements; data cloud, mobile devices and home office computer interface. The data cloud can be accessed both from home office and from the site, which enables data sharing with all stakeholders simultaneously. This procedure would help increase the speed of communication and eliminate any re-entry of the inspection data. It would also prevent any possible data loss during data transfer. Having a better representation of the field conditions and instantaneous access to inspection data would enable decision makers to make better informed decisions since they would have a better idea of the problem and direct feedback from other stakeholders such as bridge engineers and inspectors.
3D BrIM models can be downloaded to data cloud from home office where they can be accessed by inspectors in the field. Inspectors then choose an element that has a deficiency and by freezing the model they create an image where they can document the problem and enter all data that is required and upload all the inspection data back to the data cloud (Figure 2). This enables bridge engineers to access the inspection data from home office where they can conduct further analysis.

3.2 DOT Survey

A web-based survey, using the Qualtrics survey tool, was conducted in order to evaluate applicability of BrIM for inspection purposes in other states outside Iowa. The survey was sent out to eight DOTs in the Midwest in addition to New York and Pennsylvania DOTs to obtain their feedback on implementing BrIM.
technology for bridge inspection and maintenance. DOT personnel ranging from bridge engineer to a
director of bureau of structures from eight different DOTs participated in the survey.

The questions varied between open format questions where DOTs personnel provided their feedback,
and closed format questions that varied between Dichotomous questions and Likert questions. The
questions were directed to understand three key aspects; the first one was whether the DOT has any
experience in using BrIM technology and how they are using it. The second one was to find out whether
they are facing any problems with the current bridge inspection practices. Finally, the third one was to
determine the potential of the proposed BrIM based framework for inspections.

The surveyed DOTs acknowledged the benefits of BrIM and showed interest in using it. However, they
expressed several difficulties and challenges they are facing when implementing it during design and
construction phases. Furthermore, most DOTs acknowledged that BrIM would be beneficial for bridge
inspection. The detailed findings of this survey are summarized in Table 1.

4 RESULTS AND DISCUSSION

According to the survey, the number of qualified bridge inspectors range from 10 to 50 among the states
surveyed in this study. This number can reach up to 650 when consultants and freelance inspectors are
included. Typically 2-4 inspectors are required for inspection of a regular bridge. The number of
inspectors can reach up to 7 for inspection of special types of bridges such as over water bridges. The
yearly cost of inspections varies among states as the number of bridges and the size of the states vary.
When asked what means are being used for bridge inspections in the current practice, 71% of
respondents said that they use the paper based method. And the other 29% of the respondents stated
that they are using mobile computing technologies such as Personal Digital Assistant (PDA), tablets and
laptops. About 50% of the surveyed states responded that their DOTs use 3D information models and
information technologies during design and construction of civil projects, and 33% of the respondents
stated that they are using it specifically for bridge design and construction. This result is compatible with
the opinion that states that large asset owners are moving towards more comprehensive tools to manage
their assets (Howard and Björk 2008; Zhang et al. 2009).

The DOTs who participated in this survey recognized BrIM as a beneficial tool for bridge inspections.
However, they are not planning to adopt it in their bridge inspection practices in the near future. The
reason for this maybe the invalidated benefits of BrIM for the inspection process (i.e. BrIM must prove its
ability to improve inspection process over current practices). In this study, while conducting the mock-up
inspection, the time needed for inspecting each element as well as signing and dating the inspection
documents were reduced significantly. This is mainly due to the user friendly sketch drawing and input
recording functionalities of the software.

The surveyed DOTs predict several challenges that maybe faced when implementing BrIM technology for
bridge inspections. One major challenge mentioned by most survey respondents was the concern of
damaging portable electronic devices during the inspection process. They stated that electronic portable
devices used for inspection tasks must be durable in rain, sunshine and extremely cold weather
conditions. And they need to be sturdy enough so that they do not break down if dropped; should be
small enough to fit in inspector’s harness, and large enough for sketching and visualization. This problem
was also stated in the literature (Chen and Kamara 2008; Tsai et al. 2014), and can be overcome as
mobile devices are being improved continuously; e.g. their mobility, durability, hardware compatibility and
battery life being improved constantly to satisfy the needs of construction job environments. Moreover, a
variety of accessories are available to protect tablet computers in harsh outdoor environments.
<table>
<thead>
<tr>
<th>Task</th>
<th>Results</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>Inspection Means</td>
<td>71% paper based</td>
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<td></td>
<td>14% PDA</td>
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<tr>
<td></td>
<td>14% others</td>
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<tr>
<td>Number of Inspectors</td>
<td>15 – 75</td>
<td>The number can reach up to 650 with all qualified consultants</td>
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<td>No. of inspectors in each inspection</td>
<td>2 – 4</td>
<td>Can reach 7 for major over water bridges</td>
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<tr>
<td>BrIM usage in design &amp; construction</td>
<td>33% using it</td>
<td></td>
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<tr>
<td>Challenges in the current practice</td>
<td>60% have challenges</td>
<td>Close observation and management to stay on compliance</td>
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<td>Training inspectors</td>
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<td>Inadequate staff</td>
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<td>Aging staff</td>
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<td></td>
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<td>New problems with new bridge designs.</td>
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<td>Future use of BrIM in inspection</td>
<td>71% denied any future plans</td>
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<tr>
<td>BrIM staff knowledge</td>
<td>62% poor – fair</td>
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<td></td>
<td>13% good</td>
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<td>25% V.Good - Exc</td>
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<tr>
<td>Usefulness of BrIM for inspection</td>
<td>71% neutral</td>
<td>29% sees it as useful</td>
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<td>BrIM Improve the speed and precision of inspection</td>
<td>71% disapproved</td>
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<td>BrIM implementation challenges</td>
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<td>Damaging portable electronic devices</td>
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<td>Cell phone signals</td>
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<td>Sturdy equipment to handle rain, sunshine and extremely cold weather.</td>
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<td>Time invested in creating models</td>
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<td>Digital signatures issues</td>
</tr>
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<td></td>
<td></td>
<td>Integrity of data during transmission.</td>
</tr>
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<td></td>
<td></td>
<td>Confidential information</td>
</tr>
</tbody>
</table>
Another critical challenge mentioned was cell phone signals. There are many bridges located in rural areas where no cell phone service is available. The authors and other researchers (Tsai et al. 2014) suggest an offline BrIM approach to overcome this challenge. An offline BrIM tool for inspection enables downloading all models before arriving to the site. The inspector can record and save all inspection data on the device while offline and upload them to the data cloud when he/she has a wireless connection. This procedure was tested during the mock-up inspection with Iowa DOT inspectors where no cell phone signal was available under the bridge. Another challenge mentioned was related to the initial costs of implementing a new technology, along with the software costs, cost for keeping them up-to-date. In addition, initial investment in time and money to build 3D information models of existing bridges needs to be taken into consideration. The authors suggest that this barrier could be overcome by adapting new technologies into current practices gradually. In addition, case studies from institutions that received benefits from implementing new technologies in their projects would help and encourage other asset owners adopting new tools and technologies into their practices. For example, (Cox et al. 2002) documented that using mobile devices such as PDAs reduce costs and labor time during data collection.

While many DOTs listed lack of resources and initial investment cost as an institutional barrier to implementing BrIM for inspections, others listed human factor as a barrier, such as inspector’s education and training. And some DOTs were concerned about legal issues such as digital signatures of inspectors, integrity of data during transmission and the critical details that must be kept confidential for security purposes.

When asked about the current inspection practices, around 60% of the responses admitted that DOTs are facing many challenges with the current inspection practices. The main challenge is to conduct inspections on time in order to comply with the federal law. Furthermore, challenges in training inspectors, inadequate staff, aging staff and new inspection problems with newer bridge designs were also mentioned. Overall, the current inspection practices challenges DOTs in their bridge management practice as there are problems with effectively processing and integrating inspection data with bridge management databases (Agrawal et al. 2009; Lee et al. 2008; Shirolé 2010).

The surveyed DOTs stated lack of knowledge in using 3D information modelling. On a five level Likert scale ranging from poor to excellent, 62% of surveyed DOTs considered themselves having fair or poor knowledge; while 13% considered themselves as good and 25% ranged between very good and excellent. Finally, 71% of the surveyed DOTs did not think that uploading inspection data to the data cloud directly would increase the speed and precision of the inspection. This might explain the small percentage (28%) of the surveyed DOTs that indicated having future plans for implementing BrIM in their bridge inspection process.

5 CONCLUSIONS

Bridge inspection is considered a time consuming and redundant task in the traditional way. Errors are likely to occur depending on the way the inspection is conducted and based on the inspector’s experience and personal judgment. This study shows the possibility of extending the benefits of BrIM technology for bridge inspections. DOTs are recognizing the benefits of BrIM as a comprehensive solution for managing their bridge assets. BrIM based inspection would help eliminate redundant data collection, data re-entry, and minimize possible errors that may result from inspector’s personal judgment or limited experience. It would also help reduce errors and improve overall inspection quality and safety by reducing the time needed for inspection. Furthermore, it can also help reduce the time needed for each inspection by improving the way sketches are drawn on site, as well as reducing the time needed for signing and dating each inspection paper. Bringing mobile devices and BrIM to the bridge management practice is applicable. However, its sought benefits need to be validated for its adoption. For future research, the research team would recommend validating the benefits of BrIM for bridge management through several case studies.
Acknowledgements

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GUIDELINE TO APPLY HEDGING TO MITIGATE THE RISK OF CONSTRUCTION MATERIALS PRICE ESCALATION

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Abstract: Accurately forecasting cost is vital to the success of any construction project. Cost estimation encompasses uncertainty, since construction projects are exposed to many forms and degrees of risk. Materials price volatility and shocks constitute one aspect. Most current approaches for material risk assessment are deterministic and do not take into consideration material price fluctuation. The application of hedging, to mitigate the risk of construction material price fluctuations, is proposed in this research. Although it is known that using hedging as a risk management tool adds value to a financial firm, limited knowledge has been established about using hedging for construction material price risk mitigation. Hedging has also been a practice applied in the airline industry for a long time, and substantive research has been completed in the field of airline fuel hedging. The objective of this research is to identify best practices in the area of airline fuel hedging to provide an outline for implementation in the construction industry, and to develop a step-by-step guideline to applying materials hedging in the construction industry. This is considered to be the first attempt to match construction material hedging with the airline fuel hedging application. The guideline presented herein helps construction companies to apply hedging to mitigate the risk of construction material price fluctuations. This guideline improves construction companies’ ability to submit a very competitive bid on a specific project.

1 INTRODUCTION

Cost estimation is considered to be one of the most important tasks in the development of a construction project budget. However, due to the possibility of material price fluctuation, cost estimation is usually uncertain. Construction materials may encompass 50-60% of the total cost of a project if combined with other services such as equipment (Spillane 2011). When left unmanaged, materials may have a greater significant impact on total project cost fluctuation. Materials price uncertainties are extensive throughout the project lifecycle, occurring at project initiation and continuing until termination. Fluctuations of materials’ prices, which are volatile, are a driver of project costs. The engineering and construction (E&C) industry has tried to address materials risk through numerous approaches. Most current approaches for material risk assessment are deterministic, which means that they treat variables such as price as if they were fixed. However, in reality, material prices fluctuate up and down (EUFRA M 2014). Indemnification and insurance provisions are the primary risk mitigation devices in any construction contract. These provisions obligate the party with less bargaining power to insure the other against certain risks. These provisions could help the two parties allocate materials risk and other risks contractually (Thomas 2014). However, they cannot address unforeseen circumstances that can affect materials pricing (i.e., the 1973 oil embargo). Current approaches for material risk assessment do not reflect price volatility issues. The construction industry has been slow to realize the potential benefits of new methods in risk management.
Although it is known that using hedging as a risk management tool adds value to a financial firm (Marsden and Prevost 2005), limited knowledge has been established about using hedging for construction material price risk mitigation. Macdonald (2013) first suggested using hedging as a tool to mitigate material price risk. In her research, Macdonald provided an overview of the construction industry need, and introduced the problem of materials price risk mitigation in construction projects. Hedging has been the practice in the airline industry for a long time, and substantive research has been found in the field of airline fuel hedging. Identifying best practices in the area of airline fuel hedging, then applying it in the construction industry, could save time and eliminate trial and error process improvements. The objective of this research is to develop a step-by-step guideline to apply hedging to mitigate the risk of materials price in construction projects.

2 METHODOLOGY

The first step of this research was conducting a literature review to reveal what is already known in the body of knowledge about hedging practice in the airline industry and the construction industry. The literature search revealed that there is a gap in the body of knowledge about using materials hedging in the construction industry. This research is an attempt to fill this gap. The second step of this research was collecting and identifying the best hedging techniques in the airlines industry. A best practice refers to a way that has constantly shown results superior to those achieved with other means, and that is used as a benchmark (Stevenson 1996). This research considered qualitative and quantitative criteria to identify best practices in the area of airline fuel hedging. The quantitative criteria looked for the hedging practice that consistently showed the pursued results. This means that the practice has been used for a long time, and each time the practice has been used, it gave the same result. The qualitative criteria looked for the practices that had a direct or immediate effect on the results. This means that the practice had a direct relationship with the result. For example, if a company uses only swaps as a hedging technique, and the hedging was successful, then the swaps technique has a direct relationship with the result. The hedging practice should meet both criteria to consider it as a best practice. Figure 1 shows the process to identify best practices using the quantitative and qualitative criteria.

Eight primary research articles has been identified to meet the quantitative aspect, and one research article has been identified to meet the qualitative aspect. The third step was investigating the possibility of applying the knowledge collected from step two to create a guidance to help construction companies apply material hedging successfully. The researcher utilized the traditional risk analysis process to develop the guideline presented in this research. The final step was drawing conclusion and providing recommendation for future research direction.

3 NATURE OF FINANCIAL HEDGING

A hedge is an investment position projected to offset potential losses that may be incurred by a companion investment (Mattus 2005). Derivatives are financial instruments used in the hedging process.
They are contracts whose value is derived from one or more variables called underlying assets (i.e., fuel). Forward, future, option and swap are examples of derivatives contracts. Both forward and future contracts are an arrangement to buy or sell something at a future date at a fix price. Contrasting with forward contracts, futures contracts trade on central exchanges, called future markets (Morrell and Swan 2006). Another type of derivative is called an option. Options are of two types: calls and puts. Options give the buyer the right, but not the obligation, to buy or sell a certain quantity of the underlying asset, at an agreed price on or before a certain future date (Morrell and Swan 2006). The last type of derivative is called a swap. Swaps are private arrangements to exchange cash flows in the future according to an agreed formula (Morrell and Swan 2006). Hedging derivatives and their integration make up the major part of an oil company's operations in the worldwide oil market (Mattus 2005).

4 FUEL HEDGING IN THE AIRLINE INDUSTRY

Based on a survey of the relevant literature, eight primary research articles provided the level of detail to indicate best practices in airlines industry. Mercatus Energy Advisors (an independent energy trading, marketing and risk management advisory firm) conducted a survey of executives at 24 global airlines. Participants in the Mercatus (2014) survey stated that they are currently and/or have previously utilized various hedging instruments and structures. However, the majority of these airlines are utilizing fixed price swaps, call options, and collar options, which tend to be the favored hedging instruments of the industry. According to Mercatus (2014), only 3% of the companies use futures while 39% use swaps. Also, 29% of the companies use call option and 26% use collar option while 3% use forwards. Carter, Rogers, and Simkins (2006) conducted a similar study on the airline industry and they arrived at the same result as Mercatus (2014). Carter, Rogers, and Simkins (2006) stated that the call option is used primarily by airlines, since it protects them from any fuel price increase.

Options are more flexible than futures, giving the holders the ability to protect themselves against undesired price movements, while at the same time giving them the chance to participate in favorable movements. However, in order to hedge their exposure to fuel prices, airlines have more recently moved to use blends of a call and a put option called a collar (Carter et al. 2006). The call option protects the holder from price rising higher than its strike price (the price at which the contract can be exercised). The holder of this call option also writes a put option to limit any possible gain if the price decreases below its strike price (Carter et al. 2006). The total cost of taking the two options is the difference between the call option premium paid and the put option premium received. This is popular with airlines because it fixes the price for fuel between two identified values.

Carter, Rogers, and Simkins (2006) stated that a swap is often considered the "most favorite" hedging strategy for airlines. The airline would buy a swap for a period of one year at a fixed strike price for a stated amount of jet fuel per month. The average price for that month is then compared with the strike price. If the average price is larger than the strike price, the counter-party (which is a bank) would pay the airline an amount equal to the difference between the average price and the strike price times the amount of fuel (Carter et al. 2006). However, if the average price were lower than the strike price, then the airline would pay the difference. A third study is done by Gerner and Ronn (2013). They backed up the results of both Mercatus (2014) and Carter, Rogers, and Simkins (2006). Gerner and Ronn (2013) stated that most airline companies use call options to provide insurance against sudden upward price shocks. Also, buying a jet fuel swap allows airlines to hedge their exposure to jet fuel prices fluctuation. If the price of fuel goes up, the gain on the fuel swap offsets the increase in fuel cost (Gerner and Ronn 2013). On the other hand, if the price of fuel declines, the loss on the fuel swap offsets the decrease in fuel cost. Either way, once the swap is executed, the airline has locked in their fuel cost (Gerner and Ronn 2013).

According to Scott Topping, Director of Corporate Finance for Southwest Airlines, “the majority of airlines depend on plain vanilla instruments to hedge their fuel costs, including swaps, call options and collars” (Carter et al. 2004). This is consistent with the argument of the first three articles above. Cobbs and Wolf (2014) state that “the most frequently used hedging contracts by airlines are: swap contracts (including plain vanilla, differential, and basis swaps), call options (including caps), collars (including zero-cost and premium collars)”. Further, Lim and Hong (2014) state that futures are used by some airlines, but most airlines today use primarily swaps and call options to hedge their jet fuel price risk. Westbrooks (2005)
supports this argument and he state that most airlines use hedges to some extent to limit their fuel risk. This has been done mostly by utilizing swaps, call options, and collar options.

Carter, Rogers, and Simkins conducted an earlier study in (2002) investigating the fuel hedging performance of 27 firms in the U.S. airline industry during 1994-2001. They found a positive relation between using call options and swaps as hedging tools and value increases in capital investment (Carter et al. 2002). These eight articles identified call options, collar options, and swaps as the best practice for fuel hedging application in the airlines industry. One of these articles found a positive relation between using these hedging tools and capital value increases. As a result, call options, collar options, and swaps meet this research’s quantitative and qualitative criteria for best practice since they are the primary derivatives that are used by airlines and they have a positive relation with airlines companies value increase. The fuel hedging process includes nine steps as shown in Figure 2. First, the airline industry identifies all energy-related risks including market, credit and regulatory risks. These risks can be investigated using quantitative or qualitative analysis. Next, an energy risk management policy can then be established to formalize the goals, objectives and risk tolerance, and to determine who executes the hedging policy. A hedging committee is the preferred choice for the airline industry to make hedging decision (Mercatus 2014). The responsible party should determine three main values:

- The strike value, or the value of the jet-fuel at which the contract starts to pay out.
- The tick value, or the payout amount for $ increment change in a gallon of jet fuel price beyond the strike value.
- The maximum financial payout of the contract that need to be purchase.

Once the previous steps are in place, then the execution of hedging and trading strategies can begin. Airline companies ask financial institutions and fuel suppliers to provide them with hedging advice, data, and information. Then, the airline company purchases hedging contracts that fit their need. The
preferred types of contract are options and swaps. These contracts are traded Over-The-Counter (OTC). OTC derivatives are traded directly between the airlines and banks, and as such have counter-party risk that must be taking into consideration (Gerner and Ronn 2013). Hedges should be constantly examined to determine if they fit within the company’s goals and management policy. The positions should be enhanced when possible. As the company’s risk exposure changes, there should be an efficient process for reporting and determining if the hedging policies need to be modified or if the existing policy and strategies are correct. A call option protects the airline company from fuel price increase. As suggested by Gerner and Ronn (2013), an example of a call option for an airline is shown in Table 1.

Table 1: Call option for an airline company

<table>
<thead>
<tr>
<th>Terms</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage Period</td>
<td>from Jan 1 to June 30</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Jet Fuel</td>
</tr>
<tr>
<td>Strike Value</td>
<td>$5 per gallon</td>
</tr>
<tr>
<td>Tick Value</td>
<td>$1,000,000 per 10 cent increase per gallon</td>
</tr>
<tr>
<td>Maximum Payment</td>
<td>$5,000,000</td>
</tr>
</tbody>
</table>

In this example, the option seller would pay the airline company $1,000,000 per 10 cent in excess of $5 per gallon of jet fuel, up to a maximum payment of $5,000,000. Figure 1 shows the airline hedging process steps.

5 CONSTRUCTION MATERIALS HEDGING PROCESS

Based upon investigation of airlines fuel hedging practices, this research provides construction companies with a step-by-step guidance to apply material price hedging successfully. These steps are based on the knowledge collected from the fuel hedging application in the airline industry. As shown in Figure 3, these steps are: identify and analyze risks; determine tolerance for risk; develop hedging management policy; develop hedging execution strategies; implementation, monitoring, analyzing and reporting risk; and, finally repeat the process.

![Figure 3: The seven step guideline for construction material hedging application](image-url)
5.1 Identify and Analyze Risks

The fuel hedging process start with identifying all risks related to hedging. The construction company can apply this step during the bid process. Before bidding, the construction company estimates the cost of material needed using a cost index. That leads to an understanding of the impact of the material price fluctuation on the company profit by projecting cash flow requirements in the event that material prices significantly exceed norms. During this step, the exact type of materials that affects the company should be identified and looked at in monetary terms (i.e., price fluctuation of one ton of steel).

5.2 Determine Tolerance for Risk

The fuel hedging process mentioned determining tolerance as an important step in hedging process. Once relevant material variables have been identified, analysis of the price volatility of this material should be done to decide at what point price volatility become unacceptable for the company. Consideration of any schedule penalties (i.e., late delivery of the project), as identified in the project contract, will be incorporated into this step.

5.3 Develop Hedging Management Policy

Hedging management policy should be developed to clearly describe the decision-making process and define who (individuals and/or committees) executes the hedging and related activities. The fuel hedging process mentioned clearly the importance of determine who is responsible for hedging decisions. Based on the knowledge collected from airline fuel hedging, creating a dedicated hedging committee is the best choice for making the hedging decisions for the construction industry.

5.4 Develop Hedging Execution Strategies

Execution strategies are the process for implementing the hedging strategies, and complying with hedging management policy. For example, the execution strategies determine which hedging and trading instruments should be used to meet the targeted hedge objectives. Based on the fuel hedging application in the airline industry, the best trading instruments are swaps and options (i.e., call, put, or collar options).

5.5 Implementation

The airline fuel hedging application shows that the primary market trade for derivatives is Over-The-Counter. OTC securities are unlisted so there is no central exchange for the market. The first step a construction company must make before they can trade in OTC securities is to open a hedging account with a broker. After the company places the market order with the broker, the broker must now contact the material supplier. The material supplier then will quote the broker the ask price that the material supplier is willing to sell the security at. If the construction company accept the price quoted, the broker will transfer the necessary funds to the material supplier’s account and is then credited with the respective securities. It is important to address the following four points during the implementation process:

- At what point do material price volatility become intolerable (the strike value or the value of the construction materials at which the contract starts to pay out);
- What is the incremental cost to your company for each $ increase per ton/lb of the material (this is the tick value);
- What is the worst possible case (the maximum financial payout of the contract);
- What is the duration of the hedging instrument that fits the company need (short-term, mid-term or long-term)?

A hypothetical example of a call option for a construction company is shown in Table 2.
Table 2: Call option for a construction company

<table>
<thead>
<tr>
<th>Terms</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage Period</td>
<td>The life of the project (or a phase of the project)</td>
</tr>
<tr>
<td>Index</td>
<td>Average price of 1 ton of steel</td>
</tr>
<tr>
<td>Strike Value</td>
<td>$800 per ton of steel</td>
</tr>
<tr>
<td>Tick Size</td>
<td>$100 /Ton</td>
</tr>
<tr>
<td>Limit</td>
<td>$500,000 (for 5,000 ton of steel)</td>
</tr>
<tr>
<td>Premium</td>
<td>$50,000</td>
</tr>
</tbody>
</table>

When the steel price hits $800 per ton, the hedging contract begins to pay off $100 per ton, up to a maximum value of $500,000. The strike value, tick value, and maximum payment can all be changed to meet the company's preferred risk coverage. Companies should take into consideration that the price of a material risk hedging contract to protect against financial loss depends on the likelihood of a contract payout. If the probability of certain material price volatility is low, so will the cost of the contract.

5.1 5.6 Monitoring, Analyzing and Reporting Risk

Reporting and deciding if the hedging policies or strategies need to change is one of the process steps to apply fuel hedging. Similarly, materials risks should be continuously monitored, measured and reported. As the company's risk exposure changes, there should be a methodical process for reporting and determining if the existing policy and strategies are correct. Also, hedges should be modified when market conditions change, as noted in the next section.

5.2 5.7 Feedback Loop

Continuous revision to the entire process of material hedging is necessary, because the material price could be affected easily by a variety of factors (i.e., regulatory change, world political and economical stability). Changes in material price may then have a subsequent effect on the initial steps of the process. Further, these derivatives may be initiated for varying short-term, mid-term and long-term durations throughout the project.

6 RESULT

This research identified best practices in the area of airline fuel hedging, and discussed how these best practices can be applied to the construction industry. The identification of fuel hedging best practices provided a general outline for material hedging application. This research used the analysis of the fuel hedging process in the airline industry to develop a seven step guideline for the construction material hedging application. These steps are: identify and analyze risks; determine tolerance for risk; develop hedging management policy; develop hedging execution strategies; implementation, monitoring, analyzing and reporting risk; and, finally repeat the process.

The research concludes that applying material hedging in the construction industry could be very useful and should not be overlooked by construction companies. The guideline presented by this research helps construction companies to apply hedging to mitigate the risk of construction materials price fluctuations. This guideline could improve the ability of construction companies to submit a low price bid on a specific project.

Future work in this area could include the investigation of material hedging cost to determine if the hedging application is feasible. This is very important and could be added to the tolerance phase of this guideline to help the company decide if material hedging is economical for them. Further research could be done to investigate the best way to settle the hedging contract. This could be done by simulating different scenarios of hedging situation. Different scenarios could generate different settlement options such as moving out from the hedge early or keep the hedge contract until its due date.
References


DISCOVERING THE VALUES OF RESIDENTIAL BUILDING OCCUPANTS FOR VALUE-SENSITIVE IMPROVEMENT OF BUILDING ENERGY EFFICIENCY

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Abstract: Improving building energy efficiency is one of the best strategies to reduce building energy consumption. Recent studies emphasized the importance of occupant behavior as key means of enhancing building energy efficiency. It is critical that while we strive to improve the energy efficiency of buildings through the understanding of energy use behavior that we also understand the values (such as thermal comfort, indoor air quality, productivity) of building occupants, how these values may impact energy use behavior, and how we can improve energy efficiency without negatively impacting these values (i.e., while maintaining the satisfaction levels with these values). This paper focuses on presenting the authors work in (1) identifying potential occupant values that may impact energy use behavior and energy consumption in residential buildings, (2) discovering actual building occupant values and the importance levels of these values to residential building occupants, and (3) discovering the current satisfaction levels of residential building occupants with these values. The discovery of actual occupant values and current satisfaction levels was conducted using an online survey. A randomly selected set of 310 residential building occupants in Arizona (AZ), Illinois (IL), and Pennsylvania (PA) were surveyed using an online questionnaire. The paper discusses the value discovery, questionnaire design, survey results, results analysis, and conclusions. The results showed similarities and differences across occupants in AZ, IL, and PA in terms of what they value in buildings as well as their current satisfaction levels with these values.

1 INTRODUCTION

Residential and commercial buildings consume 40% of the primary energy and contribute 30% of the annual greenhouse gas emissions. The production and consumption of non-renewable energy, including oil and natural gas, pose adverse environmental impacts on the ecosystem in terms of air pollution and global warming. Enhancing building energy efficiency is one of the most effective ways of reducing both energy consumption and CO$_2$ emissions (Becerik-Gerber et al. 2013).

Recent studies emphasized the importance of occupant behavior as key means of enhancing building energy efficiency. For instance, a two week study revealed that dormitory occupants reduced their consumption by 31% when they received weekly energy consumption data and by 55% when they received real time energy consumption data (Petersen et al. 2007). Similarly, a short-term study compared the energy consumption of four groups: (1) control group, (2) a group of occupants that had access to their past and present individual energy consumption data, (3) a group of occupants that had
access to their past and present individual energy consumption data, in addition to average energy consumption data of all occupants in the building, and (4) a group of occupants that had access to their past and present individual energy consumption data, average energy consumption data of all occupants, and individual energy consumption data of other occupants. The results showed that the fourth group made the most significant saving (Peschiera et al. 2010).

It is critical that while we strive to improve the energy efficiency of buildings through the understanding of energy use behavior that we also understand the values (such as thermal comfort, indoor air quality, productivity) of building occupants, how these values may impact energy use behavior, and how we can improve energy efficiency without negatively impacting these values (i.e., while maintaining the satisfaction levels with these values). On one hand, values impact energy use behavior. “Values influence behavior because people emulate the conduct they hold valuable” (Boundless 2014). On the other hand, people spend the majority of their time in buildings, and therefore it is essential that while we aim to reduce building energy consumption that we also satisfy their values (Frontczak and Wargocki 2011). A number of important research efforts (e.g., Klein et al. 2012; Yang and Becerik-Gerber 2014; Gao and Whitehouse 2009; Dong et al. 2011; Agarwal et al. 2010; Mohammadi et al. 2007) primarily focused on reducing energy consumption of buildings by utilizing occupancy information. More focus is needed on understanding the interdependency between occupant values and energy consumption.

In this paper, the authors focus on (1) identifying potential occupant values that may impact energy use behavior and energy consumption in residential buildings, (2) discovering actual building occupant values and the importance levels of these values to residential building occupants, and (3) discovering the current satisfaction levels of residential building occupant with these values. The paper also compares importance ratings of values and satisfaction levels with the values across occupants in AZ, IL, and PA.

2 OCCUPANT VALUE DISCOVERY

In the context of building energy efficiency, a comprehensive literature review was conducted to identify all potential values that could be related to energy use behavior and energy consumption. As a result, three main categories of values were identified: (1) values that may impact energy use behavior and energy consumption level (thermal comfort, lighting/visual comfort, and indoor air quality), (2) values that may be impacted by the set of values in the first category (health and personal productivity), and (3) values that may motivate enhanced energy use behavior towards reduced energy consumption (environmental protection and energy cost saving).

Thermal comfort is “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE 2010). There are six primary factors that determine thermal comfort conditions: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity (ASHRAE 2010). Among these factors, metabolic rate depends on a number of subfactors such as activity level, gender, and health conditions (Maiti 2014). Clothing insulation varies by occupant clothing type. Air temperature, radiant temperature, air speed, and humidity, on the other hand, are highly dependent on the settings and parameters of the HVAC system of buildings, which in turn may impact energy consumption.

Visual comfort is defined as “a subjective condition of visual well-being induced by the visual environment” (EN 2002). Visual comfort or discomfort is impacted by luminance distribution, illuminance and its uniformity, glare, color of light, color rendering, flicker rate, and amount of daylight (EN 2002). Illuminance is the factor which associates visual comfort with energy consumption.

Indoor air quality (IAQ) is “a term referring to the air quality within and around buildings and structures” (EPA 2014). The amounts of indoor pollutants and of ventilation are the major factors that impact IAQ. Building materials, combustion sources (wood, coal, oil etc.), cleaning products, tobacco, and air pollutants entering from outdoor space are main causes of indoor pollutants (EPA 2014). On the other hand, the amount of ventilation is determined by the amount of air that enters the building. Poor IAQ is seen as the primary environmental health risk by EPA (2014). In order to maintain good IAQ to building occupants, the amount of pollutants should be controlled and a proper amount of ventilation should be provided (EPA 2014). While controlling the amount of pollutants can be achieved by improving occupant
behavior and eliminating the causes of pollutants, the amount of ventilation is highly dependent on the building ventilation system which may consume energy. Health and personal productivity are the values that may be impacted by the set of values in the first category. With the majority of people spending about 90% of their time indoors, the impact of thermal comfort, visual comfort, and IAQ on occupant health and productivity has been emphasized in recent years (EPA 2014). Good thermal comfort, visual comfort, and IAQ are linked to decreased number of illnesses and sick building syndrome symptoms and enhanced productivity.

Environmental protection and energy cost saving are values that may motivate enhanced energy use behavior towards reduced energy consumption. Energy consumption is associated with both environmental impacts and cost. Residential buildings account for 20.8% of the US total CO₂ emissions (EPA 2009) and residential building occupants spent 2.7% of their household income for home energy bills in 2012 (EIA 2013). The role of energy consumption behavior in reducing energy consumption, and in turn environmental protection and energy cost saving, is vital. EIA estimates a 50% increase in energy demand caused primarily by buildings by 2050, and highlights that this increase can be capped to 10% without any sacrifice in the comfort of building occupants, if necessary improvements in energy use behavior and energy efficiency can be achieved (2013).

3 RESEARCH METHODOLOGY

A questionnaire survey was conducted to solicit the input of a randomly selected set of residential building occupants in Arizona (AZ), Illinois (IL), and Pennsylvania (PA) on (1) the importance levels of occupant values and (2) the current satisfaction levels with these values. The scope of the energy studies are focused on IL and PA. AZ was additionally selected to capture potential variability in responses as a result of a different climate, which provides an opportunity of investigating the impact of climate on occupant values and satisfaction levels with the values. According to the Köppen-Geiger climate classification, IL and PA have a humid continental (warm summer) climate (Dfa), whereas AZ has a desert climate (Bwh). The research methodology was composed of four main research tasks: (1) questionnaire design, (2) questionnaire validation, (3) survey implementation, and (4) survey results analysis. Further details on the research methodology is provided in the following section.

4 SURVEY OF ENERGY-RELATED VALUES AND SATISFACTION LEVELS

4.1 Questionnaire Design, Validation, and Implementation

The questionnaire was composed of four sections. Section 1 included two filtering questions that were asked to verify eligibility of participation in terms of occupancy type and residency state (i.e., occupancy of a residential building and residency in AZ, IL, or PA). Responses which failed to pass Section 1 were disregarded. In Section 2, respondents were asked to rate the importance levels of occupant values to them on a 6-point Likert scale (very unimportant, unimportant, moderately unimportant, moderately important, important, very important). Section 3 was composed of three questions, all which aimed at soliciting the satisfaction levels with the values. Question 1 directly asked respondents to rate their satisfaction levels with the values on a scale of 1 to 6 (very dissatisfied, dissatisfied, moderately dissatisfied, satisfied, very satisfied): thermal comfort in winter, thermal comfort in summer, visual comfort, IAQ, energy cost saving, and environmental protection. Because both productivity and health are values which may be impacted by the values in the first category (i.e., thermal comfort, visual comfort, IAQ), Question 2 and 3 aimed at assessing satisfaction levels with productivity and health through quantifying the changes in productivity and health caused by the values in the first category. Using a 9-point scale (40% or more, 30%, 20%, 10% decrease, no effect, 10%, 20%, 30%, 40% or more increase), Question 2 asked respondents to rate how they think their personal productivity or level of activity at home is decreased or increased by the current indoor environmental conditions (temperature, lighting, IAQ) at home. Using the same 9-point scale, Question 3 asked respondents to rate how they think their perceived health is decreased or increased by the current IAQ at home. Section 4, included a set of background questions about the characteristics of the occupants, the frequency of
experiencing some health symptoms such as headaches, the characteristics of the building including energy efficiency features and level of occupant control of the building system, the level of energy cost and consumption data given to occupants, and the behavior of occupants to control the indoor environmental conditions such as opening windows.

Prior to launching the survey, a pilot study on fifteen building occupants was conducted to test the effectiveness and clarity of the questionnaire. Participants were requested to complete the survey and, then, to provide feedback on the format and content of the questionnaire. Feedback was solicited on different aspects of the questionnaire, such as question wording, response options and evaluation scale, instructions to respondents, visual appearance, and clarity of value concepts. The questionnaire was revised based on the feedback. For instance, the scale of some questions were modified in order to improve clarity.

The survey was conducted from October to November 2014. Potential respondents were recruited by Qualtrics, a provider of online panels (potential respondents). Panels were generated using samples from various database and were verified to prevent any fraudulent or duplicate respondents (ESOMAR 2014). Qualtrics hosted the survey and sent emails to potential respondents inviting them to complete the survey, for research purposes, in return for incentives. Two response quality filters were used: (1) an attention filter question and (2) a minimum survey completion time of two minutes. Responses that failed to pass these two filters were disregarded.

4.2 Survey Results and Analysis

The analysis of the survey results aimed at answering the following research questions:

- What are the ratings of the values by residential building occupants in AZ, IL, and PA?
- What are the rankings of the values by residential building occupants in AZ, IL, and PA?
- What are the satisfaction levels of residential building occupants with the values in AZ, IL, and PA?

Three statistical analysis methods were utilized to address the above research questions: (1) mean indexing, (2) Kendall’s coefficient of concordance, and (3) Kruskal-Wallis H Test. Mean indexing was used to determine the mean ratings of values. Kendall’s coefficient of concordance was computed to examine whether there was a significant agreement in the ranking among occupants across the three states. Kruskal-Wallis H test was conducted to identify whether specific values were rated differently across occupants in the three states. The Statistical Package for Social Sciences (SPSS) version 20.0 was used to conduct these statistical analyses.

4.2.1 Classification of Respondents

A total of 310 valid responses were collected. Qualtrics identified approximately 4,800 potential respondents and invited them via email. A total of 381 responses (including invalid responses) were received, representing a response rate of 8%. This is consistent with the reported response rates for online panels (Neslin et al. 2009). This sample size is statistically significant with 95% confidence level and 10 confidence interval. Responses were classified into three subgroups by state: AZ, IL, and PA. The descriptive statistics of the three subgroups are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Arizona</th>
<th>Illinois</th>
<th>Pennsylvania</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Participants</td>
<td>123</td>
<td>119</td>
<td>129</td>
<td>371</td>
</tr>
<tr>
<td>Number of Valid Responses</td>
<td>104</td>
<td>102</td>
<td>104</td>
<td>310</td>
</tr>
<tr>
<td>Response Rate</td>
<td>8%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2.2 Reliability of Survey Questions

In order to validate the internal consistency of the data, prior to data analysis, a Cronbach’s alpha reliability analysis was conducted. Internal consistency indicates the extent to which all the items in a test measure the same concept. Alpha values greater than 0.7 indicate adequacy of internal consistency (Tavakol and Dennick 2011). The overall Cronbach’s alpha values for the survey is 0.883, which indicates a high level of reliability.

4.2.3 Occupant Ratings and Rankings of Values

The rating frequencies of the values by occupants is shown in Figure 1. Overall and across the three states the majority of occupants rated the seven values as “moderately important” or higher. Health is the most important value; 93.9% of the occupants rated health moderately important or higher. Indoor air quality, energy cost saving, personal productivity, thermal comfort, visual comfort, and environmental protection, respectively, are at least moderately important to 92%, 91.6%, 91.6, 90%, 89.7%, and 85.8% of the occupants.

![Figure 1: Importance of values to residential building occupants in AZ, IL, and PA](image-url)
Table 2 and Figure 2 show the mean ratings and rankings of the values by occupants overall, in AZ, in IL, and in PA, and a comparison of the mean ratings of the values across these three states, respectively. As shown in the Table 2, all mean scores are higher than 4.00, which indicates that on average, occupants give importance to all seven values. On average, health was ranked highest among the values – overall, and across the three states, which indicates that occupants of residential buildings, across AZ, IL, and PA, valued health the most among the seven values. Previous studies are partially supportive of the survey results. For example, Zalejska-Jonsson and Wilhelmsson (2013) conducted an empirical study on residential building (single houses and apartment buildings) occupants in Sweden and investigated the importance of three values – IAQ, thermal comfort, and sound quality – through quantifying their impact on the overall satisfaction of occupants. The results showed that IAQ is the most important value, whereas sound quality is the least important value. On the contrary, however, Lai et al. (2009) conducted a study on residential apartment occupants in Hong Kong and found thermal and acoustic comfort as the most important and IAQ as the least important.

Table 2: Mean ratings and rankings of values across AZ, IL, and PA

<table>
<thead>
<tr>
<th></th>
<th>Health</th>
<th>Energy Cost Saving</th>
<th>Indoor Air Quality</th>
<th>Thermal Comfort</th>
<th>Personal Productivity</th>
<th>Visual Comfort</th>
<th>Environmental Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>Mean rating</td>
<td>5.28</td>
<td>5.07</td>
<td>5</td>
<td>4.95</td>
<td>4.83</td>
<td>4.8</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>AZ</td>
<td>Mean rating</td>
<td>5.18</td>
<td>5.07</td>
<td>4.96</td>
<td>4.84</td>
<td>4.77</td>
<td>4.73</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>IL</td>
<td>Mean rating</td>
<td>5.37</td>
<td>5.08</td>
<td>5.08</td>
<td>5.02</td>
<td>4.88</td>
<td>4.9</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>PA</td>
<td>Mean rating</td>
<td>5.3</td>
<td>5.06</td>
<td>4.96</td>
<td>4.98</td>
<td>4.84</td>
<td>4.76</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

Kendall’s coefficient of concordance (Kendall’s W) was computed to examine whether there is a significant agreement on the ranking among occupants across the three states. The results of the test were interpreted based on the W value and the significance level of the test. If Kendall’s W is 1 there is a complete agreement and if it is 0 there is no agreement at all, with the result being significant if the significant level is less than 0.05 (Kendall and Gibbons 1990). Kendall’s W value is 0.96 (p<0.05), which indicates that there is a significant high agreement on the ranking of values among occupants across the three states.
4.2.4 Occupant Satisfaction with Values

Figure 3 and Figure 4 show the rating frequencies of satisfaction levels of occupants with the values and the impact of indoor environments on their perceived personal productivity and health, respectively. Overall, on average, occupants rated their satisfaction with energy cost saving, IAQ, thermal comfort (in summer and winter), visual comfort, and environmental protection as “moderately satisfied” or higher, but a considerable percentage of occupants rated their satisfaction with the values as “moderately unsatisfied” or lower. For example, 19.7% of the occupants are “moderately unsatisfied” or lower with energy cost saving, which is the least satisfied value. Environmental protection, thermal comfort in summer, thermal comfort in winter, IAQ, and visual comfort are rated by 15.8%, 15.5%, 13.9%, 11.6%, and 11.2% of the occupants as “moderately unsatisfied” or lower, respectively. For health and personal productivity, 27.8% and 24.8% of the occupants believe that the current indoor environment conditions have a negative effect on their health and perceived personal productivity, respectively. This is consistent with the findings of a recent study (Zalejska-Jonsson and Wilhelmsson 2013), which found that a considerable percentage of occupants are dissatisfied or very dissatisfied with their indoor environmental quality.

![Satisfaction levels of occupants with the values across AZ, IL, and PA](image)

Figure 3: Satisfaction levels of occupants with the values across AZ, IL, and PA
Figure 4: Reported impact of indoor environmental conditions on health and perceived personal productivity of occupants

The difference in the satisfaction levels across the three states was examined using Kruskal Wallis-H test which is the non-parametric version of one way analysis of variance. The results show a significant difference, across the three states, in the satisfaction levels occupants with thermal comfort in winter. Occupants in AZ are more satisfied with thermal comfort in winter, than those in IL and PA. In order to identify where the differences between the groups lie, a post-hoc pairwise comparison test was conducted. The test shows that occupants in AZ are more satisfied with thermal comfort in winter than those in PA. This difference could be explained by the different weather characteristics of the two states. Other than that, there was no significant difference in the rating of satisfaction levels among occupants across the three states. Similarly, across the three states, there was no significant difference among occupants in the impact of indoor environmental conditions on their health and perceived personal productivity.

5 CONCLUSION AND FUTURE WORK

This paper presents an empirical study to discover energy-related values of building occupants. Seven energy-related values were identified and classified into three main categories: thermal comfort, lighting/visual comfort, indoor air quality, health, personal productivity, environmental protection, and energy cost saving. The importance of these values to occupants and the satisfaction levels of occupants with these values were then investigated using a questionnaire survey. The survey focused on residential building occupants in AZ, IL, and PA. The results show that residential building occupants in AZ, IL, and PA value all seven values. On average, health was ranked highest among the values – overall and across the three states. The results also show that there is a significant agreement on the ranking of values by occupants across the three states. The ratings of the satisfaction levels with the values show that a considerable percentage of occupants (11.2% to 19.7%) are unsatisfied with the fulfillment of their values, with 27.8% and 24.8% of the occupants thinking that the current indoor environmental conditions have a negative effect on their health and personal productivity. The survey results also show that there is a significant difference in the satisfaction levels with thermal comfort in winter across AZ and PA.
In their future/ongoing research, the authors will focus on three main areas: (1) developing a semantic data sensing system (including sensors and algorithms) for automatically measuring and monitoring energy consumption, indoor climate and lighting, plug loads, and occupant location, and interactively measuring and monitoring energy use behavior (e.g., energy use patterns in terms of use of plug loads, lighting, cooling, etc.) and satisfaction with occupant values; (2) developing a semantic (computer-understandable and meaning-rich) context-aware model for representing and reasoning about the sensed data and user values and deriving contextual information about the interrelationships between user values, energy use behavior, and energy consumption to analyze human values and actions and how they impact energy usage; and (3) developing hybrid semantic and machine-learning (ML) data analysis models and algorithms for analyzing the sensed data and learning how to automatically operate building controls in a way to minimize energy consumption while maintaining the values identified in this study.

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DEVELOPMENT AND VALIDATION OF REGRESSION MODELS TO PREDICT ANNUAL ENERGY CONSUMPTION OF OFFICE BUILDINGS IN DIFFERENT CLIMATE REGIONS IN THE UNITED STATES

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Abstract: Energy consumption in commercial buildings has been growing substantially in recent years. Recently, building energy consumption estimation tools have been used to calculate energy savings and emissions reduction. Energy performance of building is complicated since it depends on multiple variables associated to building characteristics, equipment and systems, weather, occupants, and sociological influences. Therefore, the objective of this study is to develop the multi-linear regression models to predict energy consumption of an office building in five different climate regions in the United States. In order to achieve this objective, a typical commercial building was selected and the effect of 17 key building design parameters on its energy performance was investigated. To quantify building energy consumption, eQuest and DOE-2, which are building energy simulation software programs, were used to develop the building profile and perform annual energy simulation. In addition, Monte Carlo simulation technique was used to create a ten thousands comprehensive dataset covering the full range of design parameters for each studied climate region. An in-house computer program was developed to implement the Monte Carlo simulation. Statistical analysis was performed using R statistical analysis program to develop a set of linear regression equations predicting energy consumption of each design scenario. The difference between obtained results from regression model and DOE-2 are largely within 5%. In addition, standardized regression coefficient was calculated to assess the sensitivity of heating, cooling, and total energy loads to different building design parameters across five climate zones. It is believed that the developed regression models can be used to estimate the energy consumption of office buildings in different climate regions when designers and engineers consider various building envelope designs in the early stages of the design.

1 INTRODUCTION

In recent years, the contribution of modern world to energy consumption has been increased significantly. World energy consumption has increased from 524 quadrillion Btu in 2010 to 630 quadrillion Btu in 2010 and 820 quadrillion Btu in 2040, a 30 year increase of 56% (EIA 2010). The same trend was seen in the United States in which total energy consumption was approximately 97.9 quadrillion Btu in 2010 with an increase rate of 8.3% (EIA 2010). According to the EIA (2010), building sector in the U.S. consume 40% of total energy which is higher than transportation and industrial sectors. Therefore, proper tools are needed to estimate and optimize energy consumption in buildings.

Several studies have been conducted to study building energy performance. In addition, there are different methods including simple regression analysis and dynamic simulation software programs (e.g.
EnergyPlus and DOE-2 (Repice 2011) to model building energy performance (Lam et al. 2010, Broun et al. 2014, Catalina et al. 2013, Asadi et al. 2012). In a study conducted by Hygh et al. (2012), EnergyPlus software was used to perform energy simulation and calculate annual building energy consumption of a commercial building in four different climate zones. Mohammadpour et al. (2014) employed EnergyPlus to model energy consumption of three retrofit projects and compared energy consumption before and after the retrofit. Asadi et al. (2014) developed multiple linear regression models to predict building energy consumption for a typical residential building in the hot and humid climate. The effect of 7 buildings shapes as well as 17 building design parameters including HVAC schedule, orientation, building envelope, etc. on building energy performance were investigated. Results of their study showed that there is a good agreement between results of the DOE-2 and regression equations and the error was less than 5% in most cases. In another study, Catalina et al. (2013) developed regression models to investigate monthly heating load in residential building in France. The inputs of the regression model include the window to wall ratio, building envelope U-value, and building shape factor. Their analysis indicated that there is a strong relationship between building shape and energy consumption. Later, Lam et al. (2010) developed regression models using DOE-2 simulation results to determine the impact of 12 building design sensitive variables on building energy performance. The authors reported that there is a strong correlation between annual building energy consumption and design parameters in the warm climates. This paper proposes a simple and realistic approach to estimate energy consumption of a typical office building in five different climate zones. The primary objective of this study is to develop a multi-linear regression model to predict and quantify energy consumption of a commercial building in the early stages of building design.

2 MATERIAL AND METHOD

Building energy simulation models are commonly used to predict energy performance. They are powerful computational tools helping users to model a building as a system and to identify potential opportunities to reduce building energy consumption. In the present study, a comprehensive set of inputs such as internal loads, mechanical and electrical system, orientation and occupancy schedule was considered to calculate energy consumption. Also five major climate zones including cold dry, cool dry, mixed humid, warm marine and hot humid were considered in this study (Table 1).

Table 1: Five selected cities in each climate region.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Representative city</th>
<th>HDD</th>
<th>CDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold dry</td>
<td>Billings</td>
<td>&gt;7000</td>
<td>&lt;2000</td>
</tr>
<tr>
<td>Cool dry</td>
<td>Salt lake City</td>
<td>&lt;5500-7000</td>
<td>&lt;2000</td>
</tr>
<tr>
<td>Mixed humid</td>
<td>Washington DC</td>
<td>&lt;4000-5499</td>
<td>&lt;2000</td>
</tr>
<tr>
<td>Warm marine</td>
<td>San Jose</td>
<td>&lt;4000</td>
<td>&lt;2000</td>
</tr>
<tr>
<td>Hot humid</td>
<td>Houston</td>
<td>&lt;4000</td>
<td>≥2000</td>
</tr>
</tbody>
</table>

HDD=Average heating degree-days, CDD= Average cooling degree-days (EIA, Noaa 2012)

Monte Carlo simulation was performed by randomly selecting 17 variables based on uniform distribution to generate a new input file for the simulation software. This process was repeated 10000 time to effectively examine the configuration space. The eQuest and DOE-2 software programs were utilized to calculate the annual heating and cooling consumption for each design scenario based on Monte Carlo simulation. eQUEST software, which adds an additional graphical wizards capability to DOE-2, facilitates creation of building envelope and climate zones. Using DOE-2 avoids imprecisions introduced by simplifying algorithms, and since it is a configurable tool, it can be utilized for detailed design. Based on the Monte Carlo simulation, 10,000 simulation runs were defined for each of the five climate zones, covering a complete range of design parameters. In addition, a code was written in Python's programming language to help extracting required data from DOE-2. Then, these data were used to develop the multiple linear regression equations and investigate the relationship between different parameter and annual energy consumption. Figure 1 illustrates the framework of the analysis.
2.1 Base Case Model Description and Design Variables

Table 2 shows the list of parameters that were used to build the office building model using eQuest and Table 3 represents the implemented variables in the Monte Carlo Simulation. As it can be seen in Table 2, 17 design parameters including building envelop, orientation and occupant schedules were considered. The properties of all building components including wall, roof, ceiling, foundation, and floors were defined in this study. For each parameter, set of values and ranges are selected based on AHRAE 90.1 (ASHRAE 2007). In addition, a comprehensive data set was generated based on random distribution to examine all possible configuration of building envelope. Uniform distribution was applied to each parameter ensuring that all values within the specified range are investigated equally for each design choice.

Table 2: Description of eQuest inputs.

<table>
<thead>
<tr>
<th>Constant parameters</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building type</td>
<td>Office bldg., two story</td>
</tr>
<tr>
<td>Jurisdiction</td>
<td>ASHRAE 90.1</td>
</tr>
<tr>
<td>Building Area</td>
<td>2322.6 m²</td>
</tr>
<tr>
<td>Cooling Equip</td>
<td>Chilled water coils</td>
</tr>
<tr>
<td>Heating Equip</td>
<td>Hot water coils</td>
</tr>
<tr>
<td>Analysis Year</td>
<td>2013</td>
</tr>
<tr>
<td>Day Light Control</td>
<td>Daylight control</td>
</tr>
<tr>
<td>Usage details</td>
<td>Hourly end use profile</td>
</tr>
<tr>
<td>Zoning Pattern</td>
<td>One per floor</td>
</tr>
<tr>
<td>Floor-To-Floor</td>
<td>2.74 m</td>
</tr>
<tr>
<td>Floor-To-Ceiling</td>
<td>2.43 m</td>
</tr>
<tr>
<td>Door type</td>
<td>Opaque</td>
</tr>
<tr>
<td>Door Construction</td>
<td>Wood, hollow core flush, 0.02-0.096m</td>
</tr>
<tr>
<td>Windows Area method</td>
<td>Present of Gross wall area</td>
</tr>
<tr>
<td>Floor to Floor Window ratio</td>
<td>40%</td>
</tr>
<tr>
<td>Net Floor to Ceiling Window ratio</td>
<td>53.3%</td>
</tr>
<tr>
<td>Window High</td>
<td>1.59 m</td>
</tr>
<tr>
<td>Cooling Source (HVAC)</td>
<td>Evaporate resistance</td>
</tr>
<tr>
<td>Heating Source</td>
<td>Furnace</td>
</tr>
<tr>
<td>System type</td>
<td>Direct</td>
</tr>
<tr>
<td>Number of Occupants</td>
<td>105</td>
</tr>
<tr>
<td>People Activity</td>
<td>0.131 kw/hr.</td>
</tr>
<tr>
<td>Variable</td>
<td>Range</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>Top floor ceiling interior finish</td>
<td>• Acoustic Tile</td>
</tr>
<tr>
<td></td>
<td>• Drywall</td>
</tr>
<tr>
<td></td>
<td>• Plaster Finish</td>
</tr>
<tr>
<td></td>
<td>• No Board Insulation</td>
</tr>
<tr>
<td></td>
<td>• Polyurethane (R-6)</td>
</tr>
<tr>
<td></td>
<td>• Polyurethane (R-9)</td>
</tr>
<tr>
<td></td>
<td>• No Batt</td>
</tr>
<tr>
<td>Top floor batt insulation</td>
<td>• R-30</td>
</tr>
<tr>
<td></td>
<td>• R-45</td>
</tr>
<tr>
<td></td>
<td>• R-11</td>
</tr>
<tr>
<td></td>
<td>• R-19</td>
</tr>
<tr>
<td>Ceiling Insulation Parameters</td>
<td>• Wool Batt</td>
</tr>
<tr>
<td></td>
<td>• Wool Batt (R11)</td>
</tr>
<tr>
<td></td>
<td>• Wool Batt (R19)</td>
</tr>
<tr>
<td></td>
<td>• Wool Batt (R30)</td>
</tr>
<tr>
<td>Ground Floor Construction</td>
<td>Concrete</td>
</tr>
<tr>
<td></td>
<td>• 0.1m</td>
</tr>
<tr>
<td></td>
<td>• 0.3m</td>
</tr>
<tr>
<td></td>
<td>• 0.15m</td>
</tr>
<tr>
<td></td>
<td>• 0.2m</td>
</tr>
<tr>
<td>Ground Floor Interior Finish</td>
<td>• Carpet (No Pad)</td>
</tr>
<tr>
<td></td>
<td>• Vinyl Tile</td>
</tr>
<tr>
<td></td>
<td>• Ceramic/Stone Tile</td>
</tr>
<tr>
<td>Floor Interior Finish</td>
<td>• No Surface Finish</td>
</tr>
<tr>
<td></td>
<td>• Carpet (No Pad)</td>
</tr>
<tr>
<td></td>
<td>• Vinyl Tile/Stone</td>
</tr>
<tr>
<td>Occupant Schedule</td>
<td>• 08:00:00 AM to 05:00:00 PM (Monday-Friday) +HVAC 1</td>
</tr>
<tr>
<td></td>
<td>• 08:00:00 AM to 06:00:00 PM (Monday-Thursday) +HVAC 1</td>
</tr>
<tr>
<td></td>
<td>• 07:00:00 AM to 05:00:00 PM (Monday-Thursday) +HVAC 1</td>
</tr>
<tr>
<td></td>
<td>• 07:00:00 AM to 04:00:00 PM (Monday-Friday) +HVAC 2</td>
</tr>
<tr>
<td></td>
<td>• 08:00:00 AM to 05:00:00 PM (Monday-Friday) +HVAC 2</td>
</tr>
<tr>
<td></td>
<td>• 07:00:00 AM to 04:00:00 PM (Monday-Friday) +HVAC 3</td>
</tr>
</tbody>
</table>

1HVAC system turns on 1 hour before working hours and turn off 1 hour after working hours.
2HVAC system is on 24/7.
3HVAC system is on only during workings hours.
2.2 Regression Analysis

The aim of regression analysis in this study is to develop simple and accurate models to predict energy consumption in commercial buildings. A multiple regression model with more than one explanatory variable may be written as:

\[ Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \]

Where \( y \) is the output, \( \beta_i \) is the regression parameters and \( X_i \) is the input variables. The least-squares method is generally used for estimation purposes in the multiple-regression model. Once regression coefficients are identified, a prediction equation can then be used to estimate the value of a continuous output as a linear function of one or more independent inputs. A comprehensive dataset was developed based on the randomly generated building parameters using energy simulation model. Eighty percent (80%) of the simulation runs were selected randomly and used to develop the regression equations. Remaining twenty percent (20%) of the runs were used to validate the developed model. The generated dataset was used to develop regression equations predicting annual building energy consumption.

3 RESULTS AND DISCUSSION

3.1 Interaction between parameters

Analysis of the Interaction between parameters represents the combined effects of the independent parameters on the dependent variable. When an interaction effect is present, the impact of one factor depends on the level of the other factor. One of the methods to determine the interaction between parameter is to identify multicollinearity. Multicollinearity is a statistical phenomenon in which two or more predictor variables in a multiple regression model are strongly correlated. It arises when two or more predictors in the model are correlated and provide redundant information about the response. Generalized variance-inflation factor (GVIF) can be used to detect multicollinearity in the regression equation. The GVIF indicates the degree to which the confidence interval for that variable regression parameter is expanded relative to a model with uncorrelated predictors. As a general rule, GVIF>4 indicates a multicollinearity problem. The GVIF results are presented in Table 4. As it can be seen in this table, the GVIF values in all cases are less than 1.3 indicating that there is no correlation between predictor variables in the multiple regression models.

<table>
<thead>
<tr>
<th>Building Orientation</th>
<th>Billings 1.038285</th>
<th>Houston 1.035407</th>
<th>Washington, D.C. 1.028915</th>
<th>San Jose 1.034006</th>
<th>Salt Lake City 1.030121</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Floor Batt Insulation</td>
<td>1.03594</td>
<td>1.035997</td>
<td>1.034708</td>
<td>1.038009</td>
<td>1.036116</td>
</tr>
<tr>
<td>Ceiling Interior Finish</td>
<td>1.023482</td>
<td>1.021158</td>
<td>1.020389</td>
<td>1.02523</td>
<td>1.024162</td>
</tr>
<tr>
<td>Ceiling Insulation</td>
<td>1.026014</td>
<td>1.02497</td>
<td>1.023632</td>
<td>1.02252</td>
<td>1.024083</td>
</tr>
<tr>
<td>Floor Construction</td>
<td>1.038519</td>
<td>1.034395</td>
<td>1.037726</td>
<td>1.03494</td>
<td>1.026742</td>
</tr>
<tr>
<td>Top Floor Ceiling Exterior Insulation</td>
<td>1.039947</td>
<td>1.034008</td>
<td>1.037932</td>
<td>1.031834</td>
<td>1.034814</td>
</tr>
<tr>
<td>Top Floor Ceiling Interior Finish</td>
<td>1.048875</td>
<td>1.044126</td>
<td>1.045476</td>
<td>1.047932</td>
<td>1.047745</td>
</tr>
<tr>
<td>Ground Floor Construction</td>
<td>1.022871</td>
<td>1.024229</td>
<td>1.018244</td>
<td>1.022585</td>
<td>1.024278</td>
</tr>
<tr>
<td>Ground Floor Interior Finish</td>
<td>1.038625</td>
<td>1.032505</td>
<td>1.034519</td>
<td>1.028883</td>
<td>1.032269</td>
</tr>
<tr>
<td>Floor Interior Finish</td>
<td>1.025238</td>
<td>1.025422</td>
<td>1.022385</td>
<td>1.018312</td>
<td>1.02167</td>
</tr>
</tbody>
</table>
### 3.2 Regression Results and Discussion

Table 5 shows the regression equations associated with each climate zone. Five different regression equations were developed for each climate zone. The $R^2$, root mean square error (RMSE) and F-Test values are shown in this table. $R^2$ measures how close the data are to the fitted regression line. As it can be seen, the $R^2$ value is more than 0.94 in all cases which indicates that the model fits with the data.

**Table 5: Regression equations associated with each climate zones**

<table>
<thead>
<tr>
<th>Regression Coefficient</th>
<th>$y = \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 + \beta_8 x_8 + \beta_9 x_9 + \beta_{10} x_{10} + \beta_{11} x_{11} + \beta_{12} x_{12} + \beta_{13} x_{13} + \beta_{14} x_{14} + \beta_{15} x_{15} + \beta_{16} x_{16} + \beta_{17} x_{17}$</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Beta Coefficient</th>
<th>San Jose</th>
<th>Washington, DC</th>
<th>Houston</th>
<th>Billings</th>
<th>Salt Lake City</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_1$</td>
<td>-2.20</td>
<td>-0.68</td>
<td>1.68</td>
<td>-2.10</td>
<td>-0.41</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>-1.35</td>
<td>0.70</td>
<td>1.19</td>
<td>-3.52</td>
<td>-0.87</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>-2.07</td>
<td>-3.16</td>
<td>0.49</td>
<td>-5.02</td>
<td>1.80</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>0.19</td>
<td>-4.14</td>
<td>-1.62</td>
<td>-8.93</td>
<td>-7.37</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>1.30</td>
<td>1.02</td>
<td>0.73</td>
<td>0.49</td>
<td>-0.03</td>
</tr>
<tr>
<td>$\beta_6$</td>
<td>0.04</td>
<td>-0.10</td>
<td>0.31</td>
<td>-0.42</td>
<td>-0.12</td>
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<tr>
<td>$\beta_7$</td>
<td>0.57</td>
<td>-3.32</td>
<td>-1.78</td>
<td>-2.94</td>
<td>-2.15</td>
</tr>
<tr>
<td>$\beta_8$</td>
<td>1.40</td>
<td>1.41</td>
<td>2.56</td>
<td>-2.78</td>
<td>-2.64</td>
</tr>
<tr>
<td>$\beta_9$</td>
<td>-0.47</td>
<td>1.91</td>
<td>-7.04</td>
<td>-1.57</td>
<td>-2.37</td>
</tr>
<tr>
<td>$\beta_{10}$</td>
<td>-0.97</td>
<td>-2.83</td>
<td>2.65</td>
<td>2.26</td>
<td>-3.01</td>
</tr>
<tr>
<td>$\beta_{11}$</td>
<td>0.48</td>
<td>0.42</td>
<td>-0.10</td>
<td>0.21</td>
<td>0.28</td>
</tr>
<tr>
<td>$\beta_{12}$</td>
<td>-0.40</td>
<td>-0.89</td>
<td>-0.33</td>
<td>-1.33</td>
<td>-1.70</td>
</tr>
<tr>
<td>$\beta_{13}$</td>
<td>-0.42</td>
<td>0.09</td>
<td>1.30</td>
<td>-0.21</td>
<td>0.44</td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>( \beta_2 )</td>
<td>( \beta_3 )</td>
<td>( \beta_4 )</td>
<td>( \beta_5 )</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>1.64</td>
<td>-0.01</td>
<td>-0.98</td>
<td>-4.45</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>0.43</td>
<td>-1.48</td>
<td>1.51</td>
<td>3.25</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>6.29</td>
<td>12.65</td>
<td>9.80</td>
<td>15.66</td>
<td>12.53</td>
<td></td>
</tr>
<tr>
<td>-0.31</td>
<td>0.27</td>
<td>0.15</td>
<td>0.37</td>
<td>-0.32</td>
<td></td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.95</td>
<td>0.94</td>
<td>0.95</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>RMSE</td>
<td>226.2</td>
<td>221.3</td>
<td>218.4</td>
<td>-3.31</td>
<td>222.0</td>
</tr>
<tr>
<td>F-Test</td>
<td>950</td>
<td>868</td>
<td>918</td>
<td>862</td>
<td>952</td>
</tr>
</tbody>
</table>

\( x_1 \) = building orientation, \( x_2 \) = top floor batt insulation, \( x_3 \) = ceiling interior finish, \( x_4 \) = ceiling insulation, \( x_5 \) = floor construction, \( x_6 \) = top floor ceiling exterior insulation, \( x_7 \) = top floor ceiling interior finish, \( x_8 \) = ground floor construction, \( x_9 \) = ground floor interior finish, \( x_{10} \) = floor interior finish, \( x_{11} \) = interior wall, \( x_{12} \) = exterior wall, \( x_{13} \) = roof absorbance, \( x_{14} \) = exterior wall absorbance, \( x_{15} \) = roof absorbance, \( x_{16} \) = occupant schedule, \( x_{17} \) = glass category.

The objective of multiple-linear regression analysis is to predict the single dependent variable (energy consumption) by a set of independent variables (building orientation, wall insulation, glass type, occupancy schedule, etc.). Multiple regression shares all the assumptions of correlation including normality, independence, linearity, and homoscedasticity. Figure 2 shows the scatter plots of residuals which allows visual assessment of the distance of each observation from the fitted line. The residuals from a fitted model are the differences between the responses observed at each combination values of the explanatory variables and the corresponding prediction of the response computed using the regression function. As it can be seen, the residuals are randomly scattered in a constant width band about the zero line and no discernable pattern, without any relationship to the value of the independent variable is observed.

![Residual scatter plots for five locations](image1.png)

Figure 2: Residual scatter for the five locations.
To demonstrate the variation in energy consumption for each climate zone, identical parameter samples were used for all locations, but the observed range and variability of total energy were unique in different locations (Fig 3). It can be seen that number of outliers is highest in Billings where the first and third quartiles makes up less than half of the range between the minimum and maximum observed. The high variability in Billings is driven by the cold winters and hot summers, which exhibits wide variation depending on the combination of the values for the design parameters.

![Figure 3: Distribution of total energy consumption for the five locations](image)

### 3.3 Regression Model Validation

Model validation is one of the most important steps in finding the best fit for the regression model. $R^2$ and RMSE values are commonly used to validate the model. In this study two thousands of simulations runs were set aside to test the regression model performance and validate the results. Figure 4 shows the validation results for each climate region. It can be observed that the results from the model are well correlated with the data from simulations with acceptable error of less than 5%.

![Figure 4: Regression model validation results](image)
4 CONCLUSION

The goal of this study was to develop simple regression models for office building in the five major climates including cold dry, cool dry, mixed humid, warm marine and hot humid. A total of 17 key building design variables were identified and considered as inputs in the regression models. The coefficient of determination R² varies from 0.94 to 0.95 indicating that 95% of the variation in annual building energy consumption can be explained by change in 17 parameters. The analysis indicates that there is a strong interaction between building location and level of energy consumption. It also shows Billings (cold-dry) with cold winters and hot summers consume the highest amount of energy in comparison with other location. On the other hand, San Jose (warm marine) with the subtropical Mediterranean climate has the least temperature variation and subsequently has the least annual energy consumption. The difference between regression-predicted and DOE-simulated annual building energy use are largely within 5%. Consequently, the developed regression models can be used for comparative energy studies to estimate the potential energy savings during the early stage of design when different building schemes and design concepts are being considered.

Climates with the least temperature variation, subsequently have the least annual energy consumption. The difference between regression-predicted and DOE-simulated annual building energy use are largely within 5%. Consequently, the developed regression models can be used for comparative energy studies to estimate the potential energy savings during the early stage of design when different building schemes and design concepts are being considered.

The models for energy consumption prediction presented in this study, will be expanded in future and will be validated using case studies on physical commercial building to better estimate the prediction accuracy.
References


REAL-TIME ACCIDENT DETECTION USING UWB TRACKING

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\textsuperscript{2} carlo.andolfo@ucalgary.ca

Abstract: Construction industry has one of the highest numbers of fatalities among Canadian industries. Despite ongoing efforts to improve safety through trainings and promoting personal protective equipment (PPE), the number of construction fatalities in Canada is actually on the rise. Studies show that systematically monitoring construction sites and providing immediate feedback to workers are instrumental in improving safety. In particular, close monitoring of the real-time status of moving objects has been shown to improve the safety, productivity and performance on construction sites. Information and Communication Technologies (ICT) and automation techniques have shown strong potentials for identifying hazards. As a result, automated data collection to monitor the status of the construction sites has received researchers’ attention in recent decades. The objective of this study is to develop a model that prevents the accidents on construction sites using automated real-time location estimations. A model is developed to detect situations that can lead to fall or colliding with moving objects based on proximity of workers to these situations. The system will use the readings from UWB tracking and generates a visualization of the moving objects on the job site in real time. When the possibility of an accident is detected, the system will send an alarm to warn the involved personnel. The functionality and efficiency of the model in detecting accidents is examined. The results of these experiments shed light on the importance of addressing the time delays caused by UWB tracking in actual real-time applications.

1 INTRODUCTION

The high number of accidents in the construction industry compared to most other industries (AWCBC, 2014a) makes a construction site one of the most complex working environments. One of the main causes of accidents on construction sites has been identified as collision of the on-foot workers with moving objects, due to workers’ proximity to heavy construction equipment (Teizer et al., 2008). For example, crane operators have difficulty in relating their own position to that of the load they are moving, and this creates hazardous situations that might lead to accidents and injuries (Cheng et al., 2011). The limited spatial awareness is also the main factor of a second typical cause of accidents: falls from heights. In the United States alone, falls from heights cause the highest number of fatalities in the construction industry – almost 37% of workplace life losses in constructions in 2013 (OSHA, 2014).

Standard policies used to reduce the risk of accidents focus on increasing the training of the workers and their education about potential risks, consequences, and precautions they should take. In addition, measures that reduce hazards and provide collective protection, as well as the use of Personal Protective Equipment (PPE) are commonly required by the law. However, despite these efforts to improve safety through planning, training, and the use of protective equipment, the number of construction fatalities in Canada is actually on the rise, with a growth of about 17% since 2011 (AWCBC, 2014-b). This shows that managing safety issues only through standard safe work practices is not sufficient to avoid accidents.
This is mainly due to the dynamic nature of construction sites. The constant changes of the site during the construction phase create new hazards, and a rapid modification of the safety strategies is not always feasible. Recent studies show that systematically monitoring the work in progress and providing immediate feedback to workers are instrumental in improving the effectiveness of any safety strategy (Skibniewski, 2014). In particular, close monitoring of the real-time status of moving objects has been shown to improve the safety (Teizer et al., 2010), productivity and performance (Cheng et al., 2011 and Song et al., 2006). However, the effectiveness of manual methods is strongly affected by the safety awareness of front-line supervisors. Since the automation technologies have shown strong potential for identifying hazards and decreasing the time required for corrective actions, the development and implementation of an automatic system is receiving an increasing attention in recent years.

This paper presents part of a larger research work on improving safety on construction sites. The long-term goal of this research is to develop an accident prediction model that predicts potential accidents on construction sites ahead of time, long enough to provide perception and reaction time to the parties involved. This paper focuses only on the first step of this larger research, which is on real-time accident detection. Unlike prediction, in real-time detection an accident is detected only shortly before it occurs. An Accident Detection Model (ADM) is developed to analyze the estimated location of moving objects on the site (workers and equipment) provided by an UWB Real-Time Locating System (RTLS), and send a warning signal when a worker is getting too close to a hazardous situation. The ADM presented in this paper will be the basis for the development of an accident prediction model in the next steps of this research.

2 BACKGROUND AND LITERATURE REVIEW

Alerting workers when they are approaching a danger zone is an important part of real-time safety management. The preventative models are required for situations where the standard security procedures and PPE fail. Within real-time safety technology, the reactive and proactive safety approaches are differentiated (Teizer et al., 2010). Reactive real-time approaches collect data in real time, but require a post data processing to convert these data into information. On the contrary, proactive approaches collect and analyze data in real time, in order to alert workers of the dangers occurring in that moment.

Due to their efficiency in collecting data, different remote sensing technologies have been proposed to be used for various applications on construction sites. Radio-Frequency Identification (RFID) is one of these remote sensing technologies, largely used for inventory tracking in several industries including construction (Nasir et al., 2010). This technology has been applied also to the construction industry for position tracking, but since in principle it is not a localization technology, it requires to be used in combination with GPS to get information on the position of a tag, or with other tags of known locations dispersed through the area to cover (Saidi et al., 2011). However, previous researches showed that the estimated tags’ locations are within few meters of their actual positions; even if it might appear a high accuracy level, it is not enough for preventing potential dangerous situations in a construction site. For this reason, RFID technology can be very useful for estimating the locations of construction components, but not for being applied with a safety purpose in large construction environments (Torrent and Caldas, 2009).

Ultra Wideband (UWB) is another remote sensing technology that has been explored in the literature for applications on construction sites. By using very short pulses (one nanosecond) transmitted by each tag, UWB allows the filtering of reflected signals from the original signal, offering the possibility to measure distances at the decimeter and centimeter level. Due to this accuracy, UWB has been suggested for applications where more accuracy is required, such as monitor the workers’ positions on the site. Previous studies have shown that UWB offers an accuracy of less than one meter under conditions that are common on construction sites, such as the presence of metal objects, or tracking a large number of tags simultaneously (Maalek and Sadeghpour, 2013). In addition to accuracy, UWB offers other characteristics that render them suitable for the conditions of construction sites. For example, due to its high penetration ability, UWB tracking does not require line-of-sight. It also does not suffer from multipath distortion and interference (Gu et al., 2009). Furthermore, they have low installation and operational cost.
Ease of use, small and light (wearable) tags, and long range of operation have been identified as favorable characteristics of UWB tracking for construction sites (Teizer et al., 2008). For the aforementioned reasons, UWB seems to be suitable for safety management systems where accuracy is of high importance.

In recent years, a number of studies suggested the use of Real-time Location Systems for safety management on construction sites. Giretti et al. (2009) and Carbonari et al. (2011) proposed a predictive algorithm for the real-time identification of potential overhead hazards using UWB tracking system. They conducted experiments on actual construction sites and concluded that the capability of the system to identify hazards is affected by the time required by system to update the locations of the workers. Lee et al. (2012) developed a similar system that uses RTLS (without specifying which technology is used) to warn endangered workers. The workers’ positions are continuously monitored by a safety manager, who manually activates a warning signal when a worker is approaching a danger area. Riaz et al. (2006, 2012) proposed a conceptual model that could avoid possible collisions between equipment and workers. In this conceptual model, it is proposed that the workers who stand in the operational envelope of a specific equipment can be identified using RFID tracking. Finally, Hwang (2012) used UWB to monitor tower crane movements in real time and prevent potential collisions. Cranes’ possible movements were modeled and an algorithm was developed to predict the positions of the booms of two adjacent cranes, based only on their axial rotation. Overall, these studies showed strong potential for the application of RTLS, and specifically UWB tracking for safety management of construction sites. However, most of these models have either not been implemented, or been used for a specific study. The objective of this study is to advance the current status of research and develop a real-time accident warning system that can be implemented in any construction sites. The study will also investigate the effect of time latency in real-time systems on safety management applications that has not been addressed in the literature before.

3 A REAL-TIME ACCIDENT WARNING SYSTEM FOR CONSTRUCTION SAFETY MANAGEMENT

The proposed Accident Warning System is composed of two parts: a Real-Time Locating System and an Accident Detection Model. The RTLS will estimate the positions of workers and equipment by means of small tags installed on moving objects (e.g. workers’ safety helmets or construction equipment). The Accident Detection Model detects accidents by continuously comparing the estimated positions of tags with danger zones in real time. When the possibility of either an accident between two moving objects or a fall from heights is detected, the system will generate a warning. Due to its higher accuracy, UWB tracking is used in this study for real-time locating of the objects; however, the developed model can work with any other RTLS. The overall schematic of the system is shown in Figure 1. The aforementioned two parts of the Accident Warning System are described in this section.

3.1 UWB Real-Time Locating System

The UWB RTLS is composed of receivers (or readers), tags, and a location estimation platform (see Figure 1). To estimate the position of the tags, the readers receive the signals transmitted by the tags. One receiver is assigned as a “Master Receiver” and has two-way communications with the tags. This means that in addition to receiving signals from the tags, it can also send commands to them (e.g. activate the sleep mode when they are not moving). The other receivers are considered “Slave Receivers” and can only receive signals from the tags. Receivers are connected to each other by timing cables whose function is to enable time synchronization among them. Each receiver is connected to a Power over Ethernet (POE) switch through an Ethernet cable. Other than providing power to the receivers, this cable transfers the collected data to the platform for location estimation. When the system is activated, the tags send an UWB pulse to the receivers. Each receiver collects two types of data from the received signal: the Angle of Arrival (AOA) of the signal and the time when the signal reaches the receiver. The time difference between the arrivals of a pulse to two different receivers is referred to as Time Difference of Arrival (TDOA). As a result, the system can estimate the location of the tags through two different methods, AOA and TDOA, achieving a higher level of accuracy (Muñoz et al., 2009). When a tag starts transmitting its signal at a specified frequency, the receivers acquire the signal and transfer
the data to the platform, which estimates the position of the tag and generates a log file. Each row of the log file represents a single reading that, among other information, contains Date, Time, Tag ID, and $x$, $y$, $z$ coordinates of the tags at the time of reading.

![UWB Real-Time Tracking System](image)

Figure 1: Overview of the Accident Warning System

### 3.2 The Accident Detection Model (ADM)

The developed Accident Detection Model analyzes the information about the positions of the tags, and determines when an accident is about to happen. To achieve this goal, it utilizes the estimated locations from the UWB platform and compares the positions of the tags with the boundaries of the areas on the site that are defined as danger zones. As shown in Figure 1, ADM consists of three modules, namely Information Module, Detection Module, and Visualization Module. The function of each module is discussed in detail in this section.
The Information Module acquires the project site-specific parameters from the user (e.g. site manager), namely Site Boundary, Coordinate Origin, Danger Zones, and Safety Buffers (see Figure 1). The Site Boundary defines the physical boundaries for where the Real-Time Accident Warning System is activated (i.e. the part of the construction site monitored with the system). Coordinate Origin defines the origin of the coordinate system used by the UWB system on the construction site boundary. Danger Zones defines the location and boundary of the dangerous areas on the site where workers should not approach. Finally, Safety Buffer defines the dimensions of a virtual safety area that is assumed around the moving objects that are tracked on the site (i.e. workers and equipment). In the current status of the model, size of the Safety Buffer is taken as an input from the user. However, it is worthy to mention that the value assigned to it will play a major role in achieving the intended appropriate safety level on the site since the trigger of the warning is determined by the overlap between the Safety Buffers and the Danger Zones. The dimension of the Safety Buffer has been investigated in other studies and depends on a number of factors such as the moving speed, the type of activity conducted and vicinity to danger zones (e.g. Esmaeinejad and Sadeghpour, 2014).

The Detection Module is the analysis core of the Accident Detection Model and detects potential dangerous and accident-prone situations. The module acquires the information regarding the Site Boundary, the Danger Zones, and the Safety Buffers from the Information Module, and uses the Coordinate Origin to establish these boundaries. The module also acquires the estimated location of tags in real time from the UWB tracking system, and using the Coordinate Origin, it translates the estimated locations from the UWB RTLS coordinate system to that of the Site Boundary. For every new reading received from the UWB tracking (i.e. location estimation), the module checks whether the Safety Buffer of any of the moving objects overlaps with one of the defined Danger Zones on the site, or the Safety Buffer of another object. A detected overlap indicates an unsafe situation, and consequently a warning is issued (see Figure 1).

The Visualization Module acquires the Site Boundary, Coordinate Origin, Danger Zones, and Safety Buffers from the Information Module and generates a visualization of the site. Meanwhile, it receives the results of the analysis from the Detection Module. The translated coordinates of the tags and their safety status (whether their boundary at that instant is overlapping with another tag or a Danger Zone) are transferred from the Detection Module to the Visualization Module at every reading, and the module generates a real-time visualization of the positions of the moving objects on the site. If the status of the tag (moving object) is identified to be safe by the Detection Module, the tag will be represented in green color at the estimated position of the moving object. Red color is used when an overlap is detected to indicate a warning for a potential hazardous situation.

4 IMPLEMENTATION

The described Accident Detection Model was implemented in Processing 2, an open source Java development environment. The flowchart for the implemented tool is shown in Figure 2. At the beginning, the tool requires the parameters of the Information Module as an input (Step1). In this implementation, each worker is visualized as a circle that represents the virtual Safety Buffer surrounding the moving object (i.e. worker or equipment). The user also defines a rectangular Danger Zone through indicating four parameters: $x$ and $y$ of the top-left corner, and width and height of the rectangle. The user is also prompted for the location $(x,y)$ of the origin of the UWB coordinate system on the site. The boundaries of the site can either be drawn in the development environment or loaded from an external file.

Once the tracking is initiated, the tool acquires the location estimations from the UWB tracking system (Step 2). UWB keeps a record of all the readings, including the unsuccessful ones. The developed tool identifies these and filters through the records where the system failed to read the tag, and keeps track of only the successful readings. The $x$, $y$, $z$ of the estimated locations represent the position of the moving objects, and they are used as the centers of the circles that represent workers or equipment. The boundaries of these circles are compared with the defined boundaries of the Danger Zones, and the workers are displayed on the site plan as green or red circles, depending on whether they have a safe or unsafe status (Step 3). The tool continuously checks whether a new location estimation is available (Step 4). If this is the case, it reads the new position and repeats steps 3 and 4 (Figure 2).
5 FUNCTIONALITY AND EFFICIENCY OF THE IMPLEMENTED TOOL

The functionality of the implemented tool was tested in the Civil Engineering Concrete Laboratory of the University of Calgary, which is very similar to the work environment of a construction site (see Figure 3). Eight (8) UWB receivers were installed along the edges of the lab. The developed tool was setup for this site by taking in the coordinates of the site boundary. There is a cut in the concrete floor slab of the laboratory that is used for the movement of a lift between floors. This cut is protected by fence on three sides, therefore the fourth side is identified as a falling hazard. Hence, a danger zone was created next to the open edge of this cute. Two workers were initiated in the tool. Their safety helmets were equipped with UWB tags Two different Safety Buffers were assigned to each worker, one with a diameters of 2 meters and the other 3 meters; assuming that based on their movement speed and type of activity they carry the site manager required different Safety Buffers for each. The workers were asked to carry out their normal activities in the lab. The positions of the workers were monitored using the developed tool for two time spans of 10 and 30 minutes. The tool was successfully able to identify when a worker entered...
the Danger Zone. In other words, every time the Safety Buffer of one of the tags overlapped with the defined Danger Zone, the color of the Safety Buffer of the worker turned into red, and an alarm signal was issued by the tool, indicating an unsafe status for that worker. Otherwise, the tag was represented by a green circle, indicating a safe status for the worker. Figure 3 shows a screenshot of the tool at a moment where Worker 1 is entering the Danger Zone.

![Figure 3: A screenshot of the tool developed based on the Accident Detection Model](image)

The processing time of the developed tool was measured to examine its efficiency. This is the time difference between the acquisition of the estimated locations and the visualization of the workers’ or equipment's positions on the screen. This time difference is important because it translates into the delay caused by the tool in generating a warning signal when an unsafe position is detected. The two aforementioned scenarios of 10 and 30 minutes were used to measure the efficiency of the developed tool. In the first scenario with the duration of 10 minutes had an acquisition frequency of 3 Hz (i.e. 3 updates per second). In the second scenario, where the duration of the safety monitoring was 30 minutes, an estimation acquisition with a frequency of 8 Hz was used. The location estimation from the UWB system is recorded in a log file. Each location estimation (or “reading”) of the UWB is recorded in one line in the log file. Therefore, the number of lines, and as a result the size of the file, increases with the increase of data acquisition frequency and duration of the monitoring scenario. Table 1 summarizes the information regarding the two scenarios that were used in this study.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Duration (min)</th>
<th>Acquisition frequency (Hz)</th>
<th>Number of “readings”</th>
<th>File size (kB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>10</td>
<td>3</td>
<td>1,752</td>
<td>430</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>30</td>
<td>8</td>
<td>14,724</td>
<td>3,696</td>
</tr>
</tbody>
</table>

Each scenario was simulated ten (10) times using the developed Accident Detection tool. In these simulations, for each reading, the processing time - i.e. the rime between when the information is read from the log file and when it is processed and a status (safe or unsafe) decision is decided by the tool - was measured. Therefore, there were 1,752 measurements for each simulation in Scenario 1 and 14,724 measurements for each simulation in Scenario 2 (see Table 1). Considering the ten (10) simulations for each scenario, 164,760 instances of the processing time were measured in total. The time measurements were conducted on a regular office personal computer (processor Intel Core i7-3537U 2.0 GHz, 8 GB of RAM, and Windows 8.1 64-bit operating system). The average processing times were less than 8
milliseconds for the first, and less than 41 milliseconds for the second scenario, which can be deemed negligible. The details of the processing time measurements are presented in Table 2.

### Table 2: Processing time for the implemented tool in milliseconds (ms)

<table>
<thead>
<tr>
<th>Simulation Run #</th>
<th>Overall</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Mean (μ)</td>
<td>9.01</td>
<td>8.16</td>
<td>8.03</td>
<td>8.17</td>
<td>8.14</td>
<td>7.69</td>
<td>7.78</td>
<td>5.18</td>
<td>7.80</td>
<td>7.76</td>
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<tr>
<td></td>
<td>SD (σ)</td>
<td>2.32</td>
<td>2.03</td>
<td>1.97</td>
<td>2.08</td>
<td>2.08</td>
<td>2.01</td>
<td>1.86</td>
<td>2.16</td>
<td>2.16</td>
<td>2.16</td>
</tr>
<tr>
<td>n = 1,752</td>
<td>Scenario 2</td>
<td>Mean (μ)</td>
<td>41.10</td>
<td>39.89</td>
<td>39.28</td>
<td>41.10</td>
<td>41.05</td>
<td>40.93</td>
<td>40.71</td>
<td>40.99</td>
<td>40.70</td>
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<tr>
<td></td>
<td>SD (σ)</td>
<td>3.45</td>
<td>4.81</td>
<td>5.26</td>
<td>3.69</td>
<td>3.45</td>
<td>3.65</td>
<td>3.43</td>
<td>3.64</td>
<td>6.62</td>
<td>4.54</td>
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<tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Discussion:** Although the measured processing times were negligible for the defined scenarios in this study, another interesting observation was made from the results. As it can be inferred from Table 2, the average **processing time** for the second scenario is 5 times more than the first scenario (40.72 ms vs. 7.77 ms). As the measurements of processing time were conducted for individual data acquisitions from the UWB, it was surprising to notice this time difference. After more investigations, it was realized that this time difference is in fact due to how UWB system operates, and not the efficiency of the developed tool. UWB tracking system saves the readings from one tracking session (i.e. from when system is activated until it is stopped) in a single log file. Therefore, and naturally, the size of the file gets larger as the time duration of the observation is longer and as more readings are recorded, making it increasingly more time consuming to process the file. From Table 1 it can be seen that the number of readings in Scenario 2 is approximately 8 times larger than the number of files used in Scenario 1 (due to the longer duration of observation and higher frequency used for data acquisition).

Although it is not possible to identify the precise correlation between the number of readings and the **processing time** using only the above two scenarios, some interesting understandings can be derived even with simplistic assumptions. If we conservatively assume a linear relationship, using the two data points from the above two scenarios, the **processing time** \( T_{\text{process}} \) (ms) can be estimated as (Figure 4):

\[
T_{\text{process}} = 0.0025 \, N_{\text{readings}} + 3.322
\]

where \( N_{\text{readings}} \) represents the number of readings acquired by the UWB system in one session.

![Figure 4: Relationship between processing time and number of readings, assuming a linear relationship](image)
This conservative equation demonstrates an interesting point. Even if the regression coefficient in [1] may seem very small, the number of readings increases very quickly with time. For example, assuming an acquisition frequency of 8 Hz, 480 readings are recorded every minute. Consequently, the processing time ($T_{\text{process}}$) would increase of 1.20 ms every minute.

For a typical 8-hour working day, with an acquisition frequency of 8 Hz, the number of UWB readings by the end of the day would be 230,400. Considering the conservative assumption of linear increase, this means that the processing time would be about 590 ms (more than half a second) towards the end of the day. To put the importance in perspective, consider a moving object with a relatively slow speed of 10 km/hr. Half a second of time delay translates into about 1.4 meters of disposition in location of that object. It means that, even if we assume no error in the estimated location provided by the UWB, in case of detecting a dangerous situation, by the time a warning is issued the moving object is 1.4 meters inside the danger zone. It should be reminded that this estimation is conservatively assuming only a linear increase in the processing time. While more experiments are needed to define the actual relationship between $T_{\text{process}}$ and $N_{\text{reading}}$, the authors speculate that it will be higher than a first degree relationship, resulting in even larger time delays at the end of an 8-hour session. This example demonstrates the importance of time delays caused by the processing time for realistic applications of RTLS for safety management systems which has been looked in the past.

6 SUMMARY AND CONCLUDING REMARKS

This paper presented an Accident Detection Model that is developed to detect hazardous situations on construction sites shortly before they occur. The model uses estimations of the positions of moving objects (workers and equipment) provided by an UWB tracking system. It compares the estimated locations for the moving objects with defined danger zones as well as the safety buffers of other objects on construction sites, and when the possibility of an accident is detected, it generates a warning signal. A visualization tool was implemented based on the model using a Java development environment, and its functionality and efficiency were examined.

The results of the experiments in two scenarios demonstrated the model’s capability to detect unsafe situations for a monitored moving object. Measurements were also conducted to evaluate the efficiency of the developed model by measuring the processing time for each data acquisition (location estimation). The results showed that the processing time for examined scenarios were negligible. However, a more in-depth investigation revealed an interesting finding. The processing time for each data acquisition increases gradually with time and the increase in the number of reading. It was identified that this was due to the fact that UWB RTLS records all the readings from a session into a single file. During a tracking session, UWB system adds a line to this file when a new position is acquired. This means that the delay in acquiring the estimated locations of a moving object is less at the beginning of a session, because the log file is smaller, and increases with time as the number of readings, and consequently the size of the file increases. Assuming a very conservative increase in the processing time, at the end of an 8-hour working day, the processing time would be more than half a second. Such delays would not be negligible for a real-time application anymore, since it translates in a considerable disposition for the moving objects.

This study shed a light on the importance of time delays in Real-Time Location Systems for safety management systems. While the research until this point has focussed on errors in location estimation caused by the RTLS, the experiments presented in this paper demonstrated the importance of time delays for realistic applications of RTLS in safety management. The future work of this study will include devising methods to acquire location estimation data directly and before it is recorded on the log file. This will not only keep the processing time at their initial negligible values, but more importantly, will mean that the processing time will remain relatively consistent for each data acquisition during a tracking session. Having a consistent processing time during a tracking session will facilitate applying corrective measures and as such, objectively accounting for it.
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13.
THE INFLUENCE OF PUBLIC-PRIVATE PARTNERSHIPS ON DESIGN FLEXIBILITY AND DOWNSTREAM DESIGN FEEDBACK IN THE PRESIDIO PARKWAY

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Abstract: Public-Private Partnerships (P3s) offer the opportunity to improve integration among project stakeholders throughout a project’s life cycle. Stakeholder integration, in turn, can enhance design decision-making process by focusing on the project’s life cycle cost. The objective of this paper is to compare and contrast design decision-making in a P3 and design-bid-build (DBB) process to explore if life cycle considerations are better optimized under a P3 delivery method. To do this, we analyzed a project that included both P3 and DBB project delivery strategies—the Presidio Parkway. We collected data through 16 open-ended, semi-structured interviews with key project participants. We analyzed the data for design decision-making processes and found mixed evidence supporting the proposition that life cycle considerations can be better optimized under a P3 delivery method. Specifically, we found that the ability of the P3 contractor to influence project outcomes depends on the timing of the integration of the designer in a P3 and the degree of design criteria and flexibility allowed. In the case study analyzed, the P3 designer was able to influence downstream life cycle considerations, such as the operations and maintenance of the project; however, given the degree of definition of the design and the timing of integration of the P3 designer, it was not possible to influence the upstream design decisions. These findings allow researchers to better understand how P3s are being integrated from a design perspective and allow the public sector to realize how the timing and degree of definition of the design in P3s influences a concessionaire’s ability to make life cycle design choices.

1 INTRODUCTION

The use of public-private partnerships (P3s) as an alternative project delivery method to deliver highway projects has become increasingly attractive over the past two decades. A P3 is defined as “a contractual agreement formed between a public agency and a private sector entity that allows for greater private sector participation in the delivery and financing of transportation projects” (FHWA 2013). P3s are a potential solution to close the increasing gap between transportation infrastructure costs and funding (Buxbaum and Ortiz 2009). Governments may use P3s to reduce pressure on government budgets, expedite financing, or facilitate innovation (AECOM Consult Team 2007), among others. Implementing P3s is commonly attributed to the improved services and better value for money achieved through appropriate risk transfer, encouraging innovation, greater asset utilization and integrated whole-of-life management (Fitzgerald 2004). Value for money is defined as the optimum combination of whole-of-life costs and quality (or fitness for purpose) of the good or service to meet the user’s requirement (HM Treasury 2006). One of the reasons a better value for money is expected for P3 delivery is because of the ability of the private partner to implement cost-saving investments during the design and construction of a project that may lower the long-
term life-cycle cost during the operations and maintenance (O&M) phase. The private partner is incentivized to use such strategies when the design and construction of a project is bundled with its O&M phase into a single contract (Blanc-Brude et al. 2009). Because stakeholders have the greatest ability to influence the long-term life cycle performance of a project during the design phase (Paulson 1976), ‘life-cycle’ decisions are expected to take place in the design phase. Of particular interest is how information from all project phases, including construction and O&M, is integrated and considered when making design decisions for the project. The flow of design information—specifically whether it flows as a sequential ‘waterfall’ from one phase to another, or whether the information is iterated back and forth in a ‘whirlpool’ fashion—is expected to greatly impact life cycle considerations.

While previous studies have focused on the comparison of P3 projects to traditionally procured projects by using initial cost and schedule performance metrics that do not extend beyond initial delivery or compare overall life cycle cost performance (Blanc-Brude et al. 2006, 2009; Chasey et al. 2012; NAO 2003; SAIC et al. 2006), this study will focus specifically on life cycle considerations in the design decision-making processes. Because most P3 projects are long-term arrangements that last between 30-99 years, the scarcity of projects available for analysis has made it difficult to draw life cycle conclusions (CBO 2012). However, by focusing on life cycle considerations in the design process, this paper can contribute to our understanding of the project characteristics or conditions that enable the enhancement of life cycle design decision-making processes. To do so, the research team analyzed the design decision-making processes in a single case study of a project that implemented both traditional DBB and P3 delivery.

2 BACKGROUND

2.1 Project Delivery Methods

A project delivery method (PDM) refers to the contract methodology used to acquire and deliver the basic elements of any infrastructure project (Miller et al. 2000). It is “a process by which a project is comprehensively designed and constructed for an owner and includes project scope definition (concept and feasibility); organization of designers, constructors and various consultants; sequencing of design and construction operations; execution of design and construction; and closeout and start-up. In some cases, the project delivery method may encompass operation and maintenance” (Touran et al. 2009 p. 4). The manner in which these PDM functional elements are structured determines the PDM strategy that the owner of the facility will implement (Miller and Gerber 2012).

PDM strategies may be broadly categorized by the bundling of the procurement of the services needed to initially deliver the facility, and to provide its intended service, the usage of facility. These two phases, the delivery and usage, can be referred to as the relative life cycle phase responsibility (Chasey and Agrawal 2013). Increasing the private involvement through allocating different responsibilities increases the amount of risk assumed by the private sector during the delivery of a facility. Note that the finance element of a project is something that occurs throughout the life of a project, and the degree of responsibility for financing might vary depending on the contract terms of a project. By assigning such key functional responsibilities, a segmented versus combined (‘bundled’) PDM strategy is determined to deliver a project, meaning the bundling of these key functional elements. P3s are typically considered to be in between this range of the traditional ‘segmented’ delivery strategies, and fully privatized ‘combined’ strategies (Miller et al. 2000).

2.2 Public-Private Partnerships

A public-private partnership (P3) does not constitute a single PDM, and there are many delivery methods depending on how a P3 is interpreted. The literature on the definition and types of P3s is also vast (Hodge and Greve 2007, 2009). A P3 has been defined as an agreement between the government and one or more private partners in which the private partners deliver the service in such a manner that “the service delivery objectives of the government are aligned with the profit objectives of the private partners and where the effectiveness of the alignment depends on a sufficient transfer of risk to the private partners” (OECD 2008, p.8). More strictly, using the appropriate terminology of PDMs discussed above, P3s for this study are classified as those whose functional life cycle phases are combined, the delivery and usage of the facility,
and for which finance is also part of the risk transferred, primarily the Design-Build-Finance-Operate-Maintain (DBFOM) type of PDM.

To put into perspective the P3 environment in the US, one of the most recent published summaries from a major projects database (PW Financing 2014) indicates that there have been only 30 transportation P3s in the US, dated from 1993 through September 2014. Out of these 30 projects, 17 are currently under operation, and the rest under construction. Also, only 21 of these projects have been carried out under this described DBFOM delivery strategy, whereas the rest are leases (i.e. Chicago Skyway) (n=5) and build-own-operate (BOO) projects (n=4), which are not considered to be P3s per the definition established for this study. Furthermore, 8 of these DBFOM transactions have been structured under an availability-based payment mechanism (DBFOM-avail) over the past few years, and the rest have been structured as direct-toll payment structures or similar (DBFOM-toll). The number of projects that would allow for the intended research on P3 projects to be conducted in this study is very limited.

2.3 Life-Cycle Design

Project stakeholders have the greatest ability to influence the long-term life cycle performance of a project during the design phase. The concept of how design decision-making influences the long-term cost performance of a project and how the level of control over those costs decreases as the project evolves has been long understood by many industries. Paulson’s well-known “cost influence curve” (Paulson 1976), shows how the level of influence that decisions made in the earlier phases of a project’s life cycle phase have a much greater influence on project outcomes, at a minimal fraction of the cost of the project’s complete life cycle cost. By the time construction is completed the influence that any decision might have on the remaining life cycle of the project is minimal, if any, and might be a considerably large capital expense at that point.

![Figure 1: A Sequential 'Waterfall' (left) vs. an Iterative 'Whirlpool' Design Process (right)](image)

The traditional DBB design process can be compared to a linear ‘waterfall’ approach in which, given the segmented approach of each functional element, each phase is optimized for personal benefit (Thomassen 2011). The concept of a waterfall design process has emerged from the discussion of software development processes (Royce 1970). The general idea of such processes is that it can be considered to be an extremely inflexible design process, where inflexibility is characterized by frozen outcomes and sequential processes (Weisert 2003). As shown in Figure 1, this suggests that ideas and feedback for design decisions only flow to downstream activities but may not be fed upstream; furthermore, the inability of starting later phases in which other project participants get involved and may provide valuable life cycle feedback to the design process, alters the design.

Alternative PDMs on the other hand, such as design-build, and even more so in what can be considered to be a fully ‘combined’ PDM strategy, such as P3s, control of the design is removed from the engineer and given to the entire team. As opposed to the waterfall model, working in a complete linear fashion, in a P3, the design process is considered to be iterative ‘whirlpool’ process, with significant “over-the-shoulder” design reviews by the contractor, financier, operator, and, to some extent, the owner (Hatem and Gary...
The ability of having input into the design by other project stakeholders involved in different phases of the project life-cycle, provides the opportunity to better optimize the functionality of the project to improve a project’s overall life cycle performance.

3 RESEARCH METHODOLOGY

The research methodology for this study was an *embedded single-case study design* methodology (Yin 2009), as shown in Figure 2. The case study methodology was selected because the case study selected, the Presidio Parkway project discussed further below, was a *revelatory case* (Flyvbjerg 2006), meaning that it was a P3 project with a unique contextual setting that allowed for the opportunity to study the design process under special circumstances. Specifically, the case allowed for a side-by-side comparison of two delivery strategies—design-bid-build and P3—implemented to construct the Presidio Parkway Project in the US. This research analyzed the design decision-making processes within each of the two phases of this project, delivered under each respective PDM.

![Figure 2: Embedded, Single-Case Study Design](image)

### 3.1 Case Study Setting and Unit of Analysis

There have been limited transportation P3 projects in the US in the last 20 years, with only 21 existing projects delivered under a DBFOM-type of P3. To select the appropriate projects for this study, P3 projects whose design phase was on-going or recently finished were targeted. The Presidio Parkway Project, located in San Francisco, CA, was selected as the case for this study. This particular project was split into two phases delivered under different PDM strategies: Phase One was delivered as a traditional Design-Bid-Build (DBB), and Phase Two was continued as a P3 (DBFOM-type). The P3 developer for this project also assumes operations and maintenance for both phases after initial delivery of the project for a contract term of 30 years. This particular case became a project in which two design processes were considered under each respective delivery mode, and therefore the design processes were chosen for analysis to compare the influence of PDM strategy on design decision-making. Data was collected during the spring of 2014, when the design of the project was almost complete. The design processes were treated as *embedded units of analysis within a single case, given that they were part of the same project*.

The project’s condition can be considered to be a ‘hybrid’ project, meaning that it is not a brownfield nor a complete greenfield project since it is adding a significant amount of structures as well as the replacement of most of the existing facility. The project is approximately a 1.5 mile long road with a significant amount of structures, with four cut-and-cover tunnels, six bridges, and three interchanges split between the two phases. Furthermore, the P3 delivery of the project was structured as an availability-based payment mechanism, as opposed to a toll-revenue P3 mechanism.
3.2 Data Sources

This research collected data from project participants by conducting semi-structured interviews. This research analyzes the data collected from the interviews, which were the most in-depth source of data. A total of 16 on-site interviews were conducted, with 20 different participants. The interviewees were targeted to represent a broad spectrum of all stakeholders involved in the project, particularly those that could have the knowledge to discuss design issues experienced in this project. Table 1 lists the organizational role and project role for each of the participants.

Table 1: Description of Case Study Project Interviewees

<table>
<thead>
<tr>
<th>Pseudonym(s)</th>
<th>Project Phase</th>
<th>Organization</th>
<th>Project Role</th>
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<td>Waller &amp; Clayton</td>
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<td>Project Sponsor CM</td>
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</tbody>
</table>

The research team conducted exploratory, semi-structured, in-depth interviews. The format employed was meant to develop ideas and research hypotheses rather than to gather facts or statistics. Determining the number of interviews to conduct was dependent on reaching theoretical saturation, when new information was no longer mentioned. As a result, quality was preferred over quantity (Oppenheim 1992). As Oppenheim (1992, p. 67), explains, “the job of the depth interviewer is thus not that of data collection but ideas collection.” Using this approach, interviewees were asked about the design decision-making process on each phase of the project and conditions that may have enhanced or constrained life cycle considerations in the design. The semi-structured interviews began by asking directly how the choice of project delivery method had influenced the life cycle design decision-making process, particularly, characteristics of life cycle design were explored, including the integration of life cycle functional properties (Design, Construction, O&M, Reconstruction and/or End-of-Life properties).

3.3 Data Analysis

The research team used QSR Nvivo software to organize and analyze the data. The interviews were audio-recorded, transcribed into text, and imported into the software. Over 17 hours of recorded audio time for the interviews shown in Table 1 resulted in over 215 pages of text, after all audio files were transcribed word-by-word. The data was systematically coded to identify significant patterns following the coding process described by Miles et al. (2013). The coding process was primarily driven by two ‘cycles’ that allowed the researchers to draw conclusions from the interviews regarding the life cycle design decision-making process as experienced in this case. The first cycle of coding was an organizational, or structural approach to sort appropriate data into macro-categories for further analysis. Following this process, a more explicit identification of the content in the interviews allowed for more a ‘substantive’ and ‘theoretical’ description of the data to be analyzed more in line with the research objectives. For example, one of the interviewees, when discussing the life-cycle design considerations in phase two: “I think this project has not had as much leeway for innovation as what I think of is a typical P3, or a typical design-build project might,
because we have been more confined by what was done in phase one of the project with respect to the design. So in some ways I sort of feel like there has been a little bit less innovation on this project than I would have expected.” This section of the interview was coded to themes of ‘innovation’ and ‘design flexibility’.

Following the initial coding, the data was then further analyzed. During this process, we focused on explanation building (Yin 2009). Specifically, we focused on how the theoretical proposition of this study was either supported or challenged from the data collected. The theoretical proposition was: Design information in a segmented PDM strategy flows one-way, downstream in a sequential design process in which no downstream design feedback may be incorporated into upstream design activities. In a combined PDM strategy, an iterative overlapping design process allows for a two-way information exchange between upstream and downstream design activities, thereby allowing for life cycle design to be better optimized. This paper describes and explains what has happened in this single case, regarding the stated proposition. This includes interpreting and mapping the results from the case study to this proposition in order to understand it from this single case (Eisenhardt 1989).

4 FINDINGS

The Presidio Parkway had a significant amount of overlap between phase one (DBB) and phase two (P3). As a result, while the project provided an ideal laboratory setting for analyzing two different delivery methods under similar settings, the overlapping sequence of processes also created constraints for attributing differences and similarities solely to one PDM strategy employed. However, the researchers were able to identify project characteristics that influence life cycle design decisions under a P3. These characteristics are explained as the timing of implementing a P3 in a project during its development, and the design flexibility of the project. Furthermore, as part of using this case study to explain the life-cycle design decision-making process under a P3 delivery strategy, examples of downstream design feedback are also discussed. These examples are related to the design feedback that benefited constructability and the O&M phase of this project.

4.1 Timing of P3 Implementation

When the interviewees were asked about design decisions, all participants indicated that the unique phasing of the delivery methods limited the ability of the P3 designer to influence the design and consider life cycle aspects. In this case study, the P3 developer entered the project after many design decisions had been made. As Hayes shared, “just because phase one was already built, a lot of ground work was done for the P3 group, the developer, and in the contract we have some language that phase two has to be similar to phase one. So pretty much it takes the innovation out of the developer.” Other interviewees indicated that, if a P3 project is to benefit from the private sector's innovations, the P3 developer has to have the ability to alter the design and be able to provide value engineering input. As a result, the definition of the design requirements and its implications for design flexibility must be given thoughtful consideration upfront by the public sponsors. A recent report (Parsons Brinckerhoff et al. 2013) indicated that the private sector may be able to best define and incorporate design alternatives based upon life cycle considerations in a highway project prior to the conclusion of the environmental clearance process. On the other hand, a ‘post-environmental clearance’ P3 procurement may reduce the ability of the P3 developer to propose alternative technical concepts (ATCs) that will influence life cycle design optimization decisions significantly.

4.2 Design Flexibility

Interviewees’ also indicated that contract specifications limited the design flexibility of the project. These contract specifications are the contract documents in which the owner communicates a project’s requirements and how conformance with those requirements will be measured, as thus, determine the amount of flexibility allowed in the design (Loulakis 2013). The degree of specifications varies from performance-based specifications (PBS) that describe the final product based upon operational characteristics, and thus offer the P3 contractor a greater degree of flexibility in how to achieve the final product; to ‘prescriptive’ specifications that explicitly describe the final product in terms of component materials, dimensions, tolerances, weights, and even required construction means and methods, thus
giving the owner maximum control of the project (FHWA 2004). For this project, the P3 design process was considered to be relatively prescriptive. As McAllister indicated, “I think it [this project] is rather prescriptive for a P3 project because it is supposed to mimic the look of the other side so there isn’t really a lot of flexibility… innovation is probably coming from the means and methods, but in terms of appearance there isn’t really a lot you can play with.”

Because the P3 delivery finished a project half-built under a DBB, the design specifications had to be prescriptive for this project: “You don’t want to be too prescriptive, in fact you don’t want to be prescriptive at all; however, in this situation there has to be some prescription… using these contract documents is a challenge. You don’t want to restrict things too much but then, at the same time, you want to make sure what they are going to build is a mirror image of what is already there.” From a life cycle design perspective, the ideal setting for a P3 is when ‘degrees of freedom’ are given to the P3 designer to meet a functional need without limiting the design parameters that the designer might propose. Overall, the timing of the P3 and the contractual specifications of the project greatly affected the P3 developer’s design flexibility. One interviewee, Green, indicated that the limitations inherent in brownfield projects may always limit design flexibility and that the optimal conditions for considering lifecycle within the design are Greenfield projects: “Maybe the most beneficial application of a P3 is where you have more of a Greenfield project where there is a lot of flexibility, so as what the franchise can do meeting a fundamental need, but flexibility to kind of start from scratch as to what it is they can do and innovate more”.

4.3 Downstream Design Feedback

The timing of P3 implementation and the design requirements for this project limited the ability of the P3 developer to alter the early, upstream design. However, downstream from the design phase, particularly constructability issues and O&M processes benefitted from the life cycle considerations used by the P3 team.

4.3.1 Constructability

Within the P3 delivery strategy, the developer subcontracted the design and construction of the project. As previous studies have shown (SAIC et al. 2006), constructability reviews are typically incorporated into the design phase on P3 projects, thus enhancing the construction phase of projects. Within this project, we compared the approaches taken to construct the piles for the project’s viaducts. In phase one, under the DBB approach, the project sponsors were ‘conservative’—they did not want to take any risks in having the piles fail and therefore ‘over designed’ the piles. One of the project sponsors, Waller, explained their approach in phase one for this particular example: “we designed it a full depth casing because [the department] didn’t want to take a risk, if we had historic buildings next to our new bridge, we couldn’t do any pile driving because we would collapse the building, so we said ‘let’s drill down a full depth casing…’ we took an extremely conservative route plus we didn’t want to have a 12 foot diameter hole collapse on us.” Under this phase the sponsors did not try to optimize or make the design and construction process more efficient, from an economical perspective. In comparison, under the P3 delivery, phase two, the contractors chose a different design to eliminate the need for casings, as Ellis indicated: “we didn’t have the permanent case because our designers didn’t think that we needed that, we added rebar, and we did something to eliminate the need for permanent casings.”
This specific example shows how a project component was approached differently under different PDM strategies. The following excerpt from one of the interviews with the public sponsors, Clayton, highlights how this difference is reflected by their ‘motivations’: ‘We were under pressures, but different pressures, so it is kind of interesting because, okay, this is Doyle drive, this is kind of a high profile job in the Bay Area in the State of California so we were both under pressure but for different reasons. We want to get to seismic safety, we didn’t want to delay the P3, it costs us money to delay plus we don’t get the seismic safety traffic switch which is important for public safety. They had different reasons, they want to get done, they have a banker, their financier’s saying ‘hey when are you going to get done, pay us back?’ So that is kind of interesting, we have pressures but for different reasons.” Looking at this comparison, the motivations that drive these particular design decisions can be appreciated. In one phase, ‘safety’ drove the decision to build the piles with a permanent casing. Phase one’s more ‘conservative’ design approach can be argued to be driven by an underlying motivation to reduce all risk of potential failure which may delay the achievement of seismic safety, given the importance of this particular arterial road in the region for public safety. In phase two, the decision to eliminate permanent casings can be argued to be driven by an underlying motivation that resulted in a more economically efficient design, and that significantly reduced the time to construct the second high viaduct, given the financial pressure that the P3 team experienced.

4.3.2 Operations & Maintenance

During the construction of phase two, the O&M provider began operations for the scope of work delivered in phase one. As a result, there was in-depth integration of the O&M service provider with the P3 design-build team in phase two, allowing the O&M team to provide significant feedback to the designer as they began the operations of the complex facility. As discussed, the overlapping of the project phases (phase one and phase two) allowed for the O&M phase to begin during the construction of phase two. “In most projects you don’t normally get that and [the P3 designer] would tell us all day long, ‘we never really get to talk to the end user and how they want it configured, how they want it to function, you know, do you want it to do this? or do you want it to do this?’ And those are all the conversations that we have on a weekly basis” commented one of the O&M contractors, Eddy. “So those are the things that we are pushing for and we are getting on this project, but those things may not have been thought of in phase one, because hey guess what? In most cases, in most typical delivery, you never really talk to the end user, and say ‘I like your design, but me getting out there to access or do what I need to do out there could be done in a little different way, it isn’t going to cost more money, it’s just a little different way to do it and you can take into account what my needs are at the end of the day.’”
This particular response has been provided to show the type of conversations that the O&M provider is having with the P3 designers in order to benefit the O&M phase of the project for both phase one and phase two scopes of work. Phase one might have not considered the operability as in-depth, including the systems that were installed for traffic management in one of the tunnels, as much as phase two was able to incorporate. The ‘systems’ of this project, considering the fact that this project is more a ‘tunnel’ project than it is a road project, were a very important component. Having four tunnels that the O&M contractor is responsible for, which carry over 100,000 vehicles, average daily traffic, and this being the main artery connecting the North Bay to the San Francisco through the Golden Gate Bridge shows the importance of the systems in this project. This same interviewee, Eddy, commented: “a lot of times I think phase one was built as a roadway project and not necessarily a tunnel project which has a lot of more intricacies in terms of how traffic is managed, how the systems in the tunnel are managed, everything from the lights system to the fire alarms to the CCTV cameras and how that all talks and communicates together… but I think the real benefits are in the systems and devices and how that is used and that is I think something that is kind of in the back, that a lot of people don’t understand. That is where your bang is, your bang for your buck is there. In terms of the systems and how they operate, how they all intercommunicate together and how we get things off the roadway.”

This second example shows the O&M phase, being a downstream phase from a life-cycle perspective, being enhanced by the P3 strategy in this project. Having the O&M operator being closely aligned with the P3 designer, specific design input regarding the systems of the tunnels, for example, were design feedback that was incorporated to improve the operability of the project. This in turn, enhances the long-term performance of the project overall from an operations perspective.

5 CONCLUSIONS AND FUTURE WORK

This study explored and presented initial findings from how life cycle design decision-making processes are influenced by project delivery methods in the embedded case study of the Presidio Parkway project. P3s are considered to be the most integrative and ‘combined’ project delivery strategies to deliver infrastructure projects. Through the analysis of interviews conducted with project participants we found that the timing of P3 implementation, the degree of design flexibility, and the degree of overlap between the O&M and design-build team influences the ability to consider life cycle perspectives and private sector innovations during the design.

These initial findings are limited to the single case study of this project. Ongoing work will extend these findings by analyzing life cycle considerations in the design phase on two additional P3 transportation projects in the US, and by conducting a cross case comparative analysis. To conduct this analysis, we will select projects to analyze based upon characteristics such as the technical complexity of the project (i.e. structure-heavy project vs. a road project), the DBFOM payment mechanism (i.e. direct tolls vs. availability payment), the project condition (i.e. greenfield vs. brownfield), and the organizational structure of the project (i.e. a fragmented vs. integrated structure, and financial leverage).

6 REFERENCES


SAIC, AECOM, and University of Colorado at Boulder. 2006. “Design-Build Effectiveness Study - As Required by TEA-21 Section 1307 (f).”


BRAZILIAN AND CANADIAN OIL&GAS INDUSTRIES – SIMILARITIES, DIFFERENCES, CHALLENGES AND PERSPECTIVES FOR A SUSTAINABLE INDUSTRY

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Abstract: The Brazilian and the Canadian Oil and Gas industries are facing similar challenges now: both countries are developing huge oil fields; as a result, companies, governments and policy makers have started to invest escalating resources in projects and regulations. These efforts have provided both countries with a significant increase in their oil production. Brazil discovered the Pre-Salt field, located off its Southeastern coast, what resulted in complex technical researches whose outcome will guarantee a safer and more environmentally friendly production. The oil sands in the western Canada, along with the shale formations, despite the abundance, have been utterly criticized by environmentalists who report the possible impacts of the methods used to extract the oil. This paper aims to analyze the similarities, differences and challenges that both countries have to confront. In addition, as many companies in other sectors, the oil and gas industry has taken the initiative to demonstrate that their activities are in accordance with the best practices of sustainability by seeking the optimal efficiency in water consumption, energy and waste management; as well as minimizing carbon emissions to reduce the greenhouse effect. Nevertheless, the oil and gas industry still has to face the common sense that their activities cannot be innovated to reduce environmental impacts and therefore be aligned with the best sustainable practices. Analogous to the movement that has led the AEC industry to create the “green buildings”, two proposals on how to address the sustainability of these projects is presented.

1 INTRODUCTION

Despite the recent fall in oil prices, which have been striking the oil and gas industry, some projects in Brazil and Canada will be postponed or even canceled and yet many will still continue to the next phases. Brazilian and Canadian oil and gas industries are in continuing evolution and are expected to maintain it for a long time. Nevertheless, in today’s environment, more and more corporations are willing to demonstrate that their activities are in accordance with the best practises of sustainability so as to guarantee the optimal efficiency in water consumption, energy and waste management as well as to minimize carbon emissions and hence reduce the greenhouse effect. This is much expected from the Brazilian and Canadian oil and gas industry because of the reliance of global oil demand on their non-conventional oil and gas resources, as noted by Kerr (2011; 2012a; 2012b). Furthermore, sustainable development also involves an appropriate balance between environmental solutions, and social and economic issues. As a result, stakeholders, clients, investors and government parts have been demanding dramatic changes in the way companies are investing in new projects.
Aiming for better sustainable results, the oil and gas industry has a key role by addressing new practices that have been widely used to develop sustainable rating systems like the ones that have been extensively utilized to assess the green buildings such as LEED and BREEAM. However, the specific characteristics of the oil and gas industry do not permit a full application of building rating systems into industrial projects. Although many rating systems are vastly used to analyse the sustainability of green buildings, few attempts to assess the sustainability of oil and gas projects has been adopted so far. Compared to buildings, industrial projects are typically larger, have a longer lifetime, take longer to construct and consume more energy and water overall.

As part of industrial projects, the oil and gas industry has to challenge the common sense that its projects cannot be designed to reduce environmental impacts and therefore comply with the best practices of sustainability. Thus, despite the outstanding initiatives of the sector, the oil and gas industry should incorporate in its projects the valuable concepts of green buildings projects. In this work, we present two different proposed researches on how to address the sustainability of oil and gas projects. The first is the development of a universal green rating system framework that could be implemented in the oil and gas sector. The second proposal focuses on the main causes of the climate change. A method using BIM – Building Information Modelling to calculate and optimize the embodied energy and corresponding emissions of oil and gas projects is proposed.

2 CURRENT SCENARIO OF MAIN BRAZILIAN AND CANADIAN OIL AND GAS PROJECTS

A comparison between the Brazilian and Canadian oil and gas projects is structured below according to subareas of the oil and gas industry such as upstream (oil); downstream (refining); and natural gas, liquefied natural gas (LNG) and transportation.

2.1 Upstream – Oil

Brazil is the eleventh oil producer of the world (EIA, 2013), with a daily average production of 2.6 millions of barrels of oil equivalent. The Brazilian oil and gas industry is comprised of many players, with the state-owned Petrobras as the largest one. Founded in 1953, the company is already present in seventeen countries. It is controlled by the Ministry of Mines and Energy of Brazil and has operations in exploration and production, refining, oil and natural gas trade, transportation, petrochemicals, retail distribution, electricity, biofuels and renewable resources among others (Petrobras, 2014a). Located in the Atlantic ocean off the southeastern coast, the Pre-salt province discovered in 2006 (Petrobras, 2014c) has already increased Brazilian proven reserves to 15.6 billions of barrel (ANP, 2014), and it is expected to double until 2022 (Folha de Sao Paulo, 2014). The Pre-salt and other domestic demands have caused a boom in the number of proposed offshore projects in Brazil: 38 platforms (including drillships), of which 7 are already in operation, 49 vessels and 20 waterway convoys among others (Petrobras, 2014b).

Canadian crude oil reserves is the third largest in the world with 173.6 billions of barrels (EIA, 2014), just behind Saudi Arabia and Venezuela, thanks to the oil sands located in the western provinces, accounting for 167 billion barrels or nearly 96% of overall Canadian reserves. As opposed to Pre-salt in Brazil, the potential of oil sands has been widely known for decades, but they became economically viable just when oil price reached around sixty US-dollars at the beginning of the 2000’s. This permitted massive investments in in-situ and pit mining projects, increasing the Canadian daily oil production from slightly over 2 million barrels at the early years of last decade to 3.7 million in 2014 (NEB, 2015). Besides the oil sands projects, Canada has also seen investments in the offshore fields along the Atlantic coast and Western Union Sedimentary Basin. However, the offshore projects do not seem to represent a significant increase in the current level of oil output compared with the potential of oil sands (EIA, 2014).

Despite the difference of size of both national reserves, the main similarity of the Brazilian and Canadian oil reserves relies on the fact that many experts anticipate a delay in global oil peak, alleging the potential of these future oil prospects and others. They call this type of oil production non-conventional, since it cannot be produced by the well-known conventional extraction methods. However, some authors are skeptical regarding the future of the oil and gas industries of these countries, as the increase in their production will heavily depend on developing technologies and a relatively high breakeven oil price that
justifies new investments (Sorrel et al., 2010; Sorrell et al. 2012). Furthermore, the expected improvements in technologies are not only to implement oil outcome but also to guarantee a safe and environmental friendly operation.

2.2 Downstream – refining

As the Pre-salt is expected to boost the Brazilian production to about four million barrels per day until 2022, the surplus of oil should be either processed or exported. As a result, four new refineries and revamps have been proposed, which will increase the Brazilian refining capacity from currently 2.1 million to 3.3 million barrels per day (Petrobras, 2014d). One refinery, Rnest, located in the state of Pernambuco, is already under operation since December 2014. Two other projects are on hold. Brazilian downstream projects have been demanding a great effort from the owner and contractors, as refining projects are very capital intensive, require high-skilled workers, demand excellence in quality assurance and therefore a remarkable supply chain. The last refinery had been constructed more than thirty years before Rnest started up.

As opposed to the Latin American country, Canada opts to export its oil surplus to the U.S., where the actual installed refining capacity is larger, underused and more suitable to process the viscous and heavy sand oil (MacLellan, 2014). This strategy is highly controversial, as opposers argue that new refineries would generate more post jobs, more investments; and reduce the price of fuels and the international dependency on processed products, such as gasoline and diesel (Mendleson, 2013). One of the few exceptions is North West Redwater Partnership, a refinery that is under construction in Alberta and with startup expected to late 2017 (North West Redwater Partnership, n.d.).

2.3 Natural gas, liquefied natural gas – LNG and transportation

Brazil has already concluded some of the major projects considered strategic for the natural gas pipeline network. Concluded in 2010, GASCAC, or Cacimbas/Catu gas pipeline, is a 954-kilometer-length stretch, which permitted the integration between the southeast and northeast gas pipeline networks. As a result, natural gas that is imported from Bolivia can also supply the region Northeast of the country.

Brazil has also opted to construct three LNG import terminals. These facilities permit the import of natural gas on ships, opening new import markets and, consequently, reducing the dependency on the current inland natural gas imports.

Canada is already a natural gas exporter with the U.S. as the only buyer of the Canadian gas. With the significant findings of shale gas in the U.S. and Canada in the last years, Canadian market is shifting the strategy and seventeen LNG export facilities were proposed, entering the regulatory process (Natural Resources Canada, 2014). However, due to the recent fall in oil prices, only two projects sponsored by Chevron/Woodside Petroleum and Shell respectively may proceed, with the former expected to start up in 2021 (Hussain, 2015). Both projects are located in the Western Coast, British Columbia.

In Canada, there are also proposed improvements in the transport network such as Keystone XL. Under lively debate because of the allegedly environmental impact, Keystone XL pipeline, with 529 km in Canada, is expected to increase the offer of the crude oil produced in Alberta to the U.S Golf Coast refining system, whose refineries are considered more suitable to process the viscous and heavy sand oil. However, the issuance of a U.S. presidential permit has delayed its construction (TransCanada, n.d.).

2.4 Summary of projects

Table 1 provides a summary of the main projects of the Brazilian and Canadian oil and gas industries. The projects presented in this work and on the table below were selected based on their level of relevance as well as the similarities between both countries. Thus, the main goal is to illustrate the current general status of the oil and gas industry in both countries and the correlation with future challenges concerning sustainability that will be presented later. It is not intended to list all current oil and gas projects in Brazil and Canada.
Table 1: Main Brazilian and Canadian oil and gas projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Type</th>
<th>Country</th>
<th>Status</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-salt portfolio</td>
<td>Upstream</td>
<td>Brazil</td>
<td>Ongoing</td>
<td>Increase oil production to 4 million bbl/day</td>
</tr>
<tr>
<td>In-situ and open mining sand oil projects</td>
<td>Upstream</td>
<td>Canada</td>
<td>Ongoing</td>
<td>Increase oil production to 5 million bbl/day</td>
</tr>
<tr>
<td>Refining system resizing</td>
<td>Downstream</td>
<td>Brazil</td>
<td>Phase 1 RNEST concluded</td>
<td>Increase processed oil to 3.3 million bbl/day</td>
</tr>
<tr>
<td>North West Redwater refinery</td>
<td>Downstream</td>
<td>Canada</td>
<td>Ongoing</td>
<td>Increase processed oil in 150,000 bbl/day</td>
</tr>
<tr>
<td>GASCAC/GASENE</td>
<td>Natural gas</td>
<td>Brazil</td>
<td>Concluded</td>
<td>Permit network integration</td>
</tr>
<tr>
<td>Shale gas development</td>
<td>Natural gas</td>
<td>Canada</td>
<td>Ongoing</td>
<td>Increase NG production/export</td>
</tr>
<tr>
<td>Import LNG terminals portfolio (3 terminals)</td>
<td>LNG</td>
<td>Brazil</td>
<td>Concluded</td>
<td>LNG import facilities</td>
</tr>
<tr>
<td>Export LNG terminals portfolio (2 terminals)</td>
<td>LNG</td>
<td>Canada</td>
<td>Ongoing</td>
<td>LNG export facilities</td>
</tr>
<tr>
<td>Keystone XL</td>
<td>Transport</td>
<td>Canada</td>
<td>On hold</td>
<td>Oil export pipeline to US</td>
</tr>
</tbody>
</table>

3 TOWARDS A MORE SUSTAINABLE INDUSTRY

3.1 Green buildings vs. the oil and gas industry

Green buildings are designed to minimize the potential impacts of constructions on the environment, to contribute to the reduction of the emissions of greenhouse gases and thus to a long-term sustainable development. The concept of such buildings aims for environmental responsibility throughout its whole life cycle, from the design until the demolition. The main consolidated issues covered by sustainable designs are (Building Research Establishment n.d.; US Green Building Council n.d.):

- Energy efficiency
- The efficient use of water
- The environmentally efficient use of materials
- Impacts of construction methods
- Indoor environmental quality
- Operation and maintenance
- Waste management

With the advent of green constructions, the necessity of developing sustainable rating systems have been arisen so as to assess how sustainable and environmentally friendly these new projects are. Rating systems are benchmarking codes and one important step to be taken by corporations that intend to demonstrate to society that its projects are effectively green. Sustainable rating systems are structured, decision-making tools in support of measuring environmental performance throughout the project life cycle and verified by third-parties (Poveda, 2014).

Examples of factors that should be considered when developing a rating system assessment throughout the life cycle of projects should include the project size, kind of industry, surroundings, codes, standards, regulations and the stakeholder’s requirements. The majority of rating systems have been developed considering these aspects. The most popular rating systems worldwide are ATHENA (Canada), BEAT 2002 (Denmark), BREEAM (UK), CASBEE (Japan), LEED (USA, Canada, Mexico), DGNB (Germany),
NABERS (Australia), HQE (France), ENVEST 2 (Netherlands) and others. In Brazil, more recently, the ratings systems AQUA (Vanzolini Foundation, n.d.) and LEED Brazil have been launched.

Adaptation from a green building rating system to industry has no efficacy, since the specific characteristics of industrial projects do not permit a full and integrated application of building rating system. Moreover, the impacts on the environment of industrial projects are far more critical than in buildings, including the phases of demolition and disposal at the end of the economic life of the project.

Although engaged in several remarkable sustainable projects, the oil and gas industry should advance and incorporate the green philosophy already found in the building industry. As one of the first precursors, Poveda (2014) developed a rating system to measure the environmental performance of oil sands and heavy oil projects in Canada, called the WA-PA-SU project sustainability rating system. However, due to the large variety of projects of the oil and gas sector around the globe, a full application of Poveda’s framework, which was based on the oil sands in Alberta, should be carefully verified before extended to other oil and gas projects.

### 3.2 Is ISO 14000 series enough?

Many oil and gas companies in Brazil and Canada are certified ISO 14001, the most popular environmental management standard; and also demands the use of this code from its subcontractors. Based on the PDCA (Plan, Do, Check and Act) cycle, however, ISO 14001 is an environmental code that certifies the corporate management processes and does not ensure the quality of the final product since it does not define goals and indicators, which should be established, planned, measured and controlled by the certified entity. Rondinelli and Vastag (2000) point out that ISO 14001 does not measure the actual environmental performance of a plant or company. In fact, it ensures that the company has a management system to deal effectively with its environmental impacts, meet regulatory mandates and go beyond legal requirements to achieve continuous environmental improvements, but there is no way of externally verifying that such improvements actually occur.

### 3.3 Building Information Modelling (BIM) and Sustainable Engineering

Building Information Modelling (BIM) represents the development and use of n-dimensional models to simulate the planning, design, construction and operation of the future facilities (Azhar, 2007). BIM carries all information related to the model including its physical and functional features and project life cycle information as "smart objects". According to Azhar (2007), a building information model can be used for the following purposes:

- 3D visualisation of the model
- Detailed design drawings for construction and purchasing of the different facilities such as MEP systems
- Code reviews, like those done by fire departments
- Forensic analysis by simulating potential failures, such as leaks, evacuations plans etc.
- Operation/maintenance of facilities, including the use of the model for planning renovations and maintenance operation
- Cost estimating (materials quantities are automatically extracted and changed when any changes are made in the model)
- Construction sequencing (used to create material ordering, fabrication and delivery schedules for all project components)
- Conflict, interference and collision detection, for models are created in 3D space, hence all major systems can be visually checked for interferences.

More and more, for projects pursuing green certifications, designers have to conduct in-depth sustainability analysis based on a building’s form, materials, context, and mechanical-electrical-plumbing (MEP) systems, as the most important decisions regarding a sustainable project are made during the design and planning stages (Azhar et al., 2011). BIM is also a powerful tool used to optimize the use of passive solar energy for lighting, ventilation, heating and cooling and therefore reduce overall energy use
of the building. In addition, BIM is also employed to perform life cycle energy assessment simulations so as to provide designers, owners and engineers with valuable information on energy, emissions and impacts over the lifetime of the project.

3.4 Embodied energy of industrial projects

According to Harvey (2010:35), buildings account for more than one third of total energy use in world, whereas industry also represents at least one third of total energy consumption. Agriculture and transport sectors are responsible for the remaining one third. Although buildings and industry demand approximately the same amount of energy, most works involving sustainable design are just related to buildings. This is probably due to the higher level of complexity of industrial processes, more complex design and the immense variety of materials used in industry. All these aspects make it difficult to create a unique and standard green code, such as LEED, for industry.

Embodied energy is the total primary energy used to extract, process, manufacture, deliver and construct materials, assets, equipment or facilities; and should also include the feedstock energy, which is the energy value of energy commodities that eventually are incorporated in the final product (Harvey, 2010:331). Yung et al. (2013) published a literature review of 38 works involving 206 cases and concluded that the initial embody energy represents from 7.5 to 7.8 years of the total energy use in buildings’ life. It can be an indicator of the overall environmental impact of projects, since energy use produces carbon dioxide and therefore contributes to the greenhouse effect. Embodied energy approach considers only the total primary energy spent until the point in which the installation is commissioned and ready to start-up, not including the operation or decommissioning. As of this phase, the facility is operational and all energy use is classified as process energy, whose efficiency is examined by the related process engineering.

Contrary to the embodied energy approach, the life cycle assessment evaluates all the impacts over the whole life of a material or element (from cradle to grave). Although the main goal is to reduce the embodied energy of an installation, one of the most important observations derived from the embodied energy perspective is to consider embodied energy over the whole lifetime of a project, since an increase in the embodied energy might lead to a reduction in the operational energy over the lifecycle and therefore a reduction in the total energy use of the project. This trade-off relationship will depend on the percentage use of recycled materials, the performance of the individual systems, the avoidance of wastes, construction methods and many other aspects that can influence the operation and maintenance of the facility. In this sense, this method resembles the preliminary study of economical viability of the project, with energy instead of cost.

Likewise sustainable rating systems, the embodied energy analysis has been already in use by the building industry, although a great effort is still necessary to fill up the existing research gaps (Ariyaratne and Moncaster, 2014). In most works, BIM was utilized as the main tool to calculate embodied energy and respective carbon footprint. Articles, works or case studies related to the use of the embodied energy approach by the oil and gas industry could not be found until the conclusion of this work.

4 DISCUSSIONS

Based on the situation cited earlier, two proposals were identified to address the sustainability of oil and gas projects. These proposals are presented below.

4.1 Universal oil and gas green rating system

As observed earlier, the complexity and the variety of the industry do not permit a full application of current green building codes. Contrary to the industry, the building sector is a more standard-based sector. In the oil and gas industry, besides the variety of projects (plataforms, refineries, power plants and much more), the list of regulatory requirements is often longer, which demands more resources and effort to be met. In addition, most of these projects are located in remote areas, posing a higher potential impact on the environment when compared with buildings.
A universal framework of a green rating system for the oil and gas industry that could cover all types of projects around the globe is desirable. This would permit the comparison of similar projects by means of a quantitative analysis. As mentioned earlier, Poveda (2014) concluded a valuable research project about a sustainable rating system that can be applied on the oil sands and heavy oil industry in Canada, the WA-PA-SU. However, further analysis is necessary in order to evaluate the applicability of the proposed framework into other types of projects and in other parts of the globe. In addition, Hunt (2005) developed a sustainable rating system for bridges based on the LCA and replicating several existing criteria of the LEED certification. Envision 2.0 (Graduate School of Design – Harvard University, n.d.), a rating system for sustainable infrastructure covers civil infrastructure projects such as roads, bridges, pipelines, railways, airports, landfills and others. These previous works suggest that the academic community have already identified promising improvements in the effort of the industry to become more sustainable, and that a green rating system for each sector may be a coherent evolution.

4.2 The use of BIM to optimize the carbon footprint of oil and gas projects

Instead of looking for a green rating system that would address all concerning dimensions of sustainability, as the ones already mentioned in section 3.1, another proposal is to focus on the carbon footprint of oil and gas projects. The challenging emission levels, which perhaps will be agreed on the next United Nation Climate Change Conference in November 2015 by attending nations, will not tolerate the current emissions provided by business as usual – BAU. As a result, carbon caps or tax will be probably levied in many nations and therefore the lifecycle energy in industrial projects should be taken even more seriously than nowadays. This issue will be considerably more challenging in developing countries, such as the BRICS – Brazil, China, Russia and South Africa, where the current infrastructure is still under development, demanding huge amounts of equipment, construction sites and energy intensive materials, such as concrete, steel, aluminium and copper.

As seen in the AEC industry, BIM as a tool to perform a lifecycle energy analysis in oil and gas projects will play an important role due to its ability to integrate geometric features of the model with non-geometric attributes. In addition, BIM also has the ability to generate schedules and simulate the construction site, which will also interfere in the overall embodied energy of the project. All these features facilitate changes in the model, which are accomplished in a consistent and automatic way.

4.3 The role of project management in sustainable engineering

With so many requirements to be fulfilled by green projects, the role of project management has to be stressed, since the project team also have to meet the planned cost, conclude it on schedule and guarantee the quality requisites in order to be considered economically viable. One of the main complaints of owners is that green buildings normally lead to cost overruns and schedule delays. Figure 1 illustrates the main aspects discussed in this work, showing the main categories of projects (building; energy, in which oil and gas projects are included; and infrastructure) and the role of the best practices of project management to ensure that green projects will not only achieve the goals of sustainability but also guarantee their compliance with cost, schedule and quality requirements agreed with the owner and other stakeholders.

The additional sustainable requirements make projects even more challenging than traditionally they are, and only benchmarking practices of project management can assure green projects will be supported, sponsored by owners and therefore will have the chances of success of the project maximized. Once the various constraints are incorporated in the preliminary design, such as the ones mentioned in items 4.1 and 4.2, in both proposal (not only on the lifecycle energy assessment), the model can be implemented in a BIM system, for example, and used as an optimization tool in order to find the most suitable conditions allied with cost, schedule, quality assurance and sustainable indicators.

The choice for one of the proposals presented above and the respective research development is part of first author’s Ph.D. program, and further findings will be partially published later on.
5 CONCLUSION

Although the recent fall in oil prices, many oil and gas projects around the world are expected to advance to the next phases. Regarding Brazil and Canada, oil and gas specialists and corporations are growing expectations due to the potential contribution of their national oil outcomes to maintain the global oil demand in the near future. In fact, even with the claims to reduce the fossil fuel dependency and with the restrictions that can arise with international agreements at the end of 2015, the oil and gas sector will still have an important role to guarantee the global energy offer for a long period.

In this sense and despite the recognizable performance of the sector, the oil and gas industry has to go further and adopt new concepts such as the green philosophy that is more mature in the building industry, for industry and buildings are responsible for equally energy emissions and energy use. Two proposals on how to address the sustainability of oil and gas projects were presented. They will be deeply analysed on a Ph.D program and published later on. The first is an attempt to develop a universal green rating system for the oil and gas industry. The framework proposed by Poveda (2014) will be considered as an initial point. The second is the use of BIM to assess the initial embodied energy and respective carbon footprint of oil and gas projects. The latter is more closely related to climate change due to the carbon emission goals that may likely arise soon, whereas the former deals with all dimensions of sustainability more broadly. In both proposals, the role of the best practices of project management has to be underlined, for green projects still have to comply with cost, schedule and quality requirements in order to be considered viable.

Finally, the challenges of the oil and gas sector are not few, since the industry has to confront the common sense that the exploration and production of oil and gas cannot occur without reducing environmental impacts and therefore without complying with the best practices of sustainability. However,
based on notable actions, the sector has demonstrated to be open to new changes; willing and aligned with the society to evolve to achieve benchmarking results in sustainability, thereby contributing with the global efforts to guarantee the climate stabilization and the sustainable development.

References


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DESIGN AND VALIDATION OF THE FIRST PHASE OF THE NEW CHRONOGRAPHICAL STANDARD PROTOCOL FOR CONSTRUCTION PROJECT SCHEDULING

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Abstract: Graphical modeling is considered to be a suitable approach for displaying project data because of its ability to communicate information clearly and effectively through graphic means such as shapes, connectors, colours and textures. However, current methods and software do not propose a standard protocol for the graphical representation of the scheduling. Little research has been undertaken in this area and therefore, it has been up to the individual planner to set his or her own standard. We have developed the first phase of a new standard protocol for construction project scheduling compatible with Chronographical Modeling. This first phase consists of the development and validation of a graphic convention including textures and colours. The present paper discusses the validation phase of this convention. Its main objective is to validate a range of textures that represent the construction activities. This validation was performed through a case study with the participation of 15 planners, as well as graduate and undergraduate students. It consists of several tests including the application of the various textures of the proposed convention to a building scheduling. The results of the case study were used to assess the suitability of the protocol and its visual clarity while simultaneously seeking to diminish the mental effort necessary for finding information. Future phases are designed to integrate other graphic elements to the protocol, such as shapes, symbols and codes.

1 INTRODUCTION

Graphical modeling is considered to be a suitable approach for displaying project data because of its ability to communicate information clearly and effectively (Tory and Moller, 2004). However, little research has been undertaken within the domain of construction project planning to develop new approaches for the graphical modeling of non-linear project schedules. Indeed, Gantt charts combined with the precedence logic still dominate among visualization techniques, despite the fact that finding and monitoring information on the schedule can be difficult (Russell and Udaipurwala, 2002). In addition, current methods and planning software do not offer a graphic standard for schedule representation. Chronographical Modeling (Francis, 2004; 2013) addresses this issue with one of the specific goals being to propose a standard protocol for graphical representation of construction project planning.

The first phase of this protocol involves the development and validation of a graphic convention of textures and colours representing construction activities, resources and locations which was then validated through a case study with the participation of 15 professionals, graduate and undergraduate
students from within the construction industry. The study included several tests and the application of the texture convention to a construction project schedule. The results allowed us to evaluate the intuitiveness, the suitability and the visual clarity of this convention. They also demonstrate that using of textures on a schedule aids with the data search process.

2 RESEARCH MOTIVATION

Effective communication of information depends in large part upon the way that data is graphically represented and how we perceive and interpret this information. According to Encarnacao et al. (1994), the development of new visualization systems must take into account the following three approaches:

- Technology-driven: what can be done with current technology;
- Perception-driven: what makes sense considering the constraints on human visual;
- Task-driven: what the user wants.

Considerable effort has been put forth towards the Technology-driven approach, where advancements in terms of information technology are remarkable. However, little attention has been given to the Perception-driven and Task-driven approaches. Tory and Moller (2004) argue that it is necessary to think about how we analyze and interact with graphic variables and how it can affect the information visualization. Indeed, the brain is able to perceive multiple graphic elements simultaneously, but it cannot process them in parallel. Our vision focuses on small areas of the visual field and watches one element after another in an unintended sequence named "Attention" (Rodrigues et al., 2008). Ware (2013) divides the Attention process into three sub-processes:

- The Pre-Attention Process: quick parallel process where one chooses the graphic elements to be analysed;
- Visual Perception: slow series of processes where one analyses the graphic properties of the visual element comparing correspondence, differentiation, relationships, understanding and meaning;
- Interpretation: process in which one interprets the analysed information and obtain results.

Rodrigues et al. (2008) assure that the design of visualization systems should seek to maximize the impact on the pre-attentive process. According to these authors, textures and colours are among the graphic elements that encourage this. Bertin (1977) places texture third, right after colour, in terms of its effectiveness in the encoding of nominal information. Because of their separation properties, these graphic elements are extremely useful for encoding such information.

Several areas have implemented graphic standards including colours and textures. For example, a standard manual of traffic signals was already in place in the infrastructure sector in 1935 (Hawkins, 1992). The geotechnical sector uses abbreviations, textures and colours to represent soil types according to ASTM D2487-11. Urban planning, somewhat related to the construction industry, has used a standard convention of colours for the classification of land use since 1965 (APA, 2013). However, current methods and existing planning software do not offer any standard for schedules. Chronographical Modelling (Francis, 2004; 2013) addresses this issue, with one of its goals being to propose a standard protocol for the graphical representation of construction project planning.

3 RELATED LITERATURE

3.1 Using textures

Textures can be very effective for encoding information in construction schedules (Carrier-Fraser, Francis and McGuffin, 2013) since they favor data interpretation by association allowing for a search in parallel. Thus, the interpretation and learning processes are more easily carried out. However, their use has some limitations and must follow certain guidelines in order to facilitate the pre-attentive process.
Tufte (2001) and Wilkins et al. (1984) argue that streaked textures have very strong terminations and contrasts. This can cause visual discomfort and symptoms from simple fatigue to headaches. According to Healey (1999), a combined use of graphic variables such as colour and texture may not favor the pre-attentive process causing a move from a search in parallel to a search in series. Moreover, if the background brightness resembles the texture, the texture visualization will require more time and visual memory and thus be more difficult to interpret. According to Carrier-Fraser, Francis and McGuffin (2013), in order to stay within the pre-attentive process limits and ensure that the data search will be performed in parallel; the information represented by textures must be independent from that shown by colours. This facilitates the search for only one data type, but not both.

The American National Standards Institute (ANSI) and the International Organization for Standardization (ISO) proposed standards for the use of textures. The BSI standards BS 8888 (2002) and BS 308-1 (1993) compile a set of guidelines for the use of hatching. Suggestions of hatching applicable to construction can be found in the standards BS 1192-3 (1987), BS 5930 (1999) and BS 8541-2 (2011). The National Institute of Building Science (NIBS) in collaboration with the American Institute of Architects (AIA) developed the US National CAD Standard or NCS (NIBS, 2005). This document compiles hatching, objects and symbols commonly used in Computer Aided Design.

3.2 Graphical modeling in construction projects planning

Graphical modeling is not widespread in construction project planning. Tory et al. (2013) present a visual comparison tool for construction schedules. Their research addresses three main components: the graphical representation of constraint types (Echeverry, Ibbs and Kim, 1991; Koo, Fischer and Kunz, 2007), the interactive representation of precedence networks, and the comparison of different planning alternatives. Stott et al. (2005) were inspired by a subway system, representing the project planning using lines, colours and shapes. Aigner et al. (2005) propose a graphics system called Planning Lines to represent uncertainty in the time attributes of activities. This system also incorporates the concept of probability in time representing two values: the minimum and the maximum duration.

The modeling approach of the Chronographic Method (Francis, 2013) studies the graphical representation of the project in the spatial dimension (Francis, 2004; Francis and Miresco, 2011). This approach proposes classifying all the elements that make up a building project into five entities (Table 1). Chronographical Modeling analyzes the visual interface, the graphic elements and the parameters associated with these elements. The goal is to establish a standard protocol for the graphical representation of construction project planning. Textures and colours are examples of graphic elements used by this protocol. Carrier-Fraser, Francis and McGuffin (2013) propose guidelines for the use of these graphics in modeling the physical entity. According to these authors, activities can be represented by textures, and colours can be linked to resources and locations.

<table>
<thead>
<tr>
<th>Physical (PE)</th>
<th>Associative (AE)</th>
<th>Functional (FE)</th>
<th>Scale (PE)</th>
<th>Direction (DE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities / Deliverables</td>
<td>Relationships and constraints</td>
<td>Deterministic; Probabilistic et heuristic</td>
<td>Time</td>
<td>No axis (cyclic scales)</td>
</tr>
<tr>
<td>Direct and indirect labours</td>
<td>Hierarchical</td>
<td>Fixed et variables</td>
<td>Cost</td>
<td>Single axis Scaled, grouped or none</td>
</tr>
<tr>
<td>Operators / Haulers</td>
<td>Grouping</td>
<td>Optimisation</td>
<td>Quality</td>
<td>Two axis Scaled, grouped or none</td>
</tr>
<tr>
<td>Permanent materials</td>
<td>Layering</td>
<td>Decision</td>
<td>% progress</td>
<td>Three axis Scaled, grouped or none</td>
</tr>
<tr>
<td>Emplacements</td>
<td>Sheet ing (Sub)</td>
<td>Generalised</td>
<td>Performance</td>
<td></td>
</tr>
<tr>
<td>Type of contract</td>
<td>Attributes</td>
<td></td>
<td>Performance</td>
<td>Risk</td>
</tr>
</tbody>
</table>
4 PRESENTATION AND VALIDATION OF THE TEXTURE CONVENTION

4.1 Presentation of the texture convention

According to Chronographical Modeling (Francis, 2013), activities can be represented by textures. Our texture convention aims to facilitate finding, interpreting and memorizing information on a construction schedule. The following approaches were taken into account in the development of this convention:

- Prioritizing the use of standard graphics.
- Using a minimum of graphic elements through a generic convention that adaptable to the needs of construction industry and to individual users.

The texture convention includes two levels or layers in order to accommodate the demands of building projects. The base level of this convention represents construction divisions or summary activities. Several types of graphic elements were used to elaborate the textures on this level: hatching, objects, symbols, lines, shapes, and in some cases text. Most of these are standard elements (hatching, objects and symbols) that are listed in the US National CAD Standard (NIBS, 2005) and commonly used for the graphical representation of information in construction. In addition, the texture convention has been structured according to the divisions proposed by the MasterFormat Classification System (CSI, 2012). Furthermore, the US National CAD Standard (NCS) also uses MasterFormat as reference for classifying the information.

The second level of this convention uses shapes and lines to represent building elements. These elements have a generic denomination which allows users to customize their application in order to adapt to the needs of each activity and each project. Figure 1A shows a 3D view of the convention levels and the information represented. Figure 1B is the result of the superposition of these levels within the same work plane.

![Figure 1: 3D and plan views of the texture convention levels](image)

4.2 Validation of the texture convention

We conducted a case study to validate our concepts and evaluate the achievement of our goals. The design and realization of this case study followed the steps recommended by Lam et al. (2012). These steps correspond to: i) setting a goal; ii) picking suitable scenarios; iii) considering applicable approaches; iv) creating evaluation design and planned analyses. Lam et al. (2012) also identified seven evaluation scenarios according to the methods commonly used in evaluation of information visualization, as follows:

- EWP: Evaluating environments and work practices;
- VDAR: Evaluating visual data analysis and reasoning;
• CTV: Evaluating communication through visualization;
• CDA: Evaluating collaborative data analysis;
• UP: Evaluating user performance;
• UE: Evaluating user experience;
• AEV: Automated evaluation of visualizations.

Our case study has two parts: in the first part, we evaluate the visual data analysis and reasoning (VDAR) in order to assess the suitability of the texture convention and its visual clarity. In the second part, we evaluate communication through visualization (CTV) with the intention of validating if the texture convention helps to diminish the mental effort necessary for finding information on the construction schedule of a building.

4.2.1 Evaluating visual data analysis and reasoning

This part of the case study evaluates the suitability of the texture convention and its visual clarity. It was conducted using a questionnaire consisting of eight questions. The first four questions tested the intuitiveness and simplicity of this convention. First, we asked participants to intuitively associate the meanings of the graphic elements presented in each question. The purpose of this exercise was to assess whether our texture convention could be understood intuitively and without any prior explanation. After each question, we presented the answer. Then we asked the participants to repeat the exercise again in order to evaluate the ease of memorization of this convention.

Table 2 shows the success rate for questions 1 to 4. According to this table, more than half of the participants were able to intuitively identify the meaning of textures using hatching. Nearly 90% of the participants succeeded in memorising the meaning of these textures after knowing the answer. In the case of textures using objects and symbols, the results were lower compared with those of textures using hatching. While most of the objects and symbols used are listed in the NCS and are commonly associated with the proposed divisions, this result may be influenced by other factors such as occupation, specialty and overall experience of the participants. However, despite the results in terms of intuitiveness for this part of the texture convention, almost 70% of the participants were able to remember the meaning of textures after knowing the answer.

Table 2: Success rate of question 1 to 4 regarding the texture convention

<table>
<thead>
<tr>
<th>Questions</th>
<th>Evaluated topic</th>
<th>Figure</th>
<th>With knowing the answer</th>
<th>Knowing the answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 3</td>
<td>Textures using hatching</td>
<td>2A</td>
<td>56%</td>
<td>89%</td>
</tr>
<tr>
<td>2 and 4</td>
<td>Textures using objects and symbols</td>
<td>2B</td>
<td>27%</td>
<td>67%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>42%</strong></td>
<td><strong>78%</strong></td>
</tr>
</tbody>
</table>

Questions 5 to 8 aim to gather expert opinion about the meaning and graphic quality of the textures and graphics used. Participants had the opportunity to express their opinions and also offer suggestions for improvement. Table 3 shows the acceptance rate for the textures assessed in these questions. According to this table, the acceptance percentage is greater than 70% in most cases.

Table 3: Acceptance rate of question 9 to 14 regarding the texture convention

<table>
<thead>
<tr>
<th>Question</th>
<th>Evaluated topic</th>
<th>Figure</th>
<th>Accepted</th>
<th>Non accepted</th>
<th>N.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Textures using hatching</td>
<td>2A</td>
<td>72%</td>
<td>23%</td>
<td>5%</td>
</tr>
<tr>
<td>6</td>
<td>Textures using objects and symbols</td>
<td>2B</td>
<td>62%</td>
<td>28%</td>
<td>10%</td>
</tr>
<tr>
<td>7</td>
<td>Textures using lines and text</td>
<td>2C</td>
<td>71%</td>
<td>22%</td>
<td>7%</td>
</tr>
<tr>
<td>8</td>
<td>Convention representing construction elements</td>
<td>3A</td>
<td>76%</td>
<td>21%</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>70%</strong></td>
<td><strong>24%</strong></td>
<td><strong>6%</strong></td>
</tr>
</tbody>
</table>

Figures 2 and 3 present our validated proposal for levels one and two of the texture convention. This proposal has taken into account the suggestions for improvement made by participants in the case study.
Figure 2A includes textures using hatching, while Figure 2B presents textures using objects and symbols. Facility services are represented by lines and text (Figure 2C).

<table>
<thead>
<tr>
<th>Texture</th>
<th>Division</th>
</tr>
</thead>
<tbody>
<tr>
<td>03 Concrete</td>
<td></td>
</tr>
<tr>
<td>04 Masonry</td>
<td></td>
</tr>
<tr>
<td>05 Metals</td>
<td></td>
</tr>
<tr>
<td>06a Wood</td>
<td></td>
</tr>
<tr>
<td>06b Plastics and Composites</td>
<td></td>
</tr>
<tr>
<td>07a Thermal Protection</td>
<td></td>
</tr>
<tr>
<td>07b Moisture Protection</td>
<td></td>
</tr>
<tr>
<td>09 Finishes</td>
<td></td>
</tr>
<tr>
<td>31 Earthwork</td>
<td></td>
</tr>
<tr>
<td>32 Exterior Improvements</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2:** Textures representing construction divisions or summary tasks

Figure 3 shows the second level of this convention where shapes are used to represent the construction elements. Dotted lines are used to indicate a pre-construction stage; for example, the preparation and approval of workshop drawings. The straight lines indicate that the element is in construction. These elements have a generic denomination which allows users to customize their application in order to adapt to the needs of each activity and each project.

<table>
<thead>
<tr>
<th>Design Phase</th>
<th>Construction Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizontal element - Substructure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vertical element - Substructure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal element - Superstructure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vertical element - Superstructure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-structural element</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flooring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ceiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partitions</td>
</tr>
</tbody>
</table>

**Figure 3:** Convention representing construction elements
4.2.2 Evaluating communication through visualization

In this part of the case study, we applied the texture convention to the construction schedule of a building. This schedule presented the planning of the design and procurement stages, the construction of foundation, structure, finishes, facility systems and site works. Then participants in the study responded to 16 open questions regarding information that could be obtained from the prepared schedule.

The schedule was presented as a Gantt chart and was available to participants in PDF format in order to avoid influencing their performance through the use of an unfamiliar method or planning software. Participants could graphically interact with the schedule by performing simple actions, such as zooming in and out, and moving throughout schedule. Some information, such as names and durations of activities, was removed in order to ensure the use of the texture convention to obtain the requested information. To answer the questionnaire, participants had no prior training and had to use only the knowledge gained in responding to the questionnaire used in the previous section of case study (VDAR) as outlined above. They could work individually or in teams consisting of a maximum of three people.

Table 4 presents the questions asked about the schedule using the texture convention and summarizes the results. Three people worked individually and twelve people worked in teams: i) two teams of three; and ii) three teams of two. Despite the fact that participants had to use only the knowledge acquired during the first part of the case study, almost 70% of the questions were resolved correctly. If we also consider the questions that had an approximate answer, the success rate reaches 84%.

We also analyzed the impact of the use of teams on the results (Figure 4). The number of people per team does not appear to have had a significant impact in relation to the performance of the group. However, people working as a team were able to establish group discussions which positively influenced the accuracy of their responses compared with those who did so individually.

Table 4: Success rate of questions regarding a construction schedule using the texture convention

<table>
<thead>
<tr>
<th>No.</th>
<th>Question</th>
<th>Correct</th>
<th>Approx.</th>
<th>Bad</th>
<th>N. A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>How long does it take the procurement process? Note: the bidding is made after completion of the design phase</td>
<td>88%</td>
<td>13%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>The preliminary studies (soil study) are included in the schedule?</td>
<td>63%</td>
<td>25%</td>
<td>0%</td>
<td>13%</td>
</tr>
<tr>
<td>3</td>
<td>Indicate the start and end date of the foundation construction Note: do not take into consideration the workshop drawings</td>
<td>50%</td>
<td>13%</td>
<td>38%</td>
<td>0%</td>
</tr>
<tr>
<td>4</td>
<td>Could you indicate if plumbing works are required before the construction of the slab-on-grade?</td>
<td>63%</td>
<td>38%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td>The foundation construction requires the installation of wood piles?</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>6</td>
<td>The building structure is mostly made of concrete or steel?</td>
<td>75%</td>
<td>25%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>7</td>
<td>How many floors is the building?</td>
<td>50%</td>
<td>25%</td>
<td>25%</td>
<td>0%</td>
</tr>
<tr>
<td>8</td>
<td>Indicate the start and end date of the structure construction Note: the structure starts with the ground floor beams and ends with the construction of metal stairs (non-structural metallic element), do not take into consideration the workshop drawings.</td>
<td>13%</td>
<td>38%</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td>9</td>
<td>When does the interior finishing begin?</td>
<td>25%</td>
<td>13%</td>
<td>63%</td>
<td>0%</td>
</tr>
<tr>
<td>10</td>
<td>How long does it take the installation of exterior doors and windows?</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>How long does it take to finish the interior walls?</td>
<td>38%</td>
<td>13%</td>
<td>38%</td>
<td>13%</td>
</tr>
<tr>
<td>12</td>
<td>The building will have an elevator?</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>13</td>
<td>Is it possible to delay the workshop drawings activities of HVAC without affecting the successors?</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>14</td>
<td>Is it possible to delay the workshop drawings activities of Fire Suppression without affecting the successors?</td>
<td>75%</td>
<td>25%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>15</td>
<td>The plumbing fixtures requires the preliminary installation of furniture such as cabinets and countertops?</td>
<td>63%</td>
<td>38%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>16</td>
<td>When it is scheduled to begin the earthworks and exterior improvements?</td>
<td>88%</td>
<td>0%</td>
<td>13%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Average 68% 16% 14% 2%
The first phase of the new protocol for the graphical representation of construction project planning includes the development and validation of a texture and colour convention. The texture convention uses different graphic elements such as hatching, objects, symbols, lines and text to represent major construction divisions. This convention provides a second level of information through a convention of shapes and lines. Test results show the intuitiveness of this convention, with particular regard to textures using hatching. These tests also indicate that experts have a fairly positive perception in relation to the meaning and graphic quality of the textures and graphic elements used. These experts had the opportunity to propose suggestions for improvement which have helped to refine the initial concept.

We also tested the texture convention in relation to the ease of finding information on a construction schedule where the activity names have been removed. Note that the participants had no prior training and no documentation was permitted. The results show that nearly 70% of the questions were resolved correctly. The success rate reaches 84% if we also consider the questions that had an approximate answer.

The results have therefore validated both levels of this convention: the textures that represent major divisions and the convention representing construction elements. This demonstrates clearly that the use of textures and shapes helps simplify the information search process on a schedule. Future developments are planned with other graphic elements as well as a wider consultation regarding the validation and application of the texture convention on other types of projects.

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3D FINITE ELEMENT MODELING OF RECYCLED GLASS CULLETS IN ASPHALT SHINGLES

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Abstract: Recycled glass cullets in asphalt shingles may be utilized as a cool roof strategy to reduce the harmful effects of Urban Heat Island (UHI). A Three-Dimensional (3D) transient Finite Element (FE) model was developed and validated to quantify energy savings provided by the proposed recycling process under various climatic conditions. Simulations were carried out for three cities located in three climate regions in the United States representing different climatic conditions. The three cities representing each region were Kansas City (Missouri) for Zone 3, Charlotte (North Carolina) for Zone 4, and Miami (Florida) for Zone 5. Results for each of the climatic zones were quantified. Results showed that the annual energy savings ranged from $35.37 in cold climatic regions to $92.58 in hot climates.

1 INTRODUCTION

Building sector in most countries represent about one third of the total energy consumption. It is projected that the building’s energy demand will be increased 110–150% by 2050 and 160–220% until 2095 from its 2005 level. Several factors including design and building characteristics, occupants, and people who work and live in buildings can significantly contribute to the success of energy efficiency measures. HVAC systems account for the largest amount of energy consumption in both commercial and residential buildings. As a consequence, the thermal barrier (or building envelope) that controls the heat flow of building is responsible for up to 40% of residential energy use and 55% of commercial energy use. In addition, cooling load in residential building shows an increasing trend worldwide and is one of the main concerns not only for countries that are characterized by hot climatic conditions but also for cities suffering from the heat island effect. The lower albedo of urban surfaces and the replacement of vegetation by building structures are considered as contributing factors to the heat island effect. Due to this effect, the ambient temperature in urban areas is usually several degrees higher (e.g. 1°C−6°C) than that of their surrounding suburban and rural areas. Increased ambient temperatures result in thermal discomfort and increase cooling energy consumption, energy demand, and energy prices (Hassid 2000; Santamouris 2007). In recent years several experimental studies have been conducted to investigate the energy saving effects of urban heat island mitigation measures such as high albedo coatings and urban greening (Akbari 2005; Akbari 2001; Sailor 2007; Taha 1988). In parallel, important simulation studies have been carried out to identify the heat island mitigation potential of cool roofs (M. Jacobson 2012; S. Menon 2010; Savio 2006). These studies found that the precise energy benefits depend on the local climate and more significantly on the specific building characteristics.
Intensive research has been carried out on the heat island effect and cool roofs, the impact and the significance, as well as its qualitative and quantitative characteristics. Recent studies found that there is a relationship between building energy consumption and heat island effect (Hassan 2013; Hassid 2000; Yukihiro 2006). Noteworthy among these publications are the works of Akbari et al. (Akbari 2001) who found that changing the roof albedo of a residence in Sacramento, California from 0.18 to 0.73 results in energy savings of approximately 2.2 kWh/day. It was also found that increasing the urban albedo by about 20% reduces cooling load between 2.9% and 21% for Toronto and 62% for Sacramento (Akbari 1992; Taha 1994) which indicates that energy benefits differ largely as a function of the climatic conditions and the characteristics of the building. In another study conducted by Synnefa et al., several types of cool materials have been identified and tested to assess their performance in reducing heat island effect in Athens, Greece. They studied the optical and thermal properties of the selected materials and results revealed that these materials can be classified as “cool” with the ability to maintain lower surface temperatures. They defined and studied two scenarios of modified albedo including a moderate and an extreme increase in albedo scenario. The results indicated that large-scale increases in albedo could reduce ambient air temperatures by 2°C (Synnefa 2008). Within this context, Akbari and Konopacki (Akbari 2004) carried out a field study to predict the energy-saving potential of several UHI mitigation measures in Toronto. Their results indicated that the level of savings in energy varies depending on the mitigation measures and building types. However, that study did not consider the temperature distribution in the urban area.

This study investigates the application of recycling of broken and waste glass cullet in the production of asphalt shingles in order to reduce energy consumption in residential buildings and to mitigate heat island effects by increasing the solar reflectance index (SRI) of the roof asphalt shingles. To achieve this objective, laboratory characterization of glass cullet was conducted and asphalt shingles prepared with and without glass cullet were tested in the laboratory. In addition, Three-Dimensional (3D) transient Finite Element (FE) model was developed and validated to quantify energy savings provided by the proposed recycling process under various climatic conditions.

2 EXPERIMENTAL PROGRAM

Conventional and recycled-glass modified asphalt roofing shingles were prepared in the laboratory by varying the amount of glass cullet and conventional materials used in asphalt roof shingles, and acceptability was based upon the standard specifications described in ASTM D 3462. A full description of the laboratory experimental study has been presented elsewhere (Kiletico 2014). Three different colors of recycled glass cullet including green and two sources of clear glass were collected from Construction and Demolition (C&D) processing plant to prepare the asphalt shingles. Since the size of the collected glass cullet was large, a high performance mixer was used to reduce particle sizes. The ground glass cullet was then used in lieu of conventional mineral aggregates as surface granules, filler material, and backdust.

The preparation of asphalt shingles in the laboratory consisted of three steps including preparation of the formwork, preparation of the asphalt blends, and aggregate preparation. The dimensions of the prepared asphalt shingles were 76mm x 76mm x 3mm. In the first step, the metal forms containing a fiberglass mat substrate were prepared. In the next step, asphalt binder was poured in the prepared forms. A white pigment powder was used in the fabrication of the asphalt shingles. The powder consisted of 98% pure titanium dioxide (TiO2) and was added at 8% by weight of the top surface granules. To add the TiO2 pigment powder to the surface granules, two grams of powder were mixed with 23 grams of surface granules, saturated with water, and then oven-dried. The filler material was then homogeneously mixed with liquefied asphalt binder for each sample, which was heated to 204°C. After mixing the filler material, 36 grams of asphalt coating mixture was reheated to become liquefied at 230°C. The asphalt coating mixture was then poured in the metal formwork of each shingle and then placed into the oven at 204°C for impregnation of the fiberglass for 1 hour. Then, the samples were removed from the oven and firm pressure was applied on the top surface granules in order to achieve 100% surface coverage. A forced heat gun was used to separate the shingles from working surface. Finally, the backdust particles were applied to the back surface while keeping the underside heated. The new shingles are patented under Provisional Patent 61/952515 “Method for the Manufacturing of Energy Efficient Shingles using TiO2
Coated Recycled Glass Cullets. The color appearance of all the prepared asphalt shingles is shown in Figure 1.

Figure 1. Asphalt shingle with/without glass cullet

2.1 Solar Reflectance Index (SRI)

SRI incorporates both solar reflectance and emittance into a single value and is a measure of the constructed surface’s ability to stay cool in the sun by reflecting solar radiation and emitting thermal radiation. It is defined such that a standard black surface (initial solar reflectance 0.05, initial thermal emittance 0.90) has an initial SRI of 0, and a standard white surface (initial solar reflectance 0.80, initial thermal emittance 0.90) has an initial SRI of 100. Materials with the highest SRI values are the coolest choices for roofing. To calculate the SRI of the prepared asphalt shingles with and without glass cullet, their solar reflectance and thermal emittance were measured in the laboratory. The SRI of the asphalt shingle with and without glass cullet was calculated according to ASTM E 1980. The following formulas were used to calculate the SRI:

\[ SRI = 123.97 - 141.35X + 9.655X^2 \]

\[ X = \frac{((\alpha - 0.02\varepsilon)(8.797 + h_c))/((9.5205\varepsilon + h_c))} \]

Where \( \alpha \) is the solar absorptance and \( \varepsilon \) represent for the thermal emissivity of the prepared asphalt shingle samples. The calculation was conducted for three convective coefficients \( (hc) \) that correspond to low, medium, and high wind conditions \( (5, 12, \text{and} 30 \text{ W·m}^{-2}·\text{K}^{-1}) \), respectively. Table 1 shows the SRI of some of the available asphalt shingles in the market (EETD 2014).
Table 1. Solar Reflectance Index of Asphalt Shingles

<table>
<thead>
<tr>
<th>Type of the asphalt shingle</th>
<th>SRI</th>
<th>Type of the asphalt shingle</th>
<th>SRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>White</td>
<td>21</td>
<td>Black</td>
<td>1</td>
</tr>
<tr>
<td>Gray</td>
<td>4</td>
<td>Weathered Wood</td>
<td>4</td>
</tr>
<tr>
<td>Green</td>
<td>18</td>
<td>Dark Brown</td>
<td>4</td>
</tr>
<tr>
<td>Antique Silver</td>
<td>19</td>
<td>Beachwood Sand</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 2 shows the description of the shingle specimens and their SRI based on laboratory measurements. As shown in this table, the control samples had the lowest SRI (i.e., 0), which was expected. On the other hand, the sample G1, which contains clear glass and TiO2 pigment, had the highest SRI (i.e., 30).

Table 2. SRI of the prepared samples

<table>
<thead>
<tr>
<th>ID</th>
<th>Material Composition</th>
<th>SRI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top Surface</td>
<td>Filler</td>
</tr>
<tr>
<td>X1</td>
<td>Control 1: Ceramic Coated Granules</td>
<td>Limestone</td>
</tr>
<tr>
<td>X2</td>
<td>Control 2: Ceramic Coated Granules</td>
<td>Clear Glass 1</td>
</tr>
<tr>
<td>A</td>
<td>Green Glass</td>
<td>Limestone</td>
</tr>
<tr>
<td>B</td>
<td>Clear Glass 1</td>
<td>Limestone</td>
</tr>
<tr>
<td>C</td>
<td>Green Glass</td>
<td>Green Glass</td>
</tr>
<tr>
<td>D</td>
<td>Clear Glass 1</td>
<td>Clear Glass 1</td>
</tr>
<tr>
<td>C1</td>
<td>Green Glass &amp; Pigments</td>
<td>Green Glass</td>
</tr>
<tr>
<td>D1</td>
<td>Clear Glass 1 &amp; Pigments</td>
<td>Clear Glass 1</td>
</tr>
<tr>
<td>G1</td>
<td>Clear Glass 2 &amp; Pigments</td>
<td>Clear Glass 2</td>
</tr>
</tbody>
</table>

3 CLIMATE REGIONS IN THE UNITED STATES

In order to estimate the effect of the application of glass cullet asphalt shingle on the residential building energy load, simulations were carried out for three cities located in three climatic regions including Zones 3, 4, and 5 in the United States. US Energy Information Administration (EIA) categorized the climate regions in the United States into 5 main categories based on the last 30-year average heating degree-days (HDD) and cooling degree days (CDD) (EIA 2011; NOAA 2012). A HDD is a measure of how cold a location was over a period of time, relative to a base temperature of 65 °F (18.3 °C). On the other hand, a CDD is a measure of how hot a location was over a period of time, relative to the same base temperature of 65 °F (18.3 °C). Zone 3 is defined as the region with less than 2000 CDD and less than 4000-5499 HDD; Zone 4 is defined as the region with less than 2000 CDD and less than 4000 HDD; Zone 5 is defined as the region with 2000 CDD or more and less than 4000 HDD. Figure 2 shows the 3 main studied climate zones in the United States. Table 3 also provides the latitude and the longitude of the selected cities for this study.
Table 3. The latitude and longitude of the selected cities for the simulations

<table>
<thead>
<tr>
<th>City, State</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Cooling Degree Days (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miami, FL</td>
<td>25.82</td>
<td>80.28</td>
<td>2645</td>
</tr>
<tr>
<td>Charlotte, NC</td>
<td>35.22</td>
<td>80.93</td>
<td>1105</td>
</tr>
<tr>
<td>Kansas City, MO</td>
<td>39.32</td>
<td>94.72</td>
<td>1110</td>
</tr>
</tbody>
</table>

4 FINITE ELEMENT MODEL

ABAQUS 6.13 software was used in this study to develop a three dimensional transient finite (FE) element model. Two FE models were developed to simulate the heat transfer mechanisms and evaluate energy consumption in the house with conventional asphalt shingle and house with glass cullet asphalt shingle in different climate regions in the United States. The developed FE model considered all the heat transfer mechanisms that may occur within the space. It is worth mentioning that many factors affect the calculated temperature distributions and the heat flux in the roof. The inputs to the FE model include the emissivity of asphalt shingle with and without glass cullet, emissivity of insulation, attic flow rate, longitude, latitude, and time zone of the locations. Although the physical model was symmetric, the amount of solar radiation differed from one side of the roof to the other depending on the surface orientation and inclination. Thus, in order to conduct an accurate analysis, the entire configuration of the roof was simulated in the FE model. It is worth mentioning that in order to attain reliable and accurate results; a mesh convergence technique was conducted using different mesh sizes. Final mesh size was selected after considering both computational efficiency and accuracy. To model the conduction heat transfer mechanism in the roof and the ceiling, approximately 49,000 DC3D8 elements were used. Featuring a hexahedron shape with eight nodes, these linear heat transfer elements were used for all the materials except the air. To model the advection, that is, bulk motion of the air in the attic, the convection/diffusion option in ABAQUS was utilized by means of eight-node DCC3D8 elements with forced convection/diffusion capabilities. The total number of aforementioned elements was approximately 73,000. In addition, forced convection inside the roof was simulated by means of the mass heat transfer option in ABAQUS. A full description of the model has been presented elsewhere (Asadi 2012). In addition, hourly climatic data, including ambient air temperature, solar radiation, wind speed, wind
direction, and relative humidity were used in the simulation. The metrological data was obtained from the Typical Meteorological Year 2 (TMY2)(NREL 2014). Figure 3 shows the finite element mesh of the model.

Figure 3. Finite Element Mesh

Figure 4 shows the operation of the conventional and reflective roofs. During daylight hours, a roof is constantly subjected to solar energy striking its surface. A reflective roof with high SRI would have a lower surface temperature as compared to a conventional roof. In the case of a reflective roof, a lower surface temperature translates into less heat gain into the attic space or living space below the roof, which result in a cooler living space and lower cooling/heating energy consumption.

The building used in the simulation is a single story residential building with a tilted roof with area of 148.6 m2. The attic had two pitched roof sections, two vertical gable-end sections, and one horizontal ceiling frame. The thermostat set point temperature for cooling and heating was set to 26 and 21°C, respectively.

Figure 4. Operation of conventional and reflective roofs
5 RESULTS AND DISCUSSIONS

Model validation was necessary to demonstrate the precision and the viability of the FE model. Therefore, the developed models were validated based on experimental data collected in Zackary, LA. To validate the FE model, a site-located weather station was placed on the roof to measure the actual weather parameters and collected data was used in the model. Figure 5 compares the results based on FE model and experimental data for a typical day in the summer. The results showed that there is a good agreement between experimental data and FE model and error was less than 5%. The obtained results demonstrate that the finite element model could be applied with success even for more detailed situations and with better precision on the results.

![Figure 5. Model validation](image)

In order to investigate the performance of the glass cullet asphalt shingle to reduce building energy consumption, the heat flux were calculated for the control house and the house with asphalt shingle containing glass cullet in different climate regions in the United States. It should be noted that the values mentioned in this part of the study depend on the building characteristics. As expected, increasing the roof SRI resulted in reduced summer cooling loads particularly in hot climate regions. Figure 6 shows the required cooling and heating loads in the house with and without asphalt shingle containing glass cullet. For the building chosen and the climates examined in this study, it was found that the potential savings are greater in hot climate regions such as Miami, FL. It was found that the application of asphalt shingle containing glass cullet in the roof can reduce energy consumption from 7.8 kwh/m² to 6.9 kwh/m² in June in Miami-FL and save approximately $16 in this month. Results showed that increasing the SRI of a roof is clearly more advantageous in hot climate regions where cooling load dominates most of the year. This study provides further evidence that roof asphalt shingles containing glass cullet are effective strategies for urban heat island mitigation. The increased SRI of these roofs effectively reduces their surface temperature and decreases sensible heat flux into the urban atmospheric system.
6 CONCLUSIONS

The present study evaluated the application of waste glass cullet in the production of asphalt shingles in order to reduce energy consumption in residential buildings and to mitigate heat island effects by increasing the SRI of the roof asphalt shingles. Laboratory tests were conducted to determine the solar reflectance and thermal emittance of the prepared asphalt shingle samples with and without glass cullet. Based on the laboratory results, it is concluded that glass cullet can be successfully blended with conventional materials to produce a sustainable asphalt shingle that has a solar reflectance of that is significantly greater than conventional asphalt shingles. Results show that a typical black ceramic coated asphalt shingle has SRI of 0. In order to achieve cool roof attributes, the addition of a white pigment mixed together with the top surface granules increased the SRI to 30 for clear glass.

A FE model was developed to calculate and quantify the energy consumption reduction in the house with and without glass cullet. The developed model was successfully validated with measured experimental data collected in Zachary, LA. Annual models were run for three cities in five climate regions in the United States. For the building studied and the climates considered in the simulation, it was found that the potential savings are greater in hot climate regions such as Miami, FL. Results indicated that the application of asphalt shingle containing glass cullet in the roof can reduce energy consumption from 7.8 kwh/m2 to 6.9 kwh/m2 in June in Miami-FL and save approximately $16. Results showed that increasing the SRI of a roof is characteristically more advantageous in hot climate regions where cooling load dominates most of the year. This study provides evidence that roofs covered with asphalt shingles containing glass cullet are effective strategies for urban heat island mitigation. The increased SRI of these roofs effectively reduces their surface temperature and decreases sensible flux into the urban atmospheric system.
References


TEACHING ENGINEERING LITERACY TO NON-ENGINEERING STUDENTS IN FORMAL LEARNING ENVIRONMENTS

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Abstract: Since enrollment rates in American college engineering programs have been constantly dropping, formal and informal processes to teach and learn engineering are on the rise. An opportunity actually exists to formally teach engineering to construction students in US colleges and universities. If non-engineers understand how science and technology work, they can better interact with scientists and engineers in the workforce and make informed decisions about when technology can be a solution to a problem, or when other solutions maybe more adequate. To this date, higher engineering education has been repeatedly investigated through the lenses of engineering programs and degrees. This paper investigates engineering literacy for non-engineering students, by comparing the performance of engineering and non-engineering students when gaining engineering literacy. The methodology of this study consists of analyzing the performance of construction management (CON) and civil and environmental engineering (CEE) students in comparable courses taught in both programs: introduction to geotechnical engineering and geotechnical applications. Data is collected over four distinct semesters. The results reveal that CON students scored significantly higher grades when the course was offered from a non-engineering perspective rather than from an engineering perspective. The results of the study highlight the need to develop clear and consistent teaching methods and techniques that take non-engineering students’ diverse backgrounds into consideration.

1 MOTIVATION

Over the last decade, enrollment rates in American college engineering programs have been dropping constantly. The U.S. ranks well behind other countries in the percent of students earning their first university degree in engineering or science. In the U.S., 15% of undergraduates receive degrees in natural science or engineering compared to 38, 47, 50 and 67% in South Korea, France, China, and Singapore, respectively (AIAA 2003). Given that technological innovation is a key ingredient to economic growth and high paying jobs, the U.S. is in critical need of more engineers, especially with the acceleration of engineers’ production in countries such as China (NSF 2010). Because the U.S. is losing its competitive advantage in science and technology, leading business organizations set a goal of doubling the number of bachelor’s degrees in science, technology, engineering and mathematics (Business Roundtable 2005).

Engineering affects all disciplines in many ways. Since many managers, directors, and policymakers are making decisions related to key technology-based issues, it makes sense to provide them with a conceptual framework of technology (Mina 2007). Because the decisions that engineers make regarding infrastructure and consumer products involve almost everybody, even students enrolled in non-engineering curricula can benefit from examining engineering issues (Dyrud 2001).
world, engineering teams frequently comprise key individuals with non-engineering Science, Technology, Engineering, and Math (STEM) backgrounds. While not yet common, some engineering departments offer service courses for non-engineers (Krupczak and Ollis 2006). Examples of such science and technology programs that require engineering literacy include programs in computer technology, informatics, construction, environmental and biomedical sciences, aeronautical, industrial, architecture or graphic design. These science and technology programs, and many others, require students to learn engineering and design principles. The National Academy of Engineering is advocating that all Americans need to better understand all types of technology, not just computers and information technology (Pearson and Young 2002). A survey of the literature shows a positive perception towards engineering content (Krupczak et al. 2005). Scholars addressed the success of several programs and courses across the U.S. in attracting non-engineering students to engineering fields (Nahapetian 2011). These programs provided technological awareness and an understanding of technical issues to non-engineering students to develop basic literacy in engineering. Mina (2007) summarized the main incentives behind students enrolling in engineering courses: (a) to better understand the role of engineering in society and the interactions of engineering with their major field of study; (b) perform simple calculations and estimations using engineering methods; (c) make cost-benefit and risk-benefit analyses; (d) appreciate the importance of the underlying assumptions used to produce the cost-benefit and risk-benefit analyses presented by engineers; (e) make informed decisions about the desirability of engineering activities by weighing the benefits of those activities against their environmental risks; (f) understand the interdependence of the economic, environmental, and sociological aspects of technological change; (g) assess the validity and possible weaknesses in predictions of economic, environmental, and sociological consequences of technological change presented by others; (h) attain a basic understanding of the engineering design process; (i) achieve a survey-level understanding of why particular materials and processes are used to produce simple engineering devices and systems; and (j) understand the capabilities and limitations of basic manufacturing processes and engineering systems.

The inclusion of non-engineers on an engineering service learning project can significantly alter the manner in which the participants view the impacts of an engineering project. In general, engineers tend to seek quantitative solutions to a given problem, while non-engineers, particularly those who are from the liberal arts, will seek more qualitative solutions, most often addressing the impacts of the proposed engineering solutions (Polito 2005). However, the non-engineering students need specially-developed courses that take their backgrounds and skills into account. Developing and teaching non-engineering courses requires a different approach from the traditional way courses are taught to engineering students (Sadiku and Yantorno 1997). If non-engineers understand how science and technology work, they can better interact with scientists and engineers in the workforce and make informed decisions about when technology can be a solution to a problem, and when other solutions may be better. It is important that non-engineers understand enough about science and engineering so that they can apply technology where it is most useful to society (Nickels and Giolma 2000). Hence, it is the responsibility of engineering faculty to develop such courses with the intended audience and desired course outcomes in mind (Mahajan et al. 1996).

So far, the challenges associated with providing a solid engineering professional development framework for non-engineering degree seekers have not yet been tackled. To this date, higher engineering education has been repeatedly investigated through the lenses of engineering programs and degrees. However, creating an inclusive environment so that the significant mass of students in multiple technology and science programs can effectively learn core design and engineering principles has yet to be tackled. This paper aims to act as a first building block by comparing the performance of engineering and non-engineering students when gaining comparable engineering literacy.

2 RESEARCH METHODOLOGY

A statistical analysis on student performance on two parallel undergraduate courses in introduction to geotechnical engineering applications serves to compare the performance of engineering and construction management students. Indeed, two separate classes, with common learning and performance outcomes, are taught each semester for both engineering (civil engineering) and non-engineering (construction management) students by two instructors with PhD degrees in civil engineering
and with similar backgrounds. Students who successfully complete both courses have a broad understanding of soil mechanics principles related to construction. Some of the topics discussed include: rocks/geology/soil formations, deep foundations, soil classification, USCS & AASHTO, site investigations for construction, soils reports, consolidation, settlement, compaction, stresses in soils, surface loading, shear stress and Mohr’s circle, lateral soil loads, retaining walls, overturning, bearing capacity, and shallow foundations. Moreover, the performance of students in the two classes will be assessed similarly. The grade will consist of homework assignments on the various topics, a project paper, and three exams.

The methodology of this study consists of collecting anonymous performance scores of construction management (CON) and civil and environmental engineering (CEE) students enrolled in the course over four distinct semesters. For each class, the anonymous data was provided by the Academic Advising office, which keeps grade records for all classes. First, the paper compares student characteristics. Second, the paper compares the performance of CON and CEE students and tests the statistical significance of the results using an unpaired t-test with unequal variances. The tested hypothesis is that the average grade of CON students \( x \) is equal to that of CEE students \( y \). This assumption is tested, at a 95% confidence level, for the null hypothesis \( H_0 \) or its alternative \( H_1 \) as follows:

- \( H_0: x = y \) if p-value is greater than 0.05; the null hypothesis is engineering and non-engineering student performance is similar;
- \( H_1: x \neq y \) if p-value is less than 0.05; then we have evidence to reject the null hypothesis.

Third, the paper examines the factors that could affect student performance in different semesters and tests the statistical significance of the differences using ANOVA tests. The paper ends with a discussion of the results and raises several critical engineering education questions for future studies.

### 3 RESULTS AND DISCUSSION

This section presents the results of the comparison between engineering and non-engineering students enrolled in the geotechnical course, and leads to a discussion of the potential parameters that could explain the differences in performance between both groups of students. Of the 381 students, 255 are engineering students and 126 are non-engineering students (see Table 1). Figure 1 illustrates comparable percentages for CEE and CON students in the four studied semesters.

<table>
<thead>
<tr>
<th>Semester</th>
<th>CEE</th>
<th>CON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>59</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>51</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>255</td>
<td>126</td>
</tr>
</tbody>
</table>

Next, Figure 2 shows a difference in female and male student percentages between the CEE and CON students. While only 10% of CON students are females, this percentage is three times higher for CEE students. The number of women studying engineering and technology is quite low relative to other previously male-dominated professions such as law and medicine. The low percentage of women in CON in this current study is comparable to national percentages.
For example, the percentages of electrical and mechanical engineering degrees awarded to women in 2009 were also very low, sitting at just 11.5% and 11.4%, respectively (American Society for Engineering Education 2010).

Figure 2: CEE and CON students’ female/male distribution

Figure 3 provides a graphical illustration of the differences in grades between CEE and CON students, in the form of boxplots. CON students seem to score slightly higher grades, and the statistical testing of the results confirms this difference in performance. The top of Table 2 shows the t-test p-value is smaller than 0.05, which leads to rejecting the null hypothesis. Therefore, the observed differences in performance are statistically significant.
For a better understanding of the parameters that might affect the performance of CEE and CON students in the studied course, a closer examination of the grades for each semester is needed. After conducting ANOVA tests on the data and checking the significance of the differences, the results are illustrated in Figure 4 below. Except for one semester, CEE and CON student performance was similar. One of the reasons that explain the difference in CON students’ performance between semesters 1, 2, 3, on one hand, and semester 4 on the other hand, is the manner in which the course was taught. Table 3 summarizes the covered topics when the course is offered from: (i) an engineering perspective (semesters 1, 2, 3) by focusing deeply on quantitative engineering and design principles; and (ii) from a non-engineering perspective that offers a broad understanding of engineering principles with an emphasis on the practical and contractual points of view (semester 4). CON students performed much better when the course was offered from a non-engineering perspective, which catered to the students’ diverse and often non-quantitative backgrounds. While the difference in teaching methods justifies the variance in the results, other interrelated factors also may have major impacts on the performance of non-engineering students in engineering courses, including: student background, instructor background and experience, program pre-requisites, interactive teaching tools and support. The results of this study lay the foundation for a future study to explore the combination of reasons behind this noticeable variation.

Table 2: Statistical analysis – t-test (top) and ANOVA (bottom)

<table>
<thead>
<tr>
<th>T-Test</th>
<th>CON</th>
<th>CEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.71</td>
<td>2.44</td>
</tr>
<tr>
<td>Variance</td>
<td>1.11</td>
<td>1.07</td>
</tr>
<tr>
<td>Observations</td>
<td>125</td>
<td>254</td>
</tr>
<tr>
<td>P(T&lt;=t) two-tail</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>t Critical two-tail</td>
<td>1.97</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ANOVA Test</th>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-Test</td>
<td>Semester</td>
<td>30.28</td>
<td>3</td>
<td>10.09</td>
<td>10.11</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Class (CEE/CON)</td>
<td>9.79</td>
<td>1</td>
<td>9.79</td>
<td>9.8</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>Combination</td>
<td>14.51</td>
<td>3</td>
<td>4.84</td>
<td>4.84</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>372.5</td>
<td>373</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>414.3</td>
<td>380</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This study also raises several questions: (1) What teaching methods and techniques are appropriate for ensuring non-engineering students gain adequate engineering literacy? (2) How can we ensure engineering instructors are best prepared to teach engineering courses to non-engineering students? (3) What are the key learning barriers for non-engineering students to become engineering literate? Additional research is needed to answer these critical engineering education questions.

Figure 4: CEE vs. CON students’ grades per semester
4 CONCLUSIONS

If non-engineers have a good understanding of science and engineering concepts, they can better interact with scientists and engineers in the workforce and make informed decisions when it comes to engineering solutions. This paper compared the performance of engineering and non-engineering students in the introduction to geotechnical engineering and geotechnical applications course over four semesters. A deep examination reveals a significant variation in non-engineering students’ grades depending on the way the course was taught. Non-engineering students performed better when the course was offered from a non-engineering perspective, catering to students’ diverse backgrounds, rather than focusing on a quantitative engineering perspective. The results of this study highlight the need to develop clear and consistent teaching methods and techniques to ensure non-engineering students gain adequate engineering literacy. Although this paper highlights the effect of an important factor on the performance of non-engineering students in engineering courses, this preliminary study has limitations that need to be addressed in a larger research effort focusing on the topic: the sample size used in this study is limited to 381 students; the study investigates student performance in two specific courses and within one university; and the paper studies one specific factor out of several that can impact student performance. The preliminary findings of this study are currently being strengthened improved by investigating a larger sample of students and courses, and also considering including additional factors that affect the performance of non-engineering students in engineering courses.
References


American Society for Engineering Education. 2010. Profiles of Engineering and Engineering Technology Colleges. ASEE.


COMPARATIVE EVALUATION OF LEED AND QSAS CREDITS USING LIFE CYCLE ANALYSIS: CASE STUDY FROM QATAR

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Abstract: Implementation of sustainability rating systems for buildings had a recognized effect on the increased level of sustainability adoption in the construction industry. However, there is still a need for objective quantifiable evidence that the concepts adopted by the sustainability rating systems and implemented in projects lead to optimum positive impacts on resource consumption and the environment. The objective of this paper is to present research conducted to assess the actual environmental impact saved by implementing credits of both LEED (Leadership in Environmental and Energy Design) and QSAS (Qatar Sustainability Assessment System) using Life Cycle Analysis (LCA) approach. The impact of implementing LEED and QSAS credits under the categories of energy, water and urban connectivity on a selected project in Qatar was analyzed using LCA. The results of this analysis manifest the objective quantifiable benefits behind applying the respective sustainability credits and how the impact of an international rating system differs from that of a system developed for the specific region where the project is located. The relative weights allocated to these credits were also analyzed in light of the corresponding LCA results in order to evaluate the significance of such weights and how they can be reconsidered to achieve optimum reduction of impacts.

1 INTRODUCTION

The construction industry is distinguished, among other industries, by the large number of materials, processes and technologies that are incorporated within its activities. Warnock (2007) explained that the complexity of building construction is demonstrated by the various physical components used in projects, which significantly increases resource consumption and highly impacts the environment. The United Nations Environmental Program (2002) revealed that this industry consumes 40% of Europe’s energy in addition to its large contribution to the emission of greenhouse gases in the United States. Also, it is estimated that one-third of energy end-use is consumed for heating, cooling, lighting, appliances and general services in buildings whether residential, commercial or public (Ardenta 2008). Therefore, due to the referred incontestable significant impacts, achieving sustainability in construction projects has been the target for various initiatives, among which is development of sustainability rating systems.
Rating systems are used to evaluate construction projects through set of categories where each category encompasses a number of measurable targets that are evaluated under relevant credits. The objective of adopting these systems is to improve the performance of construction projects from sustainability perspective by appreciation of reducing resource consumption or harmful emission. Various rating systems have been developed in the last two decades in different countries. The use of some of these systems has gone beyond the boundaries of the countries where they were developed and are being applied internationally. Leadership Engineering and Environmental Design (LEED), for instance, was developed by the US Green Building Council (USGBC) and is currently implemented in many developed and developing countries (Kyrkou and Karthaus 2011). Building Research Establishment Environmental Assessment Method (BREEAM) has a long track record as the main rating system in UK (Fowler and Rouch 2006). In Australia, Green Star is implemented to assess environmental performance of construction projects (Lockwood 2006). Comprehensive Assessment System for Building Environmental Efficiency (CASEBEE) is the widely established as sustainability evaluation system used in Japan, (Reed et al. 2009).

2 BACKGROUND

The declaration of Qatar 2030 visionary plan endorsing environmental development as one of the four main pillars of Qatar’s National Vision (GSDP 2008) has led to various nation-wide initiatives and efforts to adopt sustainability in construction activities. One of these initiatives is the development of Qatar Sustainability Assessment System (QSAS) by the Gulf Organization for Research and Development (GORD) forming a tool to benchmark construction projects with respect to their environmental performance. However, similar to other rating systems being implemented all over the world, the current practices being adopted and supported by these rating systems do not provide sufficient quantifiable evidence that they lead to optimum saving to the environment. Rather, they have evolved from a consensus-based understanding of environmental issues. This understanding, in some cases, has been based on conventional environmental wisdom that does not always stand up to objective analysis (Trusty 2003).

One of the most powerful tools to address this issue is Life Cycle Analysis (LCA), which is a methodology used to analyze the “Cradle to Grave” impact of using a specific product or process on the environment. According to ISO standard 14040 issued by the International Standards Organizations (ISO 2006), the analysis takes into consideration the impact of all processes involved in the life cycle of such materials on the environment starting from extraction, through manufacturing, transportation, installation, operation till disposal. The Objective of this paper is to present utilization LCA as an objective assessment tool to hold a comparative evaluation between internationally recognized and locally developed rating systems with regard to their actual positive impact. The following sections of the paper demonstrate the methodology adopted to hold this comparative evaluation, the results of this application on a project in Qatar, comments on the results obtained leading to conclusion and finally, future suggested research work.

3 METHODOLOGY

As introduced in the previous sections, this paper presents research carried to utilize LCA to evaluate the efficiency of international versus local rating systems in the state of Qatar. The international rating system selected for this study is LEED and the local one is QSAS. To enable comparative evaluation of the two rating systems, the methodology proposed by Attallah et al. (2013) is implemented on a commercial center at Alshamal City, which is a project currently under construction in Qatar using the comparable credits under the two rating systems. Implementation of the methodology is described under this section and briefly illustrated in Figure 1.
3.1 **Step 1: Selection of comparable credits under LEED & QSAS**

Since the rating systems are developed in different countries and under by different organizations, they tend to be dissimilar in terms of their development of the evaluation procedures and the prioritization of credit, which is reflected in the relative weights assigned to each credit. However, since the most significant elements of the construction projects affecting the environment are basically the same anywhere in the world, we can still claim that similar language can be detected under different rating systems. For example, the water and energy consumption credits are typically of the highest relative weights under any rating systems. This is due to the established consensus among practitioners and experts that water and energy consumption are of high significance due to the processes involved in securing both, which are characterized by high resource consumption and heavy emissions.

The target here is to compare the impact of implementing two different rating systems. Therefore, we have selected the credits under LEED and QSAS that are of comparable nature and identified their relative weights in order to understand the relative contribution and consequently the relative efficiency. Table 1 shows sample of selected comparable credits under the two systems and their relative weights towards certification.

<table>
<thead>
<tr>
<th>Credit Objective</th>
<th>QSAS Credit</th>
<th>Weight (%)</th>
<th>LEED Credit</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization of Energy Consumption</td>
<td>E1</td>
<td>5.2</td>
<td>EA1</td>
<td>17.3</td>
</tr>
<tr>
<td>Use of renewable energy sources</td>
<td>E3</td>
<td>3.64</td>
<td>EA2</td>
<td>6.4</td>
</tr>
<tr>
<td>Rationalization of Water Consumption</td>
<td>W1</td>
<td>16</td>
<td>WE1</td>
<td>3.6</td>
</tr>
<tr>
<td>Decrease traffic load by improving access to public transportation</td>
<td>UC6</td>
<td>1.3</td>
<td>S4.1</td>
<td>5.5</td>
</tr>
</tbody>
</table>
3.2 Step 2: Content analysis of rating system documentation

The second step in the methodology is to analyze the contents of the respective working documents forming the basis of implementing credits and achieving the targeted certifications. The first set of documents is commonly the design guides or manuals created to provide the project participants with various ideas or approaches to improve the building performance in respect to the environmental issues addressed under each credit. These documents typically refer to relevant sections of standards or codes which are used in assessing the savings achieved. In the case of QSAS, design manuals are available for those who procure license from GORD or companies applying for project certification. For LEED, the reference for our research here is the document titles “LEED 2009 for New Construction and Major Renovation”, which is open to public. The later document was used as one single source of reference since it included the information required to carry out the analysis in the case of LEED.

The second set of documents typically refers to how the score for each credit is calculated using the relevant calculation sheets or toolkits. Designers or concerned stakeholder change parameters under each credit to come as close as possible to the reference target figures in the design manuals. The score is typically calculated by comparing the project parameter planned for the project with the set standard or reference. Assessment manuals for QSAS were obtained to complete this task. The third set of documents is the calculation tools, the form of which can be extensively different from one rating system to another as they are very specific to the nature and scope of credits under each system. The calculation tools assist the users or applicants to feed the relevant project input and perform computations for self-evaluation before submission for certification. For QSAS, set of calculation excel sheets and tool kits were obtained along with the design and assessment manuals to complete this task. As explained, the objective of this research step of the presented methodology is to establish a thorough understanding of the adopted sustainability approach, the assessment criteria, and the build-up of scores for each credit.

3.3 Step 3: Defining project parameters for achieving sustainability credits

A very critical step in the adopted methodology, linking the conceptual phase of evaluation with the quantification phase, is to determine the critical project parameters that have to be appropriately addressed and changed in order to reach the target score. Extensive analysis for each credit, which is carried out through exploring the design and assessment manuals, reveals what are the options the designer has in order to achieve the target points. The holistic approach followed under some credits, which leads to unclear intangible parameters, forms the biggest challenge for implementing this methodology on all credits. The parameters identified for each comparable credit under QSAS and LEED are shown in Table 2.
Table 2: Sample of identified parameters under QSAS & LEED credits

<table>
<thead>
<tr>
<th>QSAS Credit</th>
<th>Parameters</th>
<th>LEED Credit</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Planned (design) building energy demand versus reference figures</td>
<td>EA1</td>
<td>Saved energy versus base line design</td>
</tr>
<tr>
<td>E3</td>
<td>Percentage of energy produced by alternative renewable sources</td>
<td>EA2</td>
<td>Percentage of energy produced by alternative renewable sources</td>
</tr>
<tr>
<td>W1</td>
<td>Planned annual water consumption</td>
<td>WE1</td>
<td>Reduced percentage of potable water consumption</td>
</tr>
<tr>
<td>UC6</td>
<td>Project layout</td>
<td>S4.1</td>
<td>Estimated traffic to project</td>
</tr>
</tbody>
</table>

3.4 Step 4: Analysis of project data

Upon identifying the critical parameters for each credit, these parameters are then converted into LCA inventory data in order to quantify the associated LC impacts. To do this, we have selected a project currently under construction in Qatar to apply the concept with actual quantities derived from available drawings, specifications and other project information. The project is targeting 3 stars on the QSAS scale, which is at 50% of the maximum certification. For the comparison purpose, the LEED certification targeted is taken as 55 points corresponding to 50% on of the maximum achievement (silver level). According to this presumption, the obtained project data were explored in order to translate the change in the identified parameter (i.e. saved impact) to inventory. The following two sections provide more details on the inventory analysis and impact calculation steps.

3.5 Step 5: Project inventory assessment

The changed parameters result in saved impact on the environment and/or saved resources. In order to quantify this saved impact, we first calculate the amount of resources saved or emissions reduced due to implementing the considered credit. In some cases, the parameter is itself a quantity that can be traced through the LCA database to calculate the associated saved environmental impact. Water consumption credits in any rating system is an example, where the score is based on the amount of savings in consumed water annually due to the implementation of some strategies and the use of economical fittings or systems that reduce consumption. Nevertheless, in other cases like vegetation credits under the QSAS, the parameter identified is the area planted in relation to the project overall area. In this case, project drawings and specifications are used to identify the type of plants used and calculate the approximate annual saved CO2 due to this planting scheme. Deriving the inventory saved based on the changed parameters is the most critical step in this methodology as it requires careful reading and interpretation of the project technical data. The changed parameters to achieve certain scores can usually be measured from the project drawings. Specifications are usually required to determine the technical features of the identified parameters. Table 3 shows the calculated inventory for some QSAS and LEED credits based on the selected commercial building project.
Table 3: Calculated inventory for the selected project

<table>
<thead>
<tr>
<th>QSAS Credit</th>
<th>Saved Inventory (Annual)</th>
<th>LEED Credit</th>
<th>Saved Inventory (Annual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1,080 MWH of electricity</td>
<td>EA1</td>
<td>954 MWH of electricity</td>
</tr>
<tr>
<td>E3</td>
<td>1,477 MWH of electricity</td>
<td>EA2</td>
<td>223 MWH of electricity</td>
</tr>
<tr>
<td>W1</td>
<td>3,713 m³ of potable water</td>
<td>WE1</td>
<td>1,685 m³ of potable water</td>
</tr>
<tr>
<td>UC6</td>
<td>2 tons of fuel</td>
<td>S4.1</td>
<td>2 tons of fuel</td>
</tr>
</tbody>
</table>

3.6 Step 6: Calculation of LCA impact using Simapro

The LCA impact involves lengthy calculations of all processes involved in throughout the whole life cycle of the project components. It is well established among LCA practitioners that while the products under study are used in certain countries, portion of the life cycle impacts could be generated in other countries. For construction products like wall cladding systems, ironmongery, and carpentry, there are usually imported components from industrial countries that are not themselves the origin of the raw materials. This leads to having several locations worldwide where the traceable environmental impact could be recorded. For this reason, the LCA approach has a cross-borders nature, which justifies why an international database can be used for LCA studies even in countries different from the one where data for this database was collected. One of the available LCA databases was targeted to identify the LC impact for each saved inventory. The last step is to perform weighting of the LCA impact in order to reach a single score representing the total impact and to enable comparison of results. Weighting is done here based on the built-in figures in Simapro.

4 RESULTS

We chose the SimaPro software with application of eco-indicator 99 database built-in the software to calculate the impacts. Table 4 in the results section shows an example of the impacts as an outcome of the Simapro software after weighting. The unit Pt used in this table represents the unit adopted in the database of eco-indicator 99, which is a dimensionless unit that reflects the single-score environmental impact after applying weighting as an interpretation technique. The comparison graphs, sample of which is presented in Figure 2 highlight the relative contribution of comparable credits for the certification and as per LCA calculation as well.
Table 4: Sample of impact as calculated through Simapro for the QSAS credits

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>E1</th>
<th>E3</th>
<th>W1</th>
<th>UC6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>Pt</td>
<td>66.595</td>
<td>91.075</td>
<td>435.075</td>
<td>1.031</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>Pt</td>
<td>1.026</td>
<td>1.403</td>
<td>6.687</td>
<td>0.066</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>Pt</td>
<td>0.046</td>
<td>0.062</td>
<td>12.046</td>
<td>0.006</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>Pt</td>
<td>8.424</td>
<td>11.521</td>
<td>87.044</td>
<td>0.118</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>Pt</td>
<td>0.002</td>
<td>0.002</td>
<td>2.275</td>
<td>0.000</td>
</tr>
<tr>
<td>Ozone layer depletion</td>
<td>Pt</td>
<td>0.005</td>
<td>0.007</td>
<td>0.009</td>
<td>0.001</td>
</tr>
<tr>
<td>Respiratory organics</td>
<td>Pt</td>
<td>0.015</td>
<td>0.021</td>
<td>0.068</td>
<td>0.003</td>
</tr>
<tr>
<td>Aquatic ecotoxicity</td>
<td>Pt</td>
<td>0.007</td>
<td>0.010</td>
<td>63.570</td>
<td>0.001</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>Pt</td>
<td>0.275</td>
<td>0.376</td>
<td>7.578</td>
<td>0.002</td>
</tr>
<tr>
<td>Land occupation</td>
<td>Pt</td>
<td>0.003</td>
<td>0.004</td>
<td>3.834</td>
<td>0.000</td>
</tr>
<tr>
<td>Global warming</td>
<td>Pt</td>
<td>25.010</td>
<td>34.203</td>
<td>114.296</td>
<td>0.088</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>Pt</td>
<td>31.527</td>
<td>43.117</td>
<td>136.311</td>
<td>0.741</td>
</tr>
<tr>
<td>Mineral extraction</td>
<td>Pt</td>
<td>0.000</td>
<td>0.001</td>
<td>0.118</td>
<td>0</td>
</tr>
</tbody>
</table>

Using results as presented in the sample comparison graph in fig 2, the contribution of each of the QSAS towards certification by 3 stars along with its associated LCA single score can be compared to the contribution of corresponding comparable LEED credits towards silver certification and their associated LCA results. The LCA score for each credit under study was calculated by multiplying the score achieved to target the required certification level (2 for QSAS and 0.5 for LEED) by the assigned weights for each credit. The product was then multiplied by a ratio of 1000 for the purpose of graph presentation (to have the same primary scale). These values are referred to as the certification score in Figure 2. The objective here is to check the performance of comparable credits to reach optimum potential saved impact on the environment under different rating systems, in this case a locally developed versus international one. To illustrate the results presented in Fig. 2, the blue column represent the certification score achieved for each of the subject credits while the blue columns represent the scores recorded through LCA calculations.
5 DISCUSSION & CONCLUSION

Comparison of the E1 (QSAS) and EA1 (LEED) shows consistent trend in terms of the LCA results as opposed to the certification scores. Both contributions to certification and LCA score of E1 are higher than those of its comparable LEED credit EA1. On the other hand, while the LCA score for QSAS E3 credit is higher than the LCA score of its comparable credit EA2 under LEED with a huge difference (more than 6 times), the contribution of E3 towards certification exceeds that of EA2 with much less difference than the one noticed for LCA. Taking into consideration that these two comparable credits are essentially addressing the same environmental issue, both contribution to certification and LCA score were expected to be comparable. Since this is not the case, it can be deduced that either QSAS is underestimating the percentage allocated to E3 or LEED is overestimating the score assigned to EA1. In other words, if we assume, for the sake of clarification, that LEED's distribution of weights assigned to credits are reflecting actual benefits to the environment as it's a more developed rating system being internationally used by professionals around the globe, then QSAS developers should be considering assigning higher percentage to E3 to reflect the impact in light of the discussed LCA study. It's also noticed that, comparing E1 and E3 under QSAS, shows that the LCA score of E3 is higher than that of E1 while its contribution for certification is less than that of E1. That could also be considered a basis to reconsider the weights assigned to both credits. Higher weight should be assigned to E3 in order to reflect more realistic saved impact on the environment.

According to the above sample analysis of the results, it is perceived that although implementation of sustainability rating systems on construction projects has clear positive effect on reducing burdens on the environment, rationalization of these rating systems using fair quantifiable measures is still required. This paper presented application of a quantification methodology on two rating systems, QSAS and LEED, to explore their relative efficiency through comparing similar credits using LCA approach. As discussed, results show possible superiority of some credits over others although the relative contribution towards similar certification levels is not indicating this. Future works on this research is envisaged to be addressing all credits of these two systems whenever quantification is feasible in addition to credits of other systems especially those which tend to be used on an international scale.
Acknowledgments

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References


HAZARDOUS PROXIMITY ZONE DESIGN FOR HEAVY CONSTRUCTION EQUIPMENT

Ibukun G. Awolusi, Eric D. Marks, Nipesh Pradhananga and Tao Cheng

Abstract: The construction industry continues to be among the leading industries for workplace fatalities in the U.S. After experiencing 824 fatal injuries in 2013, the construction industry continues to rank as one of the most dangerous work environments when compared to other private industrial sectors in the U.S. Conditions of construction sites often produce hazardous proximity situations by requiring ground workers and heavy equipment to operate at close proximity. The gathered injury and fatality statistics indicate that current safety practices of construction workers have proven inadequate. The objective is to design hazard zone around pieces of heavy construction equipment in which ground personnel should not enter during construction operations. The scope is limited to construction sites and equipment at a horizontal grade and hazards between heavy construction equipment and workers-on-foot. A framework for creating the hazard zone around any piece of construction equipment is presented including detailed methodology discussions for each step. The hazard zone for a dump truck, excavator, and backhoe are shown using the created framework. Construction resource tracking data was used to validate the created hazard zone around a dump truck. Results indicate that hazard zones for ground workers can be created around construction equipment to increase hazard awareness for workers. Furthermore, additional safety standards can be formulated based on the ability to design and eventually implement hazard zones on construction equipment.

1 INTRODUCTION

Construction environments are typically comprised of multiple resources that perform dynamic activities in a specific space. This often requires construction resources, such as ground workers and heavy equipment, to operate at close proximity to each other creating potential hazardous proximity situations. The risk of injuries and fatalities increases as contact collisions between ground workers and heavy construction equipment occur.

A majority of past research efforts for hazardous proximity situations have collected and analyzed statistics for injuries and fatalities resulting from contact collisions between heavy construction equipment and ground workers (CFOI, 2011). Safety standards for hazardous proximity situations between heavy construction equipment and ground workers include Personal Protective Equipment (PPE) and equipment back-up alarms (OSHA, 2014). These regulations signify the hazards associated with ground workers and construction equipment working at close proximity, but have proved inadequate to prevent incidents from occurring.
A review of current construction worker fatality statistics resulting from hazardous proximity situations between heavy construction equipment and ground workers is completed. The created framework for designing a hazard zone for a piece of construction equipment is presented and followed by a discussion of identified limitations, benefits, and recommendations. Position tracking data of a dump truck on an active construction site was used to validate the created hazard zone. Future research work on proximity detection and alert systems for the construction industry is also addressed.

2 LITERATURE REVIEW

Construction sites are dynamic in nature and each site typically has a unique size and set of working conditions. The movement and resulting interaction between various construction resources including ground workers and heavy equipment can create hazardous proximity situations. A multitude of movements of construction resources coupled with the densely populated nature of construction sites can account for safety concerns resulting from proximity issues (Cheng et al., 2011). The following review covers current fatality incidents associated with proximity issues in the construction industry and current safety practices of construction workers with regards to hazardous proximity issues.

2.1 Construction Accident Statistics

The construction industry experiences one of the highest accident fatality rates per year when compared to other industries in the U.S. In 2012, the Bureau of Labor Statistics (CFOI, 2011) reported the construction industry experienced 806 fatalities of which 17% (136 fatalities) resulted from workers coming into contact with objects or construction equipment. Fatalities resulting from workers being struck by pieces of construction equipment accounted for 3% of the total workplace fatalities experienced in 2012 by the U.S. private industry sector (CFOI, 2013). Since 2003, the construction industry has averaged 191 fatalities resulting from construction equipment or other objects striking workers per year (BLS, 2013). Figure 1 provides the total construction fatalities and those causes by ground workers contacted with objects or equipment between 2003 and 2012 (CFOI, 2013).

![Figure 1: Construction fatalities caused by contact with objects or equipment (CFOI, 2013)](image)

One longitudinal study identified minimal significant change in fatalities resulting from contact collisions between construction equipment and ground workers between 1985 and 2009 (Hinze & Coates, 2011). Although the number of fatalities resulting from contact collisions decreased during this duration, the ratio when compared to total construction fatalities remained largely unchanged. Even in highway work zones, more worker fatalities are caused by struck-by events from pieces of construction equipment rather than commuting vehicles (Pegula, 2010). Member companies of the Construction Industry Institute (CII) also reported that a significant portion of their worker fatalities were caused by struck-by incidents.
2.2 Human-Equipment Interaction

A majority of previous research in hazardous proximity situations is largely concentrated in worker behavior. One study identified two general problems resulting in hazardous proximity issues between heavy construction equipment and ground workers (Fosbroke, 2004): (1) Workers and equipment operators - Outdated or never implemented policies, a lack of knowledge of existing specific risk factors, and repetitive work tasks, (2) Incident investigation - All incident causation data is collected after-the-face resulting in no or limited real-time incident information.

Standards and regulations required by the Occupational Safety and Health Administration (OSHA) are imperative to enhance safety in construction (OSHA, 2013a). As per OSHA regulations, construction equipment must provide alerts when moving in the reverse direction (OSHA, 2013b). Research has found that these alerts can desensitize workers to existing hazards (Duchon & Laage, 2011). Other OSHA regulations require construction site personnel to wear hard hats, reflective safety vests, and other personal PPE (OSHA, 2013b). Safety training and education, other required safety regulations, can increase the awareness of hazards associated with proximity issues between construction equipment operators and ground workers (Goldenhar et al., 2001; Huang & Hinze, 2006). Construction accident statistics indicate that back-up alerts and PPE are incapable of preventing contact collisions between workers and construction equipment.

2.3 Equipment Operator Visibility

Equipment operator visibility has impacted the overall safety of construction sites (Fosbroke, 2004). One of the leading causes of contact collisions between ground workers and heavy construction equipment is limited operator visibility (Fullerton et al., 2009). Data from an OSHA fatality database from 1990 to 2007 to shows that approximately 5% of construction fatalities during that period were caused by some type of equipment-related visibility issue (Hinze & Teizer, 2011). Table 1 shows the breakdown of visibility-related fatalities and pieces of construction equipment involved. Hazard zones were created for pieces of construction equipment that were most cited for each visibility-related fatality.

<table>
<thead>
<tr>
<th>Type of Equipment</th>
<th>Percentage of Visibility-Related Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dump truck</td>
<td>29%</td>
</tr>
<tr>
<td>Truck (not specified)</td>
<td>12%</td>
</tr>
<tr>
<td>Excavator/backhoe</td>
<td>8%</td>
</tr>
<tr>
<td>Private vehicle (car, pickup, van)</td>
<td>7%</td>
</tr>
<tr>
<td>Dozer</td>
<td>6%</td>
</tr>
<tr>
<td>Grader</td>
<td>6%</td>
</tr>
<tr>
<td>All others</td>
<td>64%</td>
</tr>
</tbody>
</table>

3 OBJECTIVE AND SCOPE

The primary objective is to present and test a methodology for creating hazard zones around pieces of construction equipment in which ground personnel should avoid during construction operation. The hazard zone is created for several pieces of construction equipment to demonstrate and test each step of the methodology. The scope is limited to construction sites, equipment, and personnel at a horizontal grade and hazards between construction equipment and workers-on-foot. The consideration of interactions between other construction resources (such as equipment-equipment or equipment-material interaction) is out of the scope of this work.
4 METHODOLOGY

Several variables and situations must be considered when calculating the hazard zone around a piece of construction equipment for a ground worker. These variables include equipment travel speed, equipment travel direction, equipment physical dimensions, equipment turning radius, equipment rotational capabilities, operator reaction time, and equipment braking distance. To create a process for determining the hazardous zone around a piece of construction equipment, a hierarchy was designed to assure each variable was considered. Figure 2 presents the methodology implemented to determine the hazard zone for any piece of construction equipment. A typical three-axle, tandem rear axle, 23,586 kg haul capacity dump truck is used as an example to demonstrate how each step is calculated and how the resulting hazard zone is determined (Harwood, 2003; Peterbilt, 2014).

Step 1: Equipment Footprint - The outermost position from the centroid of the piece of construction equipment should be determined for all of the equipment components. To determine the equipment footprint, the outermost extension at any height for each point 360 degrees around the equipment should be projected onto a 2D (two dimensional) horizontal plane. The equipment footprint for a typical three-axle dump truck is shown in Figure 3. This footprint is derived from the equipment dimensions of a typical three-axle, tandem rear axle dump truck (Harwood, 2003; Peterbilt, 2014).

Step 2: Initial Safety Boundary - The initial safety boundary is a 2-meter distance extended from the equipment footprint that performs as a safety factor in the event that other hazardous zone design steps fail to provide protection. A parallel line 2 meters offset from the equipment footprint calculated in step 1 creates the initial safety barrier (see Figure 4). The initial safety boundary was assigned a 2 meter value to account for a ground worker that may have body parts (e.g. limbs) horizontally extended (e.g. a worker with an outstretched arm). This safety boundary extends beyond the length of a person’s horizontally extended arm or leg as well as a person bending horizontally at their torso. This initial safety boundary zone can be modified depending on a unique set of working conditions.

Figure 3: Equipment footprint for a three-axle dump truck

Step 2: Initial Safety Boundary - The initial safety boundary is a 2-meter distance extended from the equipment footprint that performs as a safety factor in the event that other hazardous zone design steps fail to provide protection. A parallel line 2 meters offset from the equipment footprint calculated in step 1 creates the initial safety barrier (see Figure 4). The initial safety boundary was assigned a 2 meter value to account for a ground worker that may have body parts (e.g. limbs) horizontally extended (e.g. a worker with an outstretched arm). This safety boundary extends beyond the length of a person’s horizontally extended arm or leg as well as a person bending horizontally at their torso. This initial safety boundary zone can be modified depending on a unique set of working conditions.
Step 3: Equipment Function - The hazard zone must be designed to align with the specific function of a piece of construction equipment. For example, the equipment function of a hydraulic excavator with tracks and resulting hazard zone mainly follows a circular pattern with the maximum hydraulic arm reach as the circle's radius. Other pieces of construction equipment such as a dump truck or scraper will have a hazard zone largely based on their turning radius and maximum speed on a construction site. The equipment function is taken into consideration to determine the hazard zone for a typical three-axle dump truck as shown in Figure 5. Most pieces of construction equipment provide specific details about turning radius in the equipment specifications (Peterbilt, 2014).

Step 4: Operator Reaction Distance - This metric is used to determine the travel distance of a piece of construction equipment during the period in which a construction operator reacts to the identification of a hazard. An equation typically used for commuter traffic driver reaction time is implemented to determine the equipment operator reaction time (see Equation 1). An average operator reaction time of 2.5 seconds...
to a recognized hazard is utilized (MUTCD, 2013). The resulting reaction distance is plotted at intersecting points along the existing hazard zone from the previous step 3.

[1] Reaction Distance = 0.278Vt  where V = velocity and t = time (2.5 s)

Step 5: Braking Distance - The braking distance of the piece of construction equipment is added to the operator reaction time as an additional factor in determining the hazard zone. To calculate the braking distance, an equation typically used to measure the braking distance of commuter traffic (including semi-trucks) is used and shown in Equation 2. After the operator identifies a hazard, a separate reaction time is required for the operator to apply brakes to stop the equipment. The same average operator reaction time of 2.5 seconds is used as was discussed in step 4 (MUTCD, 2013). The resulting braking distance is plotted at all locations extended outward from the reaction distance calculated in step 4.

[2] Braking Distance = 0.039(V^2/a) where V = velocity and a = acceleration (3.41 m/s^2)

Step 6: Determine Hazard Zone - To determine the resulting hazard zone, steps 1 through 5 should be calculated and compared to identify the maximum calculated distance for each point around a piece of construction equipment. It is important to note that each step of determining the hazard zone builds from the previous step. For example, the initial safety boundary calculated in step 2 is added to the maximum extent of the equipment footprint for each point calculated in step 1. The maximum calculated hazard distance along the centerline of forward travel for the dump truck is the combined reaction time and braking distance of 6.3 meters. This value was added to the equipment function and initial safety boundary and equipment footprint that were calculated in step 3 and step 2 respectively. The resulting hazard zone for a typical three-axle, tandem rear axle dump truck is presented in Figure 6.

![Figure 6: Hazard zone of a typical three-axle, tandem rear axle dump truck](image)

5 HAZARD ZONE

The hazard zone for several pieces of construction equipment was created using the methodology presented in the previous section. Dimension values for a typical backhoe loader were used to create a hazard zone for ground workers. The backhoe loader used was a single tilt loader and was equipped with a multi-purpose 1.0 m³ (1.3 yd³) front loading bucket (Caterpillar, 2011). The resulting hazard zone for the backhoe loader is presented in Figure 7.
The hazard zone for an excavator was also created using the previously discussed methodology. The excavator used was a typical three teeth digging 0.018 m$^3$ (0.29 yd$^3$) capacity bucket (Caterpillar, 2011). The resulting hazard zone for the excavator is displayed in Figure 8.

The resulting hazard zone area data was also calculated based on the creation of the hazard zone for the dump truck, backhoe loader, and excavator. The net hazard area is calculated from subtracting the area occupied by the equipment (B) from the full hazard zone area (A). This net hazard area is the region that should be avoided by construction ground workers during equipment operation. The resulting hazard zone data is shown in Table 2.
Table 2: Hazard Zone Results for Each Piece of Construction Equipment Evaluated

<table>
<thead>
<tr>
<th>Item</th>
<th>Dump Truck</th>
<th>Excavator</th>
<th>Backhoe Loader</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of full hazard zone (A)</td>
<td>169.8 m²</td>
<td>803.7 m²</td>
<td>179.9 m²</td>
</tr>
<tr>
<td>Area occupied by equipment (B)</td>
<td>26.5 m²</td>
<td>23.1 m²</td>
<td>21.0 m²</td>
</tr>
<tr>
<td>Net hazard zone area (A – B)</td>
<td>143.3 m²</td>
<td>780.6 m²</td>
<td>158.9 m²</td>
</tr>
</tbody>
</table>

6 HAZARD ZONE DEPLOYMENT

Location tracking data of construction resources (including personnel and equipment) was used from a previous study (Pradhananga & Teizer, 2014). For this study, an active construction site was selected with an earthmoving operation involving excavators, dozers, rollers, dump trucks, and construction ground workers. Position-based data was collected using GPS identification devices calibrated to a frequency of 1 Hz mounted on various surfaces on pieces of construction equipment and to the hard hats of workers. The data was filtered using an existing filtering process (Vasenev et al., 2014).

Figure 9 shows the result of verifying the proposed hazard zone with location-based data from the construction site. Tracking data for the trajectory of one trip cycle of a single dump truck starting from the point it entered the construction site and ended when the truck passed the exit point. A hazard zone was created around the truck for its position every second based on the previously prescribed methodology.

The tracked dump truck is expected to stay within the computed hazard zone. The equipment footprint of the dump truck with respect to hazard zone computed for its immediate previous position was checked for compliance with the hazard zone (i.e. did the dump truck remain in the zone after movement). The boundary of the equipment footprint should completely lie inside the hazard zone if the computed hazard zone is adequate for the equipment (truck). In Figure 9, the portion of the truck lying inside the hazard zone is plotted in blue and the portion that extended beyond the hazard zone is plotted in red. The gray area represents the hazard zone.

Instances in which the dump truck remained static were excluded from the analysis. A total of 106 location data points were assessed. Among those points, the equipment footprint was found to cross the hazard zone boundary 33 times. This implies that the computed hazard zone was able to envelope the dump truck’s movement approximately two thirds of the times. Figure 9 also shows that red areas were
only present in cases where the truck performed forward sharp right turns. Following the analysis, a recommendation on extending the hazard zone to include very sharp right turns can be implemented. The same methodology for creating hazard zones can be used to iterate through each step to optimize the hazard zone for an equipment.

7 CONCLUSIONS

The safety practices currently used in the construction industry for ground workers and heavy equipment operating in close proximity has proven inadequate by the continued injuries and fatalities resulting from workers being struck by equipment or objects. The purpose of this research was to create and test a methodology to design hazard zones around construction equipment. These hazard zones are areas that should be avoided by ground workers during construction operation. The methodology created includes six steps that include the following: 1) equipment footprint, 2) initial safety boundary, 3) equipment function, 4) operation reaction time, 5) equipment braking distance, and 6) creation of the hazard zone. The hazard zone was created for three pieces of construction equipment (dump truck, backhoe loader, and excavator) using the presented methodology. Results of the created hazards zones indicate that hazard zones can be designed and used to increase awareness of dangers around construction equipment for construction site personnel. Location-based data for a dump truck was used to evaluate the created hazard zone methodology. By creating hazard zones around construction equipment, ground workers can be informed of and avoid dangerous areas around heavy equipment on construction sites.

The presented methodology for creating a hazard zone for pieces of construction equipment is founded singularly on construction safety considerations. The hazard area accounts for potential movements of a piece of construction equipment which in some situations can result in a rather large hazard area. The created hazard area may not be feasible on select compact construction sites or working conditions. Further research is required to understand the hazard zone’s impact on other topics within the construction industry including productivity, economic feasibly, and sustainability.

Several limitations were cited during and after creating the methodology and designing hazard zones for construction equipment. The proposed methodology only allows for a horizontal plane hazard zone and doesn’t address three-dimensional hazards (i.e. crane applications and sloped conditions). The methodology presented currently addresses independent hazard zones for each piece of construction equipment, but future research could address the dynamic activity of all pieces of equipment on a construction site simultaneously. The created hazard zone could also be used to optimize the calibration of proximity detection and alert systems. Future research efforts can create a tool for automatically creating the hazard zone around a piece of construction equipment for safety managers. Future research should also address the implementation of these hazard zones. This includes a strategy to educate workers on where hazard zones are located and how to avoid them during construction operation.

References


UNDERSTANDING THE IMPLICATIONS OF AUGMENTED REALITY OUT OF CONTEXT IN ENGINEERING EDUCATION

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Abstract: Educating building design and construction students about sustainability is critical to the development of a future workforce that is capable of making a positive impact on future sustainable buildings. Prior research has leveraged emerging computing technologies to remove some of the educational hurdles that are common among new engineering students, related to visualization and design assessment. In this prior work, an augmented reality (AR) based simulation game, called \textit{ecoCampus}, was developed to allow students to design an exterior wall for an existing building on their campus to improve sustainable performance. After users created designs in \textit{ecoCampus}, they were able to view a virtual mock-up of their design at full-scale with AR and then assess the performance of that concept using the basic simulation game interface. Using this technological approach to design, students were able to resist the tendency toward design fixation as compared to students who were not provided with the computerized \textit{ecoCampus} interface. This paper further explores the AR component of \textit{ecoCampus} to understand how students' learning is affected when the design activity is completed out of the context of the physical building. In this work, students who used \textit{ecoCampus} to design a new exterior wall concept for an existing building did so in a lab space where they were not able to physically explore the existing building for which they were designing the concept. Instead, they could only view the existing building through a single photograph that was projected on a screen. Students completed the same assessments as prior student cohorts and were allotted the same amount of time. After analyzing the collected data it was observed that, while students still employed beneficial design behaviours as compared to prior cohorts using paper-based design strategies, the process that they employed to arrive at their final design concept included fewer considerations of different design alternatives than students who used \textit{ecoCampus} in the existing building. This suggests that there may be additional value in using AR in the physical context of a space for building design and assessment learning tasks, especially when design creativity is advantageous.

1 INTRODUCTION

There has been a growing concern for the environmental impact of buildings, and subsequently, a shift in recent years to embrace more sustainable design and construction strategies. As the Architecture, Engineering, and Construction (AEC) Industry continues to adopt more aggressive sustainability standards, it becomes increasingly important for students pursuing AEC careers to understand the sustainability performance implications of the buildings they design and build. This paper extends prior research that explored how mobile computing technology can help to remove traditional barriers to
sustainable building design education to allow newer students in AEC disciplines to develop, visualize, and assess the sustainable performance of different design concepts.

A prototype mobile computer application, called ecoCampus, was developed in prior work to challenge users to design a new exterior wall for an existing building in an attempt to make it perform more sustainably (Ayer et al. 2014a). Through an augmented reality (AR) based simulation game interface, ecoCampus allows users to: design an exterior wall concept; visualize their designs using augmented reality; and assess the performance of the designs with a basic simulation game interface. ecoCampus was implemented with students at The Pennsylvania State University enrolled in courses in Architecture, Civil Engineering, and Architectural Engineering. The prior work compared the behaviour and perceptions of students who completed the same sustainable design challenge using either ecoCampus or one of two paper-based versions of the design activity. One of the paper-based design activities included a purely open-ended design activity, where students were only supplied with blank sheets of paper on which to illustrate their design concepts (Ayer et al. 2014b). The other paper-based design activity included printed images of the existing building’s exterior wall on which students would illustrate their design concepts to help provide them with a sense of scale and limitations on design requirements (Ayer et al. 2013a). From these prior implementations of different sustainable design activities, several beneficial learning behaviours were observed related to the students’ design process when using ecoCampus (Ayer et al. 2013b).

One of the research questions that these prior implementations did not explore was related to the extent to which the augmented reality (AR) component of ecoCampus affected student behaviour. In prior implementations, students who completed the design activity, regardless of format, were physically located inside the existing building for which they were designing a new wall for improving sustainable performance. This placement of students in the actual, physical building for which they were designing was hypothesized to allow the AR component of ecoCampus to add value by letting students visualize their design concepts at full-scale and in the context of the physical space. This paper explores this hypothesis by implementing the same design activity out of the context of the physical building. Instead, students involved in this work used ecoCampus in a laboratory setting, which required them to visualize their design concepts from a projected still image of the physical building. This effectively eliminated their ability to view a full-scale mock-up of their design concept through AR and also eliminated their ability to physically explore the existing building to gather information that could influence their design. By removing this component of physical location in the targeted building, this implementation served to provide an understanding of the benefits and drawbacks of using AR out of the context of a physical space.

2 BACKGROUND

Situated learning theorists suggest that the best way to educate students about content that will eventually be applied to a particular context is to learn that content in its corresponding context (Lave and Wenger 1991). This can be especially relevant for students in engineering disciplines because of the problem-based nature of their work that requires them to apply mathematics and physics concepts to an engineering context to create viable solutions (Johri and Olds 2011). For new students learning about sustainable building design and construction, situated learning theory would suggest that the best way for students to learn these concepts is in the context of a design or construction scenario. This can be a challenging scenario to create for newer students because many new students have had little, if any, design experience in the early stages of their academic career. This challenge of creating a design scenario for new students is complicated further because the traditional means for communicating design and construction information relies on the use of 2D drawings. These can be challenging for students to understand and the mental models they create from their understanding of the drawings can be prone to errors (Johnson 1997).
The potential challenge with presenting this learning content in the context in which it will eventually be applied offers some synergies with AR visualization technology, which presents virtual content in its physical context. AR is a subset of the broader “mixed reality” which involves the merging of real and virtual components along a continuum ranging from completely virtual (computer models) to completely real (what can be seen by unaided eyes) (Milgram and Kishino 1994). AR allows users to see a predominantly real world view of a space with some virtual content superimposed to “augment” their view, similar to the yellow “first-down” line on televised American football games (Azuma 1997). This superimposition of content allows AR to present virtual content in the context of a physical space. In a building design context, AR allows hypothetical or planned design models to be visualized on top of an existing building or construction site, which allows users to visually compare planned versus existing building content.

In addition to the visualization capabilities that can be afforded through AR, simulation game technology further facilitates learning by situating students in a learning context where they may experiment in an engaging way (Gee 2005). Simulations are models that attempt to approximate a situation, environment, or set of events to predict, teach, or entertain (Prensky 2004). Games, on the other hand, are defined as: having rules; having variable and quantifiable outcomes; having value assigned to possible outcomes; requiring player effort; requiring a player to become attached to the outcome; and having negotiable consequences (Juul 2003). Simulation games are, therefore, defined as contests between individuals that move toward specific goals under sets of conditions and constraints that will sufficiently model a real-world situation (Gredler 1994; Jacobs and Dempsey 1993). Prior work using simulation games applied to construction engineering educational contexts have identified pedagogical benefits enabled through the use of the technology (Nikolic et al. 2010).

In prior work conducted by the authors of this paper, these educational approaches involving AR visualization, simulation games, and situated learning environments were applied through the development and implementation of ecoCampus (Ayer et al. 2013b). ecoCampus is a mobile computing application (or “app”) that was created to challenge users to create a more sustainable exterior wall design concept for an existing building on Penn State's campus. The performance and behaviours of the students using ecoCampus was compared to other first-year students from prior semesters who completed the same design activity using non-computerized formats (Ayer et al. 2013a, 2014b). In these prior studies, all students completing the exterior wall design challenge, regardless of format, were physically present in the building for which they were designing wall concepts. This consistent educational setting allowed the researchers to vary the format of the design activity between paper-based and computerized activities, which allowed for direct comparison of findings, but also lead to additional research questions. Specifically, it was still not clear from the prior works the extent to which AR’s presentation of virtual content in its physical context affected student behaviour. This paper removes the “physical context” component of AR to specifically focus on this question.

3 METHODOLOGY

The research presented in this paper extends prior work that involved the implementation of ecoCampus. For this work, first-year engineering students enrolled in an architectural engineering course were tasked with creating an exterior wall retrofit design concept for an existing building on campus to make the building perform more sustainably. Unlike prior implementations, this implementation of ecoCampus task students with completing this activity in a lab space that was not in the same location. This eliminated the students’ ability to physically explore the existing building to gather additional information that could potentially affect their design process.
Students completed their design work in the Immersive Construction (ICon) Lab at the Pennsylvania State University, as shown in Figure 1. The ICon Lab features three, large (1.8m by 2.4m) projection screens. During implementation, an image of the building targeted in this design challenge was projected onto the center screen, which is also shown in Figure 1. This image was taken with a fiducial marker hung in the appropriate position on the wall to allow the tablet computer camera to track a user’s position and display accurately positioned and scaled AR content. Therefore, in the ICon Lab setting, students could use ecoCampus’s AR interface to see their design concepts overlaid onto the projected image of the physical space.

Figure 1: Students used ecoCampus in a lab (left) where an image of the building wall was projected (right).

Other than the modified activity setting, the research steps completed by the students remained consistent with the different prior design activity implementations. Students were able to self-direct their work to determine for themselves how to approach the design challenge. Additionally, students completed the same assessment activities, before and after designing, to generate data that could later be analyzed to assess their performance.

3.1 Pre-tests

Before beginning the design activity, each student completed a pre-test assessment. This pre-test determined baseline knowledge of sustainability and building design concepts for each student. Additionally, the pre-test gathered responses from the students related to their levels of motivation, confidence in their building design abilities, basic demographic information, and familiarity with mobile computers and the technologies incorporated into ecoCampus. All responses to pre-tests were made anonymous using experimental identification (ID) numbers, which were not known to the course instructor or researchers, to encourage candid responses from the student participants.

3.2 Design Activity

After completing the pre-tests, students were given tablet computers equipped with ecoCampus. They were given a brief, five-minute, introduction to the application, which explained the workflow. The workflow involved three main user interfaces with which a student would interact as shown in Figure 2. These included: a touch-based design interface where students would develop wall design concepts; an AR interface where students would visualize their concepts in the context of the projected image of the physical space; and a basic simulation game interface where they would receive performance data for assessment of their design concept.

After students were introduced to the application, they were asked to input their experimental ID number to link their design work to the other assessments. At each of the main user interfaces, students took screen-captured images of their work to serve as a record of what they designed. These screen-captured images were also submitted as part of their assignment for research analysis as shown in Figure 2.
Students were given approximately 40 minutes to complete the design activity using ecoCampus. They were required to complete a minimum of one design concept. As with students who completed other formats of the activity, they were also allowed to create as many additional design iterations as they felt were necessary during the class time.

![Figure 2: ecoCampus screen-captured images taken by student participants.](image)

### 3.3 Post-tests

After completing the design activity, students were given a post-test assessment where they were asked similar sustainable design understanding questions to the pre-test assessment. Additionally, they were asked questions to elicit responses related to their perception about the activity. These questions sought to understand their perceptions related to the benefits of the activity to their education, the appropriateness of the amount of time allotted to this activity, the level of enjoyment they experienced while completing the activity, and the level of interest generated in building design and sustainability from completing the activity. Using the same approach as the pre-tests, the responses to the post-test were also made anonymous through the use of experimental ID numbers.

### 3.4 Analysis

After all design activity documentation was received, the documents were reviewed and analyzed. Specific attention was given to the design process that students completed to arrive at their final design. Additionally, students’ perceptions about the value of this activity was also examined to understand if completing the ecoCampus design activity out of the context of the physical building had any observable differences from the data collected from students in prior semesters who were physically located inside the building.

### 4 RESULTS

ecoCampus was implemented in the Fall semester of 2013. During this implementation, 27 students completed all assessments and consented to allowing their responses and design submissions to be used in this research. All students who completed the design activity during this implementation were enrolled in the same first-year architectural engineering course (AE 124S), which was also the same course that was targeted in prior semesters’ implementations.
4.1 Student Perception of Activity

The responses to the post-test assessments were collected and analyzed to understand the perception that students had about completing this format of ecoCampus. The responses collected were compared to prior semesters to identify similar trends or shifts in perceptions. In this comparison to prior semesters, only data from students enrolled in the same architectural engineering course were examined to allow for consistency in comparison. The responses to the different assessments were analyzed and compared to students who completed: the same version of ecoCampus where students were physically in the existing building; a paper-based approximation of ecoCampus, where students would illustrate design concepts on top of printed images of the actual building; and a purely open-ended activity where students were given the design challenge description and blank sheets of paper on which to illustrate their concepts. Table 1 shows a summary of the findings related to student perception of the activity.

Table 1: Students’ self-reported perceptions about different design formats.

<table>
<thead>
<tr>
<th></th>
<th>ecoCampus in ICon Lab (27 Students)</th>
<th>ecoCampus in actual building (34 Students)</th>
<th>Paper-based, ecoCampus approximation (23 students)</th>
<th>Open-ended, paper-based format (65 Students)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enjoyed completing activity (%)</td>
<td>92%</td>
<td>82%</td>
<td>76%</td>
<td>84%</td>
</tr>
<tr>
<td>Increased interest in building design (%)</td>
<td>80%</td>
<td>82%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Increased interest in sustainability (%)</td>
<td>76%</td>
<td>79%</td>
<td>55%</td>
<td>69%</td>
</tr>
<tr>
<td>Did not have enough time to complete the activity (%)</td>
<td>14%</td>
<td>9%</td>
<td>43%</td>
<td>43%</td>
</tr>
</tbody>
</table>

The findings from the implementation in the ICon Lab were generally consistent with the responses from prior semesters. Students generally enjoyed completing the activity and also generally felt that it increased their interest in building design and sustainability (see Table 1). The main difference observed between the computerized ecoCampus design activity formats and the paper-based versions related to the perception about the amount of time allotted to complete the design activity. Students who completed the paper-based format were more likely to feel that there was not sufficient time provided to them to complete design. This echoes the findings of prior ecoCampus versus paper-based design format comparisons (Ayer et al. 2014b).

4.2 Design Behaviour

In addition to exploring student perceptions regarding the activity, it was also of interest to study the process they employed while performing the design activity. The screen-captured images taken by the students were analyzed and their design behaviours were documented. In prior work, one of the most noteworthy findings related to the design process employed by the students was related to the number of design iterations and materials that were considered by students during the design session (Ayer et al. 2013b). This prior work showed statistically significant increases in the number of iterations as well as building materials that were considered by students during design.

The results from this implementation of ecoCampus in the ICon Lab also indicated significant increases in the number of iterations completed as compared to students who completed either of the paper-based design activity formats (p<0.001). Additionally, the design activities submitted by the students who used ecoCampus in the ICon Lab considered more building materials over the course of the design activity.
session as compared to the students who completed either of the paper-based design formats (p<0.001). This is consistent with findings from prior ecoCampus implementations.

Perhaps the most noteworthy finding related to this implementation of ecoCampus in the ICon Lab related to the students’ design behaviour was in the comparison between the students who used ecoCampus in the ICon Lab (a virtual setting) and those who used it in the actual building. There was a statistically significant increase in the number of design iterations that students considered when they were physically located in the building (p<0.001). There was also a statistically significant increase at the 95% confidence level in the number of building materials that students considered when completing the activity in the actual building (p=0.017).

4.3 Discussion

Students who used ecoCampus in the ICon Lab to develop improved exterior wall retrofit design concepts for sustainability did so through the creation of more design iterations and considered more possible building materials than students from prior semesters who used paper-based approaches. This finding was not surprising as it echoed the findings of prior work (Ayer et al. 2013b). This behaviour of considering multiple design concepts before finalizing on a chosen concept suggests that students were successfully able to resist the tendency toward design fixation. Design fixation has been defined as adherence to a set of arbitrary rules or constraints that effectively limit creativity (Jansson and Smith 1991). Therefore, this research also reinforces this prior conclusion that an AR-based simulation game interface can help students to break the tendency toward design fixation.

The more noteworthy finding from this work relates to the finding that students used ecoCampus differently based on where they completed the activity, which affected the way that AR would function in ecoCampus. In other words, students enrolled in the same first-year seminar course, using the exact same version of ecoCampus, demonstrated a statistically significant difference in the number of design iterations and building materials that they considered in the same amount of time.

This finding was further explored to determine if there could be a separate factor that might have affected the students’ behaviour. Pre-tests were compared between the different implementations of ecoCampus to determine if the different groups of students had differing levels of experience with mobile computing technology or different levels of motivation for completing the activity. Substantial differences in these metrics could potentially cause a change in students’ design processes.

Table 2 shows the responses related to these topics from students who used ecoCampus in the lab and also those who used it in the actual building. The students in both implementations of ecoCampus responded with similar levels of motivation in the activity pre-tests. This does not suggest that their levels of motivation or experience using mobile computing technology affected their design behaviour.
Table 2: Perceptions between students using ecoCampus in different implementations.

<table>
<thead>
<tr>
<th></th>
<th>ecoCampus in ICon Lab (27 Students)</th>
<th>ecoCampus in actual building (34 Students)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students looking forward to activity (%)</td>
<td>82%</td>
<td>85%</td>
</tr>
<tr>
<td>Students who anticipated putting “very much” effort into activity (%)</td>
<td>54%</td>
<td>47%</td>
</tr>
<tr>
<td>Students who had more than 20 prior experiences using mobile computers (%)</td>
<td>93%</td>
<td>91%</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

This work explored the use of an AR-based simulation game called ecoCampus that presents sustainable building design learning content to students through an interactive design challenge. From prior semesters, several beneficial learning behaviours were observed through the use of ecoCampus. This paper presents a follow-up study to further explore the prior semesters’ implementations. In this work, students were tasked with completing the same exterior wall re-design activity, but they were not physically present in the building for which they were designing this wall. Instead students were tasked with completing this design challenge in front of a projected image of the physical space. This meant that the AR component of ecoCampus did not offer a virtual 1:1 sense of scale. It also meant that students were not able to physically explore the existing facility to gather additional information that could affect their design choices, such as what materials felt the most thermally insulated from the cold outdoor air or which materials worked best aesthetically based on the rest of the building’s design.

The findings of this work generally backed up the findings of prior research that compared ecoCampus design behaviours to paper-based design format behaviours. In this work, it was observed that even when students were taken out of the physical building for which they were designing, ecoCampus was still able to help students to break the tendency toward design fixation by considering more possible design concepts and building material options than students who completed paper-based design activity formats. The perceptions of the activity among students were also largely similar between the different ecoCampus implementations, regardless of location, which further supports prior findings.

The findings related to this work differed in comparison to prior studies when the performance of students using ecoCampus in the physical building were compared to the students who completed their work in the ICon Lab. Students who completed their design work in the context of the ICon Lab did so through the creation of fewer design iterations as compared to the students who completed their design in the building. The group of students completing their design in the ICon Lab also completed their work by considering fewer different building material choices. Both of these findings suggest that using the AR component of ecoCampus in the actual building context can increase motivation to be creative and curious during design and analysis. While this conclusion is supported by empirical evidence related to the students’ behaviour, it was not supported by their self-reported levels of motivation. The responses to these perception-based questions were not largely different between the two groups. This could potentially be due to the fact that students only completed one version of this activity. Had the experiment been conducted by offering students the opportunity to complete both formats of the activity and subsequently rate their perceptions of which one was more engaging, interesting, and valuable, a difference may have been observed.
Future work will explore how human behaviour may be influenced by augmented reality and simulation games in other contexts. This future work will explore how these technologies can influence student learning about building design and construction, but it will also be tested in industry use-cases. It is possible that the same beneficial behaviours that are exhibited by students learning these skills could be observed by industry practitioners when determining the best approach to an actual building design scenario. Finally, additional use-cases for this technology will be explored to study how tasks may be improved related to training professionals in the AEC disciplines.

Acknowledgements

The authors would like to thank the Raymond A. Bowers Program for Excellence in Design and Construction at Penn State for its financial support of this research project. We would also like to thank all the students enrolled in this course who participated in this research effort.

References

EFFECTIVENESS OF AUTOMATED MACHINE GUIDENCE TECHNOLOGY IN PRODUCTIVITY IMPROVEMENT: CASE STUDY

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Abstract: Automated machine guidance (AMG) systems are a relatively new solution to enhance the precision and improve the productivity of heavy civil operations. These systems process 3D computer models of the earthwork together with the spatial information of the end-effector of the machine, and display the relative location of the end-effector and design levels in real-time for the operator. This paper presents a case study of two large earthmoving projects to compare the performance of equipped bulldozers and excavators with non-equipped machines under similar conditions. The studied operations were summer reclamation and highway excavation for bulldozers and excavators, respectively. The results show that the automated machine guidance technology improved the productivity by 6% to 34% for bulldozers and 19% to 23% for excavators. The variation in improvement rates for bulldozers were due to different site conditions, because unstable soil conditions negatively affect the operation regardless of using automated machine guidance system. In addition to productivity improvement, application of automated machine guidance could reduce the need for surveying; the surveyor team was present 21% to 30% of the working hours for conventional operation of excavators whereas this figure was only 5% for the equipped machines.

1 INTRODUCTION

Construction is often regarded as a traditional industry that is slow to adopt productivity improvements. Historical data demonstrates that the productivity rate in US construction industry remained relatively unchanged from the 1960s to 2009 (Eastman et al. 2011). This performance is well below the increase rate of other non-farm industries. A recent study, however, showed that this inferior performance is not valid for the entire construction industry, because a considerable portion of construction operations have been moved into manufacturing setting and the productivity of off-site operations is higher than that for on-site activities (Eastman et al. 2011; Eastman and Sacks 2008).

Despite all criticisms, earthwork operations are among the pioneers of adopting new technologies to improve productivity and accuracy (Navon 2005). Earthmoving operations depend on heavy equipment, and technical advancement in various features of these machines could improve their performance and help them remain economically viable (Tatum et al. 2006). Some of the areas of improvement include efficient engines with lower fuel consumption and emissions, lower service and maintenance costs, better electrohydraulic systems, and integrated monitoring and control systems.

In addition to the evolution of the machines, a number of add-ons have been developed to enhance the performance of the operations. On-board diagnostic system (OBD), automated machine guidance (AMG) technology, weight sensors, and rear-view cameras are among the main new add-on products. AMG
technology is one of the major advancements that gives the machine operator real-time visual information about the location of the end-effector with respect to the design level, such as the location of grader’s or bulldozer’s blade, excavator’s bucket, or screed of pavers. AMG systems mostly use high accuracy GPS systems, such as real-time kinematic (RTK) GPS, to localize the end-effector. Since these antennas capture data under harsh condition (such as jittering), the signals are filtered for better results. Then, the system emulates the movement of the machine in a virtual environment which also contains the geographical data of the design. The whole process is visualized in a graphical user interface (GUI) in real-time. For example, Figure 1.a shows a dual GPS antenna system installed on the blade of a bulldozer and Figure 1.b depicts a typical graphical view of the operation displayed in the cabin. This way, the operator is able to guide the machine with more confidence than in the conventional approach; it also requires less staking and related interruptions during the operation, because these heavy machines sometimes knock down the stakes during operation (Barrett 2008; Han et al. 2006; Han et al. 2005). Moreover, application of an AMG system could reduce the possibility of rework. These products have become popular in the last decade and several companies fabricate a wide range of product lines for different machines, varying from a simple 1D depth estimation device to a full 3D AMG system.

AMG technology has been the subject of some research projects, such as the evaluation of accuracy of GPS-based systems for road pavement (Peyret et al. 2000) and excavation operations (Bernold 2002; Huang and Bernold 1997). In addition to accuracy, the effectiveness of AMG devices is a key factor in improving productivity. For instance, project planners and cost estimators need to adjust their productivity estimations based on the rates that could be achieved through the use of AMG systems (Han et al. 2005). It is also important for the decision makers to be able to estimate the payback rate of these relatively expensive systems before purchase. Therefore, a few research efforts used simulation methodology to compare the performance of the conventional earthmoving with GPS-based operation (Shehata et al. 2012; Han et al. 2008; Han et al. 2006; Han et al. 2005). In addition to simulation, some of the machine control companies provide case studies about the productivity improvement of their products. These case studies, however, are mainly carried out to promote the product and may not adhere to the basics of scientific approach. Therefore, there is a need for an independent scientific field study to evaluate the performance of the AMG technologies regardless of their make. The outcome could be useful for construction planners and decision makers, as well as for comparison with future studies.

This paper explores the productivity benefits achieved through the use of GPS-based AMG systems on bulldozers and excavators. This study examines the productivity rates in conventional and AMG-based operations, as well as the required surveyor time in both methods.

Two types of automated machine guidance devices are investigated in this research: 3D dual antenna grade control for bulldozers and 3D pose estimation system for excavators. The first system uses two RTK GPS antennas installed on both sides of a dozer’s blade (see Figure 1.a) to calculate location (x, y, z) and angles (pitch, yaw, roll) of the blade. It is also possible to implement this system using only one GPS receiver which has lower accuracy compared to dual GPS. Then the system processes the 3D locational data together with the 3D CAD model of the design profiles and displays them together in a monitor installed in the cabin for the operator. These systems usually have the options to show virtual plan and side view of the operation (see Figure 1.b).
The 3D solution for excavators is more complicated than for bulldozers, because extreme working conditions prevent tracking the end-effector using a GPS antenna. There are a variety of products for excavators in which the high-end solution (full 3D) uses a combination of two RTK GPS antennas installed on the cabin for localization of the machine and estimation of the yaw angle of the boom, and a series of angle sensors attached on the arm, stick, and the bucket to monitor the pose of the articulated arm (See Figure 2.a). The samples studied in this research were equipped with this type of 3D system.

Figure 1: a) Dual GPS antennas for bulldozer, b) virtual in-cabin display of bulldozer and blade relative to design levels

Figure 2: a) Dual GPS antennas + angle sensors for excavator, b) virtual display of excavator’s end-effector relative to design levels in cabin
A practical approach to evaluate the effectiveness of these automated machine guidance technologies is to compare the performance of equipped with non-equipped machines under relatively similar working conditions. The job conditions include the same location, same type of soil, same skill level of operators, and the same machine capacity. In addition, the job quantities should be large enough to capture the effectiveness of the system over the long term, which would provide satisfactory comparison data.

2 CASE STUDIES

Two large earthmoving operations were selected for this field survey, and both operations were carried out by a large construction company. There were two main reasons to choose these two cases: First, the contractor used same capacity machines for the same work zones, and some of the plants were operated conventionally while the rest of the machines were equipped with AMG devices. This provided the opportunity to compare their productivity rates. Second, this company uses an effective monitoring system to track the required data for productivity measurement, including working hours, operation locations, and work quantities of each machine, with high accuracy.

2.1 Bulldozer Study

A summer reclamation project in Northern Alberta, Canada, was studied to assess the performance of a 3D grade control system for bulldozers. This project included reclaiming land that was previously used for mining operations. This land had to be restored to its natural contours and pre-mining site condition. The bulldozer production rates were tracked based on time and material being placed. The total volume of earth material moved to the designed grade for the months of June and July 2013 was 181,950 bank cubic meters. The total bulldozer time allocated to the placement of cover-soil materials was 822 hours for the bulldozers without automated machine guidance and 561 hours for the equipped machines. The specified cover material included sub-soil, low-sodic soils, topsoil, and muskeg material with lifts of 70 cm, 50 cm, 30 cm, and 50 cm, respectively. Materials were hauled by off-highway dump trucks to the cover soil placement areas. Then the bulldozers spread out the dumped stockpiles to the required placement thickness and design grades.

Summer reclamation is not as efficient as reclamation in cold months due to large settlements on the placement area. Thawing of the frozen ground in the summer season causes these settlements, which result in unstable ground condition. Therefore, lightweight bulldozers would be more useful during summer reclamation as heavy bulldozers could float over the unstable material.

The average length of the earth-fill sections for this case study was 45 meters, which was an inefficient length. This was mainly due to the fact that haul trucks were not able to move the dump material over the areas where cover-soils were being placed. Nine Caterpillar D6Ts and two Caterpillar D8Ts were used during this case study. Four bulldozers were equipped with AMG including three CAT D6T bulldozers and one CAT D8T. The data was collected using transaction reports, surveying data, and site supervision notes. The transaction report is the company’s internal form of tracking hours assigned to each specific cost code to track time allocated to each task. Working hours of all bulldozers, even those without AMG systems, were tracked using mobile hour recorders. This method provides accurate machine hours. The construction supervisors tracked the work zone of each bulldozer. Onsite project coordinators compiled these records at the end of each day to ensure the acceptable productivity was achieved for each task and for each machine. An accurate survey of the work area of each bulldozer was completed after large sections of work were inspected and approved by a client representative. This inspection/approval procedure followed every two days on average, and the bulldozer would typically wait for an approval before starting work on a new zone. The bulldozer assigned to a specific area would not be moved until the completion of the cover soil in that particular zone, as a way to minimize downtime due to bulldozer relocation. These monitoring processes provide working hours, specific working areas, and approved bank volume of material associated with each bulldozer. These measurements allow for tracking the productivity of each bulldozer based on the actual work volumes with little interpolations required for production estimation of each machine. Figure 3 presents the average of production rates with regards to each month, material type, and bulldozer type.
Application of AMG systems on three CAT D6Ts resulted in 30% increase in average productivity in June subsoil placement. The productivity improvement for the equipped CAT D8T, however, was only 6% in the same operation. The much lower productivity improvement for the CAT D8T compared to CAT D6Ts was due to placement conditions. The D8T had floating issues on the placement areas, causing non value added (NVA) hours which diminished the overall productivity improvement of the automated machine guidance system. The productivity improvement for CAT D6Ts was significant; because the smaller bulldozer causes less ground pressure than a D8T (Caterpillar 2014), the D6Ts experienced less downtime and operated on the placement more efficiently.

June Topsoil placement was done using only CAT D6T bulldozers and the results demonstrate an overall productivity increase of 34%. July muskeg placement was also performed by CAT D6T bulldozers due to material conditions. Muskeg is an unstable type of earth material and related earthwork should be performed by skilled operators with lightweight equipment. As presented in Figure 3, the productivity of CAT D6T bulldozers in placing Muskeg was lower than any other cover soils. The overall productivity increase in placing muskeg with AMG was about 28%. July Topsoil placement was completed using both CAT D6T and CAT D8T bulldozers. There is a substantial difference between the productivity rates of topsoil placement in June and July for CAT D6Ts; rainfall at the end of June saturated the soil and therefore diminished the performance in July. Summer reclamation is highly weather dependent; for example, extreme precipitation could slow down the operation. The improvement rate for the equipped CAT D6T bulldozers in July Topsoil placement was about 28% which was lower than 34% improvement in June, but this figure was still higher than the 20% improvement for the equipped CAT D8T.
These results demonstrate that the productivity improvement rate obtained by the use of automated machine guidance technology is not constant in every scenario. This value also depends on the working situation, namely soil condition, and the AMG systems for bulldozers are more effective in suitable working conditions.

2.2 Excavator Study

This part of the study compared the productivity rates of similar excavators, equipped with a 3D AMG system and without such technology, in a large highway twinning job in the province of Ontario, Canada. This project included large volumes of excavation to accommodate the large cuts and fills of this highway design. The collected data covers the period of June – July 2013, when a total of 101,686 bank cubic meters of earth material were excavated. Total working excavator hours are broken down to 337 hours of conventional operation and 436 hours using AMG technology. In this project, excavators worked on the benches above the material to be excavated while the dump trucks were on the bottom of the other side of the bench being loaded. This case study excluded rock excavation which required extra operation, resulting in much lower productivity rates than the soil excavation. Seven excavators were assigned to the earth excavation task, and two were equipped with a full 3D automated machine guidance system. The machines working on earth excavation included three CAT 345DLs, one CAT 345D, two CAT 336Es, and one LinkBelt LBX700. The LinkBelt LBX700 is similar in size and power to a CAT 345. One CAT 345DL and one CAT 336E were equipped with AMG technology.

The data collection process was similar to that described above for the bulldozers, included tracking of machine hours, work areas, and detailed surveying data of each machine’s work zone to measure excavation quantities. Data recording units installed in all working equipment (even equipment without AMG) recorded working hours. The work zones specific to each machine were tracked by site supervisors and the excavation quantities were jointly measured and approved by the surveyors of the contractor and client. In addition to these three types of data, the time allocated for surveyors guiding the operators of the equipment was also tracked.

Figure 4 presents the compiled productivity rates; the operation with the use of AMG outperformed the conventional approach. The average productivity improvement rate was about 23% for the CAT 345 excavator compared to other non-equipped similar excavators while 19% productivity improvement was observed with the CAT 336 excavator compared to other non-equipped CAT 336.

![Production Rates of Excavators](image)

**Figure 4:** Graphical presentation of excavator productivity rates
The productivity improvement rates for the excavators were less variable than the bulldozers, possibly due to the stationary operation of excavators. Because of the nature of their function, excavators are less susceptible to the negative effects of unstable ground.

In addition to the productivity improvement, application of AMG system on an excavator results in more savings due to the reduced surveying time. Contractor’s surveyors must carry out some grade checks to ensure that the excavation correctly proceeds based on the designed grades. However, a conventionally operated excavator requires more frequent supervision and grade checks, because it requires some visual stakes during the excavation. Moreover, during conventional operations, some visual markers disappear or are knocked down and must be reset. Figure 5 presents allocated surveyor hours versus total working hours of each of seven excavators during the time of study. Surveyors helped the operators of the AMG-equipped excavators in only 5% of the operation time while this value varies from 21% to 30% of time for conventionally operated machines. It should be mentioned that the utilization of survey time in the conventional approach also depends on the number of excavators performing work. A job with a few excavators might require greater surveyor time per excavator, as the surveyors need to spend the time among few work zones.

![Equipment hours vs. surveyor team hours for different excavators](image)

Figure 5: Equipment working hours vs. surveyor hours for all seven studied excavators

The survey times allocated to cover-soil placement areas in the bulldozer case study were not tracked, but the use of grade control systems for bulldozers could reduce the need for this labour-intensive task as well (Han et al. 2006; Han et al. 2005). Another important factor in effectiveness of GPS-based automated machine guidance systems is the GPS signal loss, which was not studied in this research, but it could be problematic in areas with natural obstacles (such as trees and narrow valleys) or human-made obstacles (such as urban canyons) (Meguro et al. 2009).
3 DISCUSSION

The results from these case studies demonstrate that the use of AMG systems increases productivity between 6% and 34% for bulldozers and between 19% and 23% for excavators. This field study revealed that the productivity improvement for bulldozers depends on site conditions. The findings of this study could be compared with the outcome of the simulation-based studies on the use of GPS-based machine control technology in earthmoving projects. Table 1 provides these results.

Table 1: Outcomes of similar studies

<table>
<thead>
<tr>
<th>Study</th>
<th>Methodology</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Han et al. 2006</td>
<td>Discrete event simulation</td>
<td>Two different GPS-based earthmoving scenarios were analyzed and the productivity improvement rates over the conventional system were 21.74% in short haul and 5.67% in long haul distance</td>
</tr>
<tr>
<td>Han et al. 2008</td>
<td>Discrete event simulation</td>
<td>Productivity improvement depends on site conditions. Two models were analyzed with 34.36% and 16.38% productivity improvement rates for the GPS-based system</td>
</tr>
<tr>
<td>Shehata et al. 2012</td>
<td>Discrete event simulation</td>
<td>Time saving of 18.57% and productivity improvement of 41.47% for the GPS-based operation</td>
</tr>
</tbody>
</table>

4 ECONOMIC ANALYSIS

The productivity improvement rates are useful during the scheduling and planning of major heavy civil construction projects. To help exemplify the noticeable benefits of the implementation of AMG systems, a simple scenario is presented. This case examines operating costs and payback based on increased productivity for a D8 bulldozer. Operating costs for the machine and the operator were obtained using OPSS 127 (Ontario Ministry of Transportation 2014) and Statistics Canada (2014), respectively. Based on these sources, the hourly rate of a D8 bulldozer is 243.5 CAD (= $218.8 for machine + $24.68 for the operator). An initial investment of $60,000 Canadian is considered for the 3D automated machine guidance system. It was assumed that the bulldozer has an average productivity of 165 bank cubic meters per hour and the productivity improvement rates of 20%, 25%, and 30% were used in this analysis. As presented in Figure 6, the operation cost of a machine with an AMG will be lower than an unequipped bulldozer after a certain point. For example, in the case of 25% productivity improvement, the initial investment will pay for itself after 203,000 cubic meters of earthmoving, and the subsequent operations would have a larger profit margin than the conventional operation.
5 CONCLUSION

This research project investigated the effectiveness of machine control technology on bulldozers and excavators using systematically collected data from two large earthmoving projects. The results demonstrated overall increases in productivity by using AMG technology in both types of equipment. The rate of productivity improvement, however, is not consistent in all cases and depends on the site conditions, more specifically soil condition. The observed productivity improvement rates for bulldozers varied from 6% to 34% in different conditions and the improvement rate varied from 19% to 23% for excavators. In addition, the required survey time for excavators was also tracked, and showed considerable reduction for equipment with AMG. The equipped excavators required surveyors only 5% of the time, while this value was 21% to 30% of the time for the conventionally-operated excavators.

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HYBRID OBJECT DETECTION AND MARKER RECOGNITION SYSTEM TO MONITOR PERFORMANCE OF THE HAULING DUMP TRUCKS

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Abstract: Various sensing technologies have been developed for real-time monitoring of the earthmoving fleet on construction and surface mining jobsites. Computer vision-based methods are among the most recent techniques employed to track earthmoving machines in a construction field. All the research efforts in this area investigated computer vision algorithms to detect and track different types of equipment, but they were unable to identify individual machines within the fleet. This paper introduces a hybrid system which uses a combination of an object detection method and a marker recognition algorithm to identify individual dump trucks using specific markers attached on them. Background subtraction and Histogram of Oriented Gradients (HOG) algorithm were used to detect candidates in the video frames and then the system zooms on the detected bounding boxes to obtain a better resolution for marker detection. Next, the marker recognition module searches the zoomed frame for a marker and in case of successful identification; it verifies the detection and records a trip for that individual truck. The results showed promising performance, in which the system identified 83% of the hauling trips made by the marked machines without producing any false positives.

1 INTRODUCTION

Real-time monitoring of the construction equipment is beneficial for proactive equipment management and productivity measurement and, in addition, the collected productivity data can be used for simulation, planning, and cost estimation of future projects. Manual monitoring is costly, labour-intensive, and non-real-time, therefore, different automated data collection systems have been developed to monitor earthmoving machines, namely GPS, which has been the main tool for locating the equipment fleet in construction and open-pit mining fields. The GPS-based systems can only provide spatiotemporal data, i.e. time and location, which cannot precisely represent machine actions.

Computer vision-based monitoring systems are among the most recent techniques tested for monitoring construction equipment performance. It has been argued that the vision-based techniques are
appropriate options as they are not intrusive, cost-effective, and can successfully operate in open field jobsites where clear sightlines could be selected. A number of research projects studied the feasibility of using cutting-edge image and video processing algorithms for recognition (Memarzadeh et al. 2013; Rezazadeh Azar and McCabe 2012a; Rezazadeh Azar and McCabe 2012b; Chi and Caldas 2011), tracking (Rezazadeh Azar et al. 2013; Park et al. 2012; Brilakis et al. 2011; Gong and Caldas 2011), and activity identification purposes (Golparvar-Fard et al. 2013; Rezazadeh Azar et al. 2013; Gong and Caldas 2011). All the mentioned research efforts, however, have a major shortcoming as they cannot identify a certain machine among the in-class equipment. The developed recognition methods are only able to distinguish machine types, e.g. backhoe and dump truck, and fail to identify individual machines, e.g. dump truck # 8. Therefore, these vision-based monitoring systems are unable to track the productivity of individual machines, which is a major disadvantage compared to radio-based sensing technologies such as GPS and UWB. As a result, a main research gap is to investigate vision-based identification methods to address this problem. Vision-based identification is an evolving field of computer vision and can be grouped into model- and marker-based identification. Model-based identification algorithms try to recognize a certain target based on the unique visual features of that individual. Face identification is the most active topic in this area that is heavily used for security purposes, and related algorithms use certain features of the existing model(s) of the target to identify it in surveillance videos and images. The model-based methods are exclusively useful for identification of the targets that have unique visual features within its class, e.g. human face. This approach, however, is impractical to identify individual machines in a mining or construction jobsite, because most of in-class machines are completely similar in shape, unless they are painted in different color which is uncommon in most large heavy construction and mining jobsites.

Therefore, the second identification approach—marker-based method— is the practical choice to identify individual machines. There are several robust marker recognition techniques that are able to identify tags under challenging visual condition. These algorithms use a specific type of markers, called fiducial markers, which are made of a set of easy-to-detect features for robust recognition performance. For example, ARToolkit (Kato and Billinghurst 1999), ARTag (Fiala 2005), and AprilTag (Olson 2011) are the popular marker recognition algorithms, which are mainly developed to facilitate augmented reality generation processes. This research project aims in utilizing a fiducial marker-based approach to identify labeled dump trucks in real-time construction videos, and estimate their hauling trips. This paper introduces a pipeline framework to monitor construction equipment using attached markers. First, it describes the architecture of the system, and then it explains the modules of the framework. Next, the performance of the system is evaluated using a number of test videos and finally, the potential applications and shortcomings of this hybrid system are discussed.

2 SYSTEM ARCHITECTURE

A straight-forward approach is to simply search for the attached fiducial markers using a marker recognition algorithm in real-time frames. This brute-force approach, however, has several shortcomings: 1) markers should have a certain resolution (in pixels) to be robustly detectable in frames. This requires optical zooming on the work zone, which limits the field of view and eventually results in missing the big picture of the operations and in addition, the work zones often change and someone should adjust the viewfinder accordingly. 2) This brute-force approach is computationally-intensive.

Therefore, a pipeline framework is developed to detect the most probable candidates, and then zoom on these potential targets to get a high resolution view for the marker recognition process. Next, it passes detected machines to a tracking module which monitors the truck until it exits the view. This way, the system would be able to count hauling trips of individual dump trucks. Figure 1 shows the entire process of this system, in which different modules of the framework are highlighted by color.
First, the system grabs 1280x960 (pixels) frames and creates a 640x480 (pixels) resized copy of each frame. The higher resolution frame is kept and only used for marker recognition, and the lower resolution 640x480 frame is used for other processes, including background subtraction and object recognition. The background subtraction module isolates moving particle (see Figure 2.a) and checks whether any of moving particles are larger than a certain size, which triggers the object recognition module. The object detection module searches frame for dump trucks (Figure 2.b) and detection of a dump truck triggers the zoom control element, which changes the focal length of the lens to optically zoom on the target (Figure 2.c). Afterwards, the system applies an autofocus function to obtain a high contrast view (Figure 2.d), and then employs the marker recognition module to search a high resolution 1280x960 frame for a marker (Figure 2.e). Successfully identified dump trucks are passed to the tracking module, which will be tracked until they exit the scene. This confirms the trip of that individual dump truck. Details of each module are described in next section.
3 MODULES OF THE SYSTEM

As described before, this system is made of several components which are described in detail in the following subsections.

3.1 Background Subtraction

Background subtraction methods are used to isolate moving particles from a static background in the videos captured by a stationary camera. Mixtures of Gaussian (Stauffer and Grimson 1999), a Codebook-based method (Kim et al. 2005), and a Bayesian Model-based (Li et al. 2003) were tested in construction videos, in which the Codebook-based and Bayesian-based methods showed promising performance in detecting moving objects in construction videos (Gong and Caldas 2011). Therefore, the Bayesian-based background subtraction method was selected as the first filter of this pipeline framework. In addition, a process, called connected-components analysis (Bradski and Kaehler 2008), was used to remove random noise from the filtered frame and combine the correlated particles, designated “blobs”. The presence of a blob indicates the appearance of a moving object in the video, which might be one of the targets. But the system only selects moving objects for the next step – object recognition – which are larger than a pre-defined threshold. The threshold was defined given the minimum size (in terms of pixels) of a truck that could be detected by the object recognition algorithm. The object detection algorithm uses a sliding window approach with a minimum size of 128x80 pixels to detect trucks, therefore it would be useless to accept a moving particle with smaller size than 128x80 pixels as it simply cannot be picked by the object recognition. As a result, the width and height of the bounding box of a blob to be qualified for the next step should be larger than 128 and 80 pixels, respectively.

3.2 Object Detection

The Histogram of Oriented Gradients (HOG) (Dalal and Triggs 2005) algorithm was used in this research, because this popular object recognition method has provided promising results in detection of construction equipment (Memarzadeh et al. 2013; Rezazadeh Azar and McCabe 2012a; Rezazadeh Azar and McCabe 2012b). Details of the background effort for the object detection module of this framework to recognize dump trucks is described in Rezazadeh Azar and McCabe (2012a). Implementation of this
algorithm using parallel computing on a Graphics Processing Unit (GPU) could dramatically improve the computation runtime (Rezazadeh Azar et al. 2013). The next step in identifying individual trucks is to recognize attached markers, therefore, object recognition searches only for the views in which the marker could possibly be visible. The markers were attached to the sides of dump trucks in this research, thus the object recognition engine searches for the side viewpoints.

The HOG algorithm generally employs a binary classifier, SVMlight (Joachims 1999), in which the classifier uses a threshold to classify candidates. Therefore, the detection threshold of the classifier was lowered in this system to avoid the risk of false negatives (i.e., failing to select views in which a dump truck was visible), although it could also result in more false positives (i.e., selecting windows in which the machine does not exist). This is not a major concern as the next module of this cascade system – marker recognition – is designed to reject the possible false positives.

3.3 Fiducial Marker Recognition

Fiducial marker identification is a well-investigated topic in the field of computer science and several methods have been developed to address this issue. Marker recognition algorithms were initially developed for superimposing virtual objects in augmented reality, but they have been gradually adopted in other field, namely pose estimation in robotics. Fiducial markers are artificial tags designed with a set of black and white features to create simple geometric shapes, such as straight lines, and sharp angles and edges, to be robustly detected in low resolution, rotated, unevenly lit conditions, or in the corner of an occluded image. The fiducial marker recognition methods essentially differ from general 2D barcode detection techniques, such as QR code (Figure 3.a), because they also have to provide the camera position and orientation relative to the detected marker. ARToolkit (Kato and Billinghurst 1999), ARTag (Fiala 2005), and AprilTag (Olson 2011) are among the most popular marker recognition methods. Figure 3 illustrates instances of ARToolkit (Figure 3.b), ARTag (Figure 3.c), and AprilTag (Figure 3.d) markers. AprilTag algorithm outperformed other methods (including ARToolkit and ARTag) in detection rate and localization accuracy under various visual conditions, including distance and the angle between the camera’s optical axis and the tag’s normal (Olson 2011). Therefore, this algorithm was selected as the last step of the identification process.

AprilTag is a sequential algorithm which firstly computes the gradient at every pixel, including magnitudes and direction. Then, the pixels with similar gradient magnitude and direction are clustered using a graph-based algorithm. Afterwards, it fits multiple line segments to form the boundary of each cluster and finally, existing quadrilaterals are detected and decoded to identify a candidate tag ID.

![QR code, ARToolkit, ARTag, AprilTag](image)

Figure 3: Samples of a) QR code, b) ARToolkit, c) ARTag, d) AprilTag

3.4 Zoom control

As mentioned above, detected trucks have low resolutions in the wide angle frames, which are not sufficient for the marker recognition, therefore the system needs to zoom on the potential candidates for marker recognition. The size of the markers (in pixels) is the key factor to robustly detect them, which depends on both the distance and orientation of the marker (Olson 2011). Application of optical zooming could overcome these limitations. A set of experiments was carried to determine the size (in pixels) of an
AprilTag marker to be reliably recognized (>98%). The results are presented in Figure 4, in which an AprilTag marker should be at least 18x18 pixels to achieve more than 98% detection rate. It should be mentioned that no false positive was observed in these tests.

Based on this result, an automated zoom control module is necessary to zoom on the targets to achieve a reliable marker resolution. This module changes the focal length of a motorized lens to provide a resolution sufficient for the marker identification.

![Figure 4: Detection rate of various resolutions of AprilTag markers](image)

First, a set of tests was done to determine a linear relationship between the focal length and the magnification factor of the camera lens. For this purpose, the length of a specific target (in pixels) was measured in the frames captured from the same viewpoint but with altered focal lengths. Second, the module should calculate the magnification factor required to achieve sufficient resolution based on the size of the detected dump truck (in pixels). Then, it finds the corresponding focal length and therefore, sets the focal length of the lens. Magnification factor is determined using the ratio of actual length of the marker to the actual length of the machine (e.g. 0.6m: 8m) and the minimum detectable marker size (18x18 pixels). For example, if the size of a detected dump truck is 200x125 pixels, the expected size of the marker would be 15x15 (200x(0.6/8) = 15), which is not sufficient for robust marker recognition. Therefore, the magnification factor should be 18/15 = 1.2. Moreover, the calculated magnification factor is increased by 20% to compensate the effects of variations in the size of the detected bounding box, and variations in size of different models of dump trucks. Thus, the scale factor of the example would be adjusted to 1.2x1.2 = 1.44.

This module should also examine whether the detected target will remain in the frame after magnification. For example, an object might be detected in the corner of the frame, but it might not remain after zooming, which makes the zoom useless. A scale affine transformation is used to calculate the coordinates of the object in the zoomed frame, and analyze whether it will appear within the zoomed view. This process is illustrated in Figure 5. First, the origin of the coordinate system is moved to the center of the frame as most computer vision applications use the frame’s top-left corner as the origin (see Figure 5.b). This change is due to the fact that the lens zooms toward the center of the view. The coordinates of the detected dump truck (see Figure 5.c) are multiplied by the calculated magnification factor (see Figure 5.d) to examine if the target will appear in the view after zooming.

The magnified frames are usually blurred from the change of the focal length, thus an autofocus process (a function provided by the camera manufacturer) is employed to enhance the contrast of view. Then, the AprilTag algorithm searches the frame for a marker.
3.5 Tracking

The system passes identified dump trucks to the tracking module for monitoring purpose. A hybrid tracking algorithm was developed that provided promising performance in tracking slow-moving objects in construction videos, such as dump trucks (Rezazadeh Azar et al. 2013). This hybrid tracking method uses a combination of the HOG object recognition and KLT feature tracking (Tomasi and Kanade 1991). The hybrid structure of this tracking algorithm allows handling orientation and scale changes of a slow-moving target. The tracking module has two main applications in this system: first, it continually locates the dump after identification until it exists the frame, therefore it can prevent double identification of a dump truck. The system examines the location of the candidates with the location of tracked machines and will ignore the candidates which have more than 50% overlapping area with a tracked machine. Second, it confirms a hauling trip for an individual dump truck when it exits the scene.

4 EXPERIMENTAL RESULTS

This framework was developed in Visual Studio Express 2010 using three open source libraries: 1) IC Imaging Control C++ Class Library for frame acquisition and camera control (The Imaging Source 2014), 2) OpenCV 2.4.4 library for background subtraction and the HOG object recognition (OpenCV 2013), 3) cv2cg library for AprilTag marker recognition (Feng 2013).

This system can only process real-time videos as it must change the focal length of the camera based on the real-time information provided by other modules. Therefore, all the experiments had to be carried out on-site, which limited the testing opportunities. The experiments were done in two stages: First the performance of the system was evaluated using videos of scale model equipment to validate the concept,
and then it was tested using real-world cases. Altogether, eight videos with the total length of 25 minutes and seven videos with the total length of 43 minutes were processed for scale model and actual dump trucks, respectively. Three unique AprilTag markers were attached on three dump trucks in actual test cases. The camera was positioned in overlooking locations to obtain a clear sightline of the hauling operations. Four criteria, including runtime efficiency, precision, recall, and identified trips rate, were used to evaluate the performance of the system.

4.1 Runtime efficiency

This system should be able to operate on a regular computer in real-time. Therefore, all the experiments were carried out using an ordinary laptop with a 2.2 GHz Intel Core i7 CPU, 8 GB RAM, and an NVIDIA GeForce GT 525M GPU. This system has a pipeline structure, which includes a chain of processing elements and the output of each element is the input of the next. Table 1 presents the process times of the compute-intensive elements of this chain. The rest of the elements —such as frame grabbing and zoom control— are simple processes and immediate. It was aimed to achieve five frames per second (5Hz) runtime efficiency, which is sufficient for a real-time monitoring of hauling operations.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Frame size (pixels)</th>
<th>Average process time (millisecond)</th>
<th>Average frame per second (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background subtraction + segment connected components</td>
<td>640 x 480</td>
<td>45</td>
<td>22</td>
</tr>
<tr>
<td>HOG object recognition using GPU</td>
<td>640 x 480</td>
<td>300</td>
<td>3.3</td>
</tr>
<tr>
<td>AprilTag identification</td>
<td>1280 x 960</td>
<td>400</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The background subtraction and component segmentation are quick processes and meet the requirement, but the HOG object detection and AprilTag identification processes are quite slow. These runtimes, however, did not delay the average five frames per second performance of the entire system as they are occasionally used in this pipeline system. For instance, the object recognition is only triggered when a large moving object is detected and subsequently, AprilTag is merely used when the HOG object detector locates a candidate in a possible zooming region. Moreover, an interval constraint (four seconds) was set to avoid pointless searches. For example, the background subtraction detects a moving entity but the HOG algorithm could not identify a dump truck (e.g. the moving object was a grader), so the HOG will not search the subsequent frame; rather, it waits for interval constraint and then searches for candidates, if there is any. This way, the system could maintain the average five frames per second throughout all the real-time experiments of this research project.

4.2 Identification performance

The experiments were carried out in two stages: scale model machines and actual equipment. The size of the AprilTag labels installed to the real machines was 60 cm x 60 cm, and the same ratio was used for 1:32 scale models which resulted in 1.9 cm x 1.9 cm markers. Table 2 provides the overall performance of the system, which contains three evaluation parameters:

- Recall: True positives / (True positives + False Negatives)
- Precision: True positives / (True positives + False positives)
- Identified trips: Number of identified hauling trips made by individual machines/ total number of hauling trips

Recall and identified trips are two different evaluation criteria as the identified trips only considers detection of dump trucks’ trips whereas the recall also considers unsuccessful identification attempts (i.e., false negatives).
Table 2: Performance of the system in test videos

<table>
<thead>
<tr>
<th>Experiment</th>
<th>No. appeared machine</th>
<th>No. identified machines</th>
<th>No. attempts</th>
<th>Precision</th>
<th>Recall</th>
<th>identified trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC model Dump truck</td>
<td>28</td>
<td>25</td>
<td>32</td>
<td>100%</td>
<td>78.1%</td>
<td>89.3%</td>
</tr>
<tr>
<td>Actual Dump truck</td>
<td>24</td>
<td>20</td>
<td>28</td>
<td>100%</td>
<td>71.4%</td>
<td>83.3%</td>
</tr>
</tbody>
</table>

A noticeable outcome of these experiments is the precision rate, which was 100% in all test cases. This indicates that the results did not include any false positives, which was mainly due to the robust performance of the marker recognition module in rejection of all false positives. The rates of identified trips were higher than the recall rates in both cases, because the system had several failed marker recognition attempts, in which the marker recognition could not detect the marker in the zoomed frames. In particular, the system was unable to identify a few fast moving trucks, because the system could not zoom and focus on targets on time. This system requires about 1.6 seconds (0.045 sec for background subtraction + 0.3 sec for HOG recognition + 0.25 sec changing focal length + 1 sec autofocus) to grab a zoomed frame for marker recognition, which demonstrated to be too long to identify a marker attached on the fast moving dump trucks. In addition, the system was not able to identify the dump trucks with obscured markers, e.g. by other equipment. This is an inherent disadvantage of any vision-based method compared to radio-based devices, which do not require clear sightline.

5 CONCLUSION

Vision-based systems showed promising performance in detection and tracking of key resources, such as heavy equipment, in construction jobsites. These systems, however, were not able to identify individual machines, which prevent them from providing detailed performance data of each machine. A hybrid vision-based system has been developed which uses a pipeline combination of a background subtraction, an object detection method, and a marker recognition algorithm to identify tagged dump trucks, and then passes them to a tracking module. This system includes a smart zooming feature to zoom on the potential targets for marker recognition. This framework could identify 83.3% of the hauling trips made by dump trucks in construction jobsite. In addition, application of a robust marker recognition algorithm – AprilTag – proved to be effective in rejecting all false positives. Despite the promising performance, some shortcomings, such as limited coverage area and inability to detect fast moving targets, exist with this system. Thus, future research effort aims in addressing these issues by adding smart panning and tilting features to the system, and also tracking of other equipment-intensive operations will be investigated.

Acknowledgment

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References


OPTIMIZATION OF AN OFFICE BUILDING ENVELOPE FOR ENVIRONMENTAL IMPACT MINIMIZATION

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Abstract: The key objective of the present article is to use artificial neural network and genetic algorithm optimization techniques along with environmental Life-Cycle Assessment (LCA) methodology to find the optimum building envelope design in an office building for minimization of life-cycle impacts on the environment. Insulation material type, glazing type, window frame material, wall R-value, and window-to-wall ratio (WWR) are the design characteristics of interest. Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), smog formation potential (SFP), and ozone depletion potential (ODP) are the environmental impact categories of interest. We use eQuest 3.65 and Athena Impact Estimator to simulate the energy and environmental performance of 89 combinations of building envelope design. The results are then used in a hybrid neural network and genetic algorithm approach to find the combination with the least environmental impacts.

Because of significant impacts of buildings on the environment – e.g., about 40% contribution of buildings to fossil-fuel energy use and CO\textsubscript{2} emissions - , the results could raise design teams’ awareness about the impact of their decisions on natural environment.

Keywords: environmental LCA, optimization, building envelope, energy use

1 INTRODUCTION

Life-Cycle Assessment is widely applied to assess the environmental impacts associated with products, projects, processes, and programs (Heijungs and Suh 2002). The quantitative technique uses a four-step methodology (ISO 14040, 2006): goal and scope definition, inventory modeling, impact assessment, and interpretation of results.

Numerous studies have attempted to apply the technique in construction and compare different building materials, systems, and components. Dodoo et al (2014), for instance, uses the consequential-based LCA at the scale of building systems to compare three versions of timber structures; i.e., cross-laminated timber, beam-and-column and modular structures. In a research at the scale of building materials, Tingley et al (2015) applies LCA to compare three different insulation materials when applied in a typical dwelling. As another example, Azari and Kim (2012) use process-based LCA to examine the effect of change in curtain wall mullion materials on life-cycle environmental impact of buildings. Azari (2014) is another
example of LCA studies in which a parametric LCA analysis is conducted by applying an integrated energy and environmental LCA analysis to examine a limited number of combinations of building envelope design characteristics with regard to their impacts on the environment. A limitation of this study, however, is the few combinations that are investigated. This limitation would naturally impair a comprehensive conclusion on the optimum combination of design parameters.

To consider all possible combinations of design parameters, an optimization problem needs to be defined. An optimization problem formulation starts with the identification of design variables and proceeds with identification of risks and constraints, finding the objective function, setting the minimum and maximum thresholds on design variables, choosing an optimization algorithm, and eventually obtaining the results; i.e., the optimum solution (Deb 2012).

The target audience is therefore architects, professional community and researchers in the field of built environment. The main goal of the current study is the establishment of an intelligent LCA optimization algorithm capable of precisely predicting appropriate input parameters, consisting of building envelope design characteristics (insulation material, window frame material, wall R-value, glazing type, south WWR, and North WWR), that would result in desired outputs, i.e. the simultaneous minimization of the main indicators of environmental impacts (GWP, AP, EP, ODP, and SFP). Table 1 shows the input and output parameters of interest.

Table 1: Input and Output Parameters.

<table>
<thead>
<tr>
<th>Input Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation material</td>
</tr>
<tr>
<td>Frame material</td>
</tr>
<tr>
<td>Wall R-value</td>
</tr>
<tr>
<td>Glazing type</td>
</tr>
<tr>
<td>South WWR (%)</td>
</tr>
<tr>
<td>North WWR (%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental impact</td>
</tr>
</tbody>
</table>

2 METHODS

In the first step of the present research, we identified 89 combinations of input parameters, out of all possible combinations, as a representative sample of population. We then used a hypothetical two-storey open-concept office building in Seattle (3600-sf floor area; 60-year service life) as the base-case and conducted energy performance modeling, using eQuest 3.65, and life-cycle environmental assessment, using Athena IE, on all 89 combinations of input parameters; i.e. building envelope design characteristics. Seattle was selected because of availability of its inventory data in Athena IE with the assumption that it could be first in a study considering various geographical locations.

To select optimum values of input parameters, a two-step optimization algorithm was developed. In the first phase, each output, such as GWP, was separately modeled with an artificial neural network. To do this, a five-layer ANN was defined with 5-3-4-2-1 neurons in hidden and output layers, respectively. The number of neurons in the input layer equals the number of input variables, i.e. 6 neurons.

To train the defined ANNs and precisely compute their weights and biases, an evolutionary optimization algorithm is used. A well-organized computer program was developed capable of handling a predefined ANN and stochastically computing and readjusting its weights and biases applying genetic algorithm.
evolutionary method. We then used the results of energy and environmental life-cycle assessment for training the above-mentioned ANNs. The data set was randomly divided in training and test subsets in the proportion of 70% and 30%, respectively. All input and output experimental data were normalized in the range of -1 to +1. Moreover, a hyperbolic tangent sigmoid is utilized as an activation function for the hidden and output layers that produces outputs in the range of -1 to +1. The performance of the neural networks was evaluated applying mean squared error (MSE) as the difference between the target output and the network output. The optimization of ANNs was set to stop as soon as its training and test errors reach 1% and 2%, respectively. Figure 1, shows the training error versus epochs for ozone depletion potential output, for instance. It is obvious that the neural network parameters (weights and biases) are continually readjusted and modified by the applied evolutionary algorithm and the error decreases to a predefined minimum at 1%. To illustrate the performance and precision of obtained neural network, the difference between ANN predictions and target values of ozone depletion potential for all data set including training and test subsets is depicted in Figure 2, which demonstrates the compliance between the targets and the ANN outputs.

![Figure 1: Training error versus epochs for ozone depletion potential case](image1.png)

![Figure 2: A comparison between ANN predicted and target values of ODP for experiment numbers of training (1-52) and test (53-74) partitions.](image2.png)

Table 2 represents the performances of five artificial neural networks trained to predict the environmental impacts of an office building envelope varying constructing materials and design parameters.
Table 2: Performances of ANNs trained to model and predict environmental impacts

<table>
<thead>
<tr>
<th></th>
<th>Training MSE</th>
<th>Test MSE</th>
<th>Training Error (%)</th>
<th>Test Error (%)</th>
<th>Epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP</td>
<td>0.00039</td>
<td>0.00131</td>
<td>0.99989</td>
<td>1.81015</td>
<td>19489</td>
</tr>
<tr>
<td>AP</td>
<td>0.00039</td>
<td>0.00038</td>
<td>0.99936</td>
<td>0.97279</td>
<td>4397</td>
</tr>
<tr>
<td>ODP</td>
<td>0.00039</td>
<td>0.00034</td>
<td>0.99888</td>
<td>0.92179</td>
<td>642</td>
</tr>
<tr>
<td>EP</td>
<td>0.00039</td>
<td>0.00031</td>
<td>0.98851</td>
<td>0.88025</td>
<td>114</td>
</tr>
<tr>
<td>SFP</td>
<td>0.00039</td>
<td>0.00073</td>
<td>0.99992</td>
<td>1.35052</td>
<td>1897</td>
</tr>
</tbody>
</table>

In the second phase of optimization effort, another computer code was developed to stochastically find the optimal input variables results in minimum environmental impacts applying genetic algorithm optimization method. To do this, six input variables including insulation material, window frame material, wall R-value, glazing type, and south and north WWRs are codified into a chromosome. The number of initial population and mutation percent were set to be 50 and 5%, respectively. Having implemented the trained ANNs into the code, the computer program was capable of precisely predicting and calculating the fitness of each chromosome (randomly generated scenarios for an office building envelope). It is noteworthy to mention that the fitness of each chromosome was defined as the sum of the calculated values of five above-mentioned indicators of environmental impacts. Figure 3 represents the optimization trend.

![Convergence characteristics of the evolutionary algorithm.](image)

3 DISCUSSION OF RESULTS AND CONCLUSION

The results of the optimization effort, as shown in table 3, revealed the values of the genes for the fittest chromosome, i.e. the optimal input variables for the office building envelope design. According to the results, an office building envelope in Seattle which consists of walls with the R-value of 21, and about 10.476% north WWR and 59.812% of south WWR, and double-glazed Fiberglass/Vinyl-framed windows would yield the optimum, i.e. the minimum, overall life-cycle environmental impacts.
Table 3. Optimal values of input parameters and their corresponding impacts

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Batt+ Fiberboard</th>
<th>Fiberglass/Vinyl Fixed</th>
<th>R-21</th>
<th>Double-glazing</th>
<th>59.812%</th>
<th>10.476%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Frame material</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Wall R-value</td>
<td></td>
<td></td>
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<td>South WWR (%)</td>
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<td>North WWR (%)</td>
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Figures 4-9 show the impact of changes in north and south WWR on environmental impacts of the building envelope of interest in this study with respect to operational energy, operational energy (OE), Global Warming Potential (GWP), Acidification Potential (AP), Ozone Depletion Potential (ODP), Eutrophication Potential (EP), and Smog Formation Potential (SFP). As figure 4 shows, highest operational energy consumption in double-glazed windows occur at higher percentages of north WWR. In triple-glazed windows, higher north WWR should be concerning only at lowest south WWR.

Acidification Potential generally increases with the increase of windows from both types on north façade. The same pattern is evident in ozone depletion potential in double glazing windows when increase of north WWR elevates the contribution to ozone depletion. Highest ODP in triple glazing windows occur at highest WWR in both north and south facades. Eutrophication Potential also gets to its peak in line with WWR.
Figure 4: Association between operational energy and WWR(%) in double- and triple-glazing.

Figure 5: Association between global warming potential and WWR(%) in double- and triple-glazing.

Figure 6: Association between acidification potential and WWR(%) in double- and triple-glazing.
Figure 7: Association between ozone depletion potential and WWR(%) in double- and triple-glazing.

Figure 8: Association between eutrophication potential and WWR(%) in double- and triple-glazing.

Figure 9: Association between smog formation potential and WWR(%) in double- and triple-glazing.
The optimum south WWR of about 59.8% is in general agreement with the literature and indicates that heating, cooling and lighting loads at this WWR are balanced to yield optimum environmental impacts as well as energy use. R-value of 21 was the highest R-value studied. Achieving R-21 as the optimum R-value did not surprise us as high R-values, and therefore low U-factors, help further limit the heat transfer through the building envelope and would contribute to lower energy use and lower environmental impact. Interestingly, the results supported double-glazed window over triple-glazed window. While triple-glazed windows are considered to be a better alternative in reducing energy use, their greater use of glass increases the overall life-cycle environmental burden associated the building envelope.

4 LIMITATIONS

The present research is subject to several limitations. First, due to limitations of the inventory database of Athena IE and input entry possibilities in eQuest 3.65, limited design variables and limited values for those variables could be examined. The optimization in this research was based on 89 combinations of design inputs. Future research can increase the number of modeled combinations in order to generate a more representative sample of population. Future research can also examine a parametric study that incorporate various building types, geographic locations, climate, building envelope materials, etc.

References

PUBLIC-PRIVATE PARTNERSHIPS – ANALYSIS OF GOVERNMENT IMPLEMENTATION UNITS

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Abstract: In the international Public-private partnerships (PPP) market, there is a common use of PPP units for the initiation and management of PPPs. The common examples include Partnerships BC, Partnerships UK, and Partnerships Victoria. A PPP unit could be a policy unit, implementation unit, or both. In the United States PPPs have been implemented through the same offices that manage the conventional design-bid-build projects. Content analysis and a case study approach have been used in this research to examine the use of PPP units in the United States. The analysis shows that PPP transportation projects are delivered in the PPP-enabled states through the internal resources of the departments of transportation without centralized government office. Around fourteen states have internal PPP offices that provide partial/full policy formulation/guidance, coordination, and promotion. Only five states have expanded the functions to the real PPP procurement management work, and that those states are also the leading states in PPP implementation. Having a unit that carries only policy guidance might not be as effective as a unit that does both PPP policy and procurement management. Without centralized units, the implementation of PPP would not be effectively streamlined and implemented in government. The analysis also shows that Florida and Texas are expanding their PPP toward more public facilities and infrastructure; this signifies that the more a state became familiar with PPP, the more it used it for the delivery of projects. The research provides insights to public agencies on the use of PPP units.

1 INTRODUCTION

1.1 Background

Public-private partnership (PPP) units are entities established to support the use of PPP in infrastructure development. Their use has been on the rise and the Organization for Economic Co-Operation and Development reported that over half of its member countries have PPP units (17 of 29) (OECD 2010). A PPP unit can take several roles including policy guidance and development, transaction advice, evaluation, and ongoing oversight or contract management throughout the life of a contract. However, PPIAF (2007) mentioned that the idea behind PPP units was not fully grasped in the PPP global market. A review of literature reveals that a PPP unit may have several definitions, structures, features, and roles:

- A PPP unit is “any organization set up with full or partial aid of the government to ensure that necessary capacity to create, support and evaluate multiple public-private partnership agreements is made available and clustered together within government” (OECD 2010).
- “A PPP unit is any organization designed to promote or improve PPPs … have a lasting mandate to manage multiple PPP transactions, often in multiple sectors.” (PPIAF 2007)
A PPP Unit is an entity designed to fulfill functions such as quality control, policy formulation and coordination, technical advice, standardization and dissemination, and/or promotion of PPPs... it is not the procuring agency" (B-R 2011).

“A PPP unit is established as a point of coordination, quality control, accountability, and information related to PPPs either within a single sector or across a range of sectors. These units are created as a new agency or within a ministry such as the finance ministry.” (ADB 2008)

The United States has been expanding the use of PPPs at the state level. Recent statistics from the Federal Highway Administration shows that there are thirty-three states, District of Columbia, and Puerto Rico to have authorization to use PPPs (FHWA 2014). The objective of this research is to investigate and examine the use of PPP units in the United States in terms of their structure, location within government, and the type of functions they do. The first section of the work reviews the general need for PPP units, the organizational structure, and the functions performed by such units. In section two, three international successful PPP units are investigated for their structure, functions, and projects. Section three investigates the PPP-enabled states through content analysis and a case study approach.

1.2 Need for PPP Units

The need for establishing PPP has emerged over time. Initially, governments used PPPs as an approach to attract private finance into public infrastructure delivery that suffers from a shortage of public funding. However, the need evolved into achieving better value for the money (VfM) spent on public infrastructure, and for optimal, rather than maximum, risk transfer that also achieve VfM (PPIAF 2007).

Governments have established PPP units to provide certain capacities that were not available under the traditional public sector methods. Some of these capacities include: designing projects that balance the risks and rewards in a way to attract more of the private sector companies, calculating the cost to taxpayers of such new PPP transactions, establishing managerial and contract management skills to supervise private operations over the long term of such contracts, establishing guidance materials for the different levels of governments, and designing educational/promotional programs about PPPs (WB 2006).

From another perspective, specialized PPP units are created to fix deficiencies that occurred due to different governmental and institutional failures in the PPP management and procurement. (PPIAF 2007).

1.3 Organizational Structure/Type of PPP Units

The most common forms of PPP units are independent units and centralized units (B-R 2011). Another arrangement is where the unit would be established as a central unit or office arranged by sector or division. In an independent model, a PPP unit act as an agency or joint venture fully or partially owned by the government. Examples include Partnership BC, a corporation owned by the BC government, and Partnerships Germany, a mixed corporation (60 percent owned by the government and 40 percent by a holding company). PPP agencies enjoy more freedom from the political effects, and more flexibility in attracting experienced personnel. These agencies would still be regulated by a central government. The independent joint model carries concerns of conflict of interest between the private sector objectives in profit generation and the public agencies accountability and guaranteeing value for money. Joint PPP agencies might be seen as promoting PPP in order to justify their existence as an entity. However, OECD (2010) argued that such concerns could be minimized or prevented by establishing for transparency in all aspects of work, and issuing work rules and conduct.

In a centralized PPP model, a PPP unit would be established in the Ministry of Finance or Treasury, which is the common model among the OECD countries (OECD 2010). While close to where decisions are made and to in-house expertise, this model may suffer from political impacts on how the unit will function or accept projects. Examples of this model are Infrastructure UK and Partnership Victoria.

1.4 Functions of PPP Units

There are several functions that can be performed by a PPP unit, including (ADB 2008, OECD 2010): policy formulation and guidance, procurement management and technical support, promotion and
capacity building (including training), quality assurance/control, and review of proposals, projects, and programs against PPP statutes/regulations.

Some PPP units would be classified as policy units while others classified as PPP implementation units (Abdel Aziz 2007). PPP policy units emphasize on policy formulation, guidance document development, and PPP training. The guidance would include guidelines for PPP options analysis, feasibility, procurement documents (drafting RFQ, RFP, and agreements), negotiations, and post-award contract monitoring. Examples of such policy units include Partnerships Victoria, the Scottish Private Finance Unit, and HMT Private Finance Unit (OECD 2010). On the other hand, PPP implementation units carry out procurement management and technical support functions. The functions would include an assessment of value-for-money, establishing discount rates, allocation of risk between public and private sectors, assistance in the procurement stages (RFQ, RFP, negotiation). An example includes Partnerships BC, which perform procurement management and financial advisory functions. However, a PPP unit can be a multi-function unit, with policy guidance and technical support for the main functions. B-R (2011) raised a concern over conflict of interest for those PPP units that perform both quality control and technical assistance as they would be working by the same rules that they established themselves.

2 PPP UNITS INTERNATIONAL EXAMPLES

2.1 Partnerships BC, Canada

Founded in May 2002 by the British Columbia Treasury Board, Partnerships BC (PBC) performs a comprehensive financial and procurement management in delivering performance-based infrastructure. PBC has completed several projects in healthcare, water treatment, transportation, sports, and education.

2.1.1 Organizational Structure

Partnerships BC (PBC) is an independent corporation wholly owned by the province of British Columbia. PBC is governed by a five-member Board of Directors that reports to its sole shareholder, the Minister of Finance (PBC 2011). The Board of Directors includes members from both public and private sectors that have a substantial experience in developing and managing PPPs, as well as joint-venture projects. The Board's major function is to guarantee that the company's operations and actions reflect the interests of the shareholder. Moreover, two committees support the Board; these committees are Audit and Risk Management Committee, and Human Resources and Governance Committee. The company is managed and operated by a seven-member management team, and is structured into three major strategic service units Projects, Finance and Administration, and Partnerships Services.

2.1.2 Functions and Projects of Partnerships BC

PBC provides three major service categories: business planning support (e.g. project screening, concept plans, procurement options and business case), procurement management (e.g. competitive selection, evaluation, and contract negotiation), and advisory services during the design, construction and operations phases. PBC's mission is to plan and structure partnership delivery solutions for public infrastructure that are expected to accomplish value for money, implement these delivery solutions effectively and maintain a self-sustaining organization through a strong base of clients (PBC 2011). PBC, however, does not have the approval right on projects as it belongs to The Ministry of Finance.

Partnerships status report of February 2015 shows 43 projects of which 23 are operational, 14 under construction, and 6 in procurement. The projects include the following facilities: 16 healthcare, 10 transportation and transit, 4 educational, 4 accommodations, 2 for each of correctional, bio-energy, power, water/wastewater plants, and 1 sports facility.

2.2 Partnerships UK and Infrastructure UK

Following to UK’s Private Finance Initiative (PFI) in 1997, a Treasury Task Force (TTF) was established. TTF had a policy formulation/guidance office and a projects’ office with the main objective to initiate,
standardize, and train on PPPs. By 2000, the projects section was made into Partnerships UK. In 2010, the government reviewed PFI and introduced PF2. PF2 provided more support for PPP in local governments, increasing transparency, adding more scrutiny and testing value for money, and updating guidance relating to financing. Further, Infrastructure UK was introduced replacing Partnerships UK.

2.2.1 Organizational Structure

Unlike Partnerships BC, PUK was a joint-venture with 51 percent private sector and 49 percent public sector represented by HM Treasury. PUK worked closely with the Treasury supporting the different levels of government while maintain the business freedom as in the private sector. PUK operated on a fee-for-service basis, in addition to other funds that came from governments who paid PUK in return for providing assistance for their PPP projects (Farrugia et al. 2008). PUK's structure included more than 70 specialists in procurement, project management, law, finance, accounting and other fields (Farquharson 2009).

Following to the recession of 2008/2009 and the difficulty in obtaining funds, HM Treasury created the Infrastructure Finance Unit (TIFU) to lend PPP/PFI projects using similar terms to commercial lenders. In 2010, HM Treasury developed Infrastructure UK from the government three existing offices - TIFU, the program and project delivery team of Partnerships UK, and the Treasury PPP Policy Unit (Farquharson and Encinas 2010). Infrastructure UK is a unit within the Treasury and governed by the Infrastructure Advisory Council, which is made of fifteen government and private sector members.

2.2.2 Functions and Projects of Partnerships UK

PUK worked as a PPP policy support and project implementation technical support entity. This technical support for project review included value-for-money review, affordability review, project management, stakeholders’ support and risk allocation. It also closely monitored any departures from the standard PPP contracts for all projects before signature. PUK had no decision-making power, its recommendations were enforced through the relevant approval bodies (Farrugia et al. 2008). PUK provided other services such as marketing and promotion of PPPs, policy formulation, and quality control (PPIAF 2007).

The new IUK had several functions mainly, coordinating planning and prioritization of investments in UK infrastructure, securing private sector investments, and achieving higher infrastructure value for money.

Following PFI and by March 2012, the number of PFI projects reached 717 projects (at £54.7 billion) including various project types such as healthcare facilities, transportation, housing, and education. In the 2012/2013 financial year, a total of 15 projects were signed, and 22 projects were in procurement.

2.3 Partnerships Victoria, Australia

In Australia, Victoria has one of the largest PPP programs followed by New South Wales. Established in 2000, Partnerships Victoria (PV) is a unit of the Department of Treasury and Finance (DTF). DTF has established PPP guidelines, requirements, and framework to be followed by each new PPP project; an example is the Investment Lifecycle and High-Value High-Risk Prove and Procure Guidelines. Victoria PPP guidelines promote government objectives including maximizing the efficiency, social and economic returns from government expenditure, promoting growth and sustainability and ensuring value for money.

By 2008, Infrastructure Australia (IA) was established as the federal entity promoting for PPPs and setting PPP policies and guidelines. In consultation with the Council of Australian Governments (COAG), IA introduced the National PPP Policy and Guidelines which superseded all other guidelines that were in use by all other states. Both the national and PV guidelines principally focus on seeking value for money, innovation, market competition and good project governance. PPP projects in Victoria have to follow both the National PPP Guidelines and the specifics of Victoria’s PPP guidelines.

2.3.1 Organizational Structure

Partnerships Victoria (PV) is an office representing one of the seven subgroups under the Infrastructure Advice and Delivery group, which is one of the eighteen groups under Victoria’s Department of Finance
and Treasurer. PV has two teams, policy, and projects. OECD (2010) mentioned PV has 12 full-time employees including the Director of the group. The Government funds PV through its budget. It is worth mentioning that other government departments may have their own PPP experts.

2.3.2 Functions and Projects of PV

Two entities share responsibilities for PPPs in Victoria: 1) the Procuring Agencies of the relevant Portfolio Minister, and 2) the Department of Treasury and Finance and its PV office. In terms of functions, Procuring Agencies establish a procurement team and governance framework, develop a Public Sector Comparator and performance specifications, secure government approvals, manage key stakeholders, and deliver the project based on the National PPP Guidelines and the Victorian PPP requirements.

On the other side, DTF and its Partnerships Victoria arm are not responsible for the direct project delivery or procurement management; their roles are for review, advice, and quality assurance. DTF monitors project risks through the High Value High Risk Assurance Committee, sets as a member of the PPP Project Steering Committee, and is consulted on key appointments (e.g. for project directors, managers, and advisors). DTF/PV must do a review within the PV PPP framework, which include six gateways; review at gate 1 (Strategic Assessment) for preliminary business case, and review at gate 2 (full business case, procurement options analysis, preliminary public sector comparator, public interest test). Approvals for each of the framework gates are to be done by the government through the Portfolio Minister. It is fair to say that PV is more of a policy and oversight PPP unit rather than an implementation unit.

Based on the National PPP Guidelines, infrastructure projects over $50 million are required to be evaluated against a PPP procurement option. Options analysis follows the new National PPP Guidelines Procurement Options Analysis, Victorian guidelines. By February 2015, Partnerships Victoria website reported 24 projects contracted, worth around $12.4 billion in capital investment. These projects included Healthcare, education, correctional center, transportation and others.

3 PPP UNITS IN THE UNITED STATES

The number of jurisdictions authorizing the use of PPP reached 33 U.S. States, District of Columbia, and one US territory. However, the actual number may vary since some states allow its PPP authorization to expire without renewal. This research surveyed those states using state documentation, organizational structures, and online material. With content analysis, Table 1 shows a summary of the findings. A preliminary review shows that a suitable listing of the functions include the following: G - Guidance for policy formulation, and guidelines and best practice development, C - Coordination among the relevant departments and/or with upper authorities or stakeholders, P – Promotion, outreach and training, PM Procurement Management and technical support, and Q – Quality assurance/control.

As shown in Table 1, fourteen states have PPP offices that mainly do a combination of guidance, coordination, and promotion with partial or full capacity. Of those states, five do engage in procurement management in partial or full capacity; those include Colorado, Florida, Puerto Rico, Texas, and Virginia. The rest of the other 34 states has no dedicated P3 office, rely on the resources of the Department of Transportation, and would be supported by external consultants. A more detailed review is as follows.

3.1 California - Public Infrastructure Advisory Commission (PIAC)

California DOT (Caltrans) is one of the leading states for transportation PPPs since enacting Assembly Bill 680 in 1989, AB 521 and AB 1467 in 2006, and finally to Senate Bill Second Extraordinary Session 4 (SBX2 4) in 2009 which is set to expire by 2017. PPP is managed internally by the Caltrans through a PPP Program. The program has five members including members from the Office of Innovative Finance, and the Planning and Modals Office, along with a program manager, analyst, and attorney. The PPP program is supported by the Office of Innovative Finance, which mainly focuses on utilizing innovative public and private financing along with traditional financing. Caltrans PPP Program can be considered as a PPP Coordination office that implements PPP with the help of the finance and planning offices.
In 2009 and following the SBX2 4 Senate Bill, California created a dedicated PPP advisory office, the Public Infrastructure Advisory Commission (PIAC), under the Business, Transportation, and Housing state agency (BTH). In 2013, BTH was superseded by California State Transportation Agency. PIAC has 20 commissioners from diverse backgrounds; academia, industry, and government. The BTH agency funds PIAC. PIAC can only advise Caltrans and the regional transportation authorities (RTAs) on PPP issues. PIAC has several PPP roles and functions including promotion and training, technical support and screening, and policy guidance. However, since PIAC is an advisory group, it still has to build capacity and hire experts to do such functions as procurement management. As concluded by the California Legislative Analysis Office, PIAC has not yet published any best practices, outsources P3 reports, lacks members with state finance, procurement, and labor issues (CLAO 2012). The power to proceed with a PPP project is still with the relevant transportation agency. Also, SBX2 4 statute requires the California Transportation Commission to establish the evaluation criteria for each PPP project, a function that should have been delegated to PIAC! Finally, PIAC should have been created as an independent public agency for all infrastructure types in CA.

By 2013, California was among the top four states that have more than 10 PPP projects; it had 16 projects at a value of $9.5 billion. The PPP Program previously managed SR91 and SR125, and currently working on the Presidio Parkway and has seven projects in the pipeline. The Presidio Parkway was the first project to be reviewed and recommended by the new advisory commission PIAC.

3.2 Colorado – Office of Major Project Development (OMPD)

OMPD was established as an integrated effort between HPTE (Higher Performance Transportation Enterprise) and Colorado DOT. HPTE was created based on the Colorado PPP act in order to seek out opportunities for innovative and efficient means of financing and delivery of important infrastructure. OMPD/HPTE has certain roles including policy formulation and coordination, develop best practices, assessing the feasibility of projects, manage project development and provide technical assistance. By 2013, Colorado had 9 PPP projects worth $5.7 billion, and currently has multiple PPP project.

Table 1: PPP offices in the United States

<table>
<thead>
<tr>
<th>State</th>
<th>Name of PPP Office</th>
<th>Location</th>
<th>Dedicated PPP Unit/Office</th>
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<td>California</td>
<td>PPP Program/ Innovative Finance O.</td>
<td>PPP Program in DOT</td>
<td>G, C, P</td>
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<td></td>
<td>Public Infra. Advisory Commission</td>
<td>PIAC in CA State Trans Agency</td>
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</tr>
<tr>
<td>Colorado</td>
<td>Office of Major Project Development</td>
<td>Transportation (DOT)</td>
<td>G, C, P, PM</td>
</tr>
<tr>
<td>Florida</td>
<td>Office of Construction/Office of Project</td>
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<td>G, C, P, PM</td>
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<td></td>
<td>Finance</td>
<td>Comptroller Office</td>
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<tr>
<td>Georgia</td>
<td>P3 Program</td>
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<td>G, C, P</td>
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<td>Massachusetts</td>
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<tr>
<td>Minnesota</td>
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<td>G, C, P</td>
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<td>Ohio</td>
<td>Division of Innov. Delivery</td>
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<tr>
<td>Oregon</td>
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<td>G, C, P</td>
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<td>Office of Policy &amp; PPP</td>
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<td>Puerto Rico</td>
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<td>Commonwealth of P R</td>
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<td>Washington</td>
<td>Transportation Partnerships Office</td>
<td>Transportation (DOT)</td>
<td>G, C</td>
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3.3 Florida – Office of Construction and Project Finance Office

Florida is one of the major states in using PPPs in transportation. PPP is one of the alternative contracting systems administered jointly by the Office of Construction and the Project Finance Office of the State DOT. The Office of Construction had a number of template documents for PPPs such as RFP. The Project Finance Office is one of the four offices under the Office of Comptroller of the State DOT; it...
provides support, coordination, and oversight in the PPP areas of build-finance, DBF, and DBFOM. It is fair to say that there is no dedicated PPP unit. The availability of a dedicated Project Finance Office has contributed to the advances and implementation of PPPs.

As of 2013, Florida had 17 projects worth of $6 billion, and there are other 7 projects under construction as of early 2015; of these projects is the I-4 Ultimate Improvements in Orange & Seminole Counties (a $2.3 billion DBFOM road project), and the Palmetto Section 5 – SR 826/836 Interchange (a $566 million DBF project). It is worth noting that Florida was one of the few states that started the use of availability payment in three of its PPPs, the Port of Miami Tunnel (DBFOM), the I-454 Improvements (DBFOM), and the I-4 Ultimate Improvements (DBFOM). This signifies that the experience in Florida has advanced to start using other forms of contractor’s compensation, a one that is mainly based on performance.

Florida has gone beyond transportation by enacting a new legislation, House Bill in 2013, which opened the door to local governments, counties and cities to use PPPs in social infrastructures and any facilities used for public purposes. A requirement of the Act was to establish a task force that would recommend a uniform process for establishing PPP. This effort was the first cited in the United States and a great step for streamlining PPP as a delivery system for public facilities and infrastructure. However, it lacked introducing a government unit(s) that would consolidate the experience in PPPs.

3.4 Georgia - PPP Program,

In 2009, the state of Georgia passed a renewed P3 legislation to create a P3 program team. This team is located within the Georgia Department of Transportation and is supported by external advisors. It is responsible for developing a policy framework and guidelines to promote P3s as well as identifying potential P3 projects. The office can be considered as a PPP Guidance, Coordination, and Promotion office. PPP procurement management and technical assistance will still be done by the DOT internal resources, e.g. planning, finance, construction, and procurement offices. The team has also started the procurement process for several transportation projects such as I-285 & SR 400 improvements, Northwest Corridor, and Multimodal passenger terminal. Georgia’s P3 framework can accelerate project delivery and encourage life cycle cost efficiencies. However, it solely focuses on transportation projects.

3.5 Illinois – Office of Innovative Project Delivery (OIPD)

Illinois has the OIPD as the small office leading the effort into PPPs. The office objective is to assist in determining the best project delivery method, research, develop policy, develop legislation as needed, deliver, and oversee the procurement of PPP projects. The office can be considered as a PPP Guidance, Coordination, and Promotion office. PPP procurement management and technical assistance will still be done by the DOT internal resources, e.g. planning, finance, construction, and procurement offices. By 2013, Illinois DOT is known for the 2005 Chicago Skyway (99-year long term lease, $1.83 billion) and investigating other PPPs, e.g. the Iliana Corridor project and the South Suburban Airport.

3.6 Massachusetts – Public-Private Partnership Oversight Commission

Following to the Transportation Reform in 2009, the MA legislature created the PPP Oversight Commission. The Commission has a panel of six executives and seven members appointed by the Governor, Senate President and House Speaker, and State Treasurer. The mission was to facilitate the formation of transportation PPPs, to develop, facilitate and promote the use of innovative financing, design-build, and other PPP tools, and to encourage the acceptance of the use of PPPs. The Commission can be considered a PPP promotion and quality assurance unit supported by the DOT resources. MA DOT in 2000 delivered a one DBF project at $385 million; it is the Rout 3 North.

3.7 Minnesota – Joint Program Office (JPO) for Economic Development and Alt. Finance

Following the passage of the 2013 Omnibus Transportation Finance Law (HF 1444), a new office, JPO, was added to MnDOT. The JPO office can be considered as a PPP Guidance, Coordination, and Promotion office. PPP procurement management and technical assistance will still be done by the DOT internal resources, e.g. planning, finance, construction, and procurement offices. While the office has yet
to identify projects, by 2013 MnDOT had 5 DB projects at a total cost of $1.2 billion, including Hiawatha Light Rail, TH 212, St Anthony Falls Bridge, US 52 reconstruction, and I-494 reconstruction.

3.8 Ohio – Division of Innovative Delivery
Following the passage of HB 114, Ohio DOT created the Division of Innovative Delivery to manage its PPP projects. The office has five members. The Division office can be considered as a PPP Guidance, Coordination, and Promotion office. PPP procurement management and technical assistance will still be done by the DOT internal resources, e.g. planning, finance, construction, and procurement offices. By 2013, there were 2 DB projects at a total cost of $487 million, the I-90 Innerbelt Bridge, and the I7/670 Interchange. The office is currently working on the Brent Spence Bridge (DBFOM).

3.9 Oregon – Office of Innovative Partnerships and Alternative Funding (OIPAF)
In 2003, Oregon Legislative Assembly passed Senate Bill 772 to establish the Innovative Partnerships Program (OIPP) within the Oregon Department of Transportation. OIPAF was created as a PPP implementation unit supported by the internal DOT resources, e.g. planning, finance, construction, and procurement offices in order to run the OIPP and evaluate the PPP proposals. Due to limited capacity, ODOT has contracted consultants to assist in procurement, evaluation of proposals, negotiation of agreements, and management of public-private initiatives. The Oregon Transportation Commission has the ultimate authority to approve the projects that go forward and the terms of each agreement.

3.10 Pennsylvania – PennDOT Public-Private Partnerships Office
Pennsylvania is a new to the PPP market with its PPP Act 88 of 2012 which created the PennDot P3 office. The office has an executive board of six members from public and private officials. The office is gearing up as a PPP Guidance, Coordination, and Promotion office. PPP procurement management and technical assistance will still be done by the DOT internal resources. It has a new PPP project, the Rapid Bridge Replacement project (replacement of more than 4000 structurally deficient bridges).

3.11 Puerto Rico - The PPP Authority (P3A)
Following to the Public-Private Partnership Act of 2009, the Public-Private Partnerships Authority (P3A) was established as a centralized dedicated PPP unit for managing PPPs in public infrastructure, schools, rail, social infrastructure, airport, roads, and water. The P3A Authority is responsible for promoting PPP policy and has developed regulations/procedures for PPPs. The P3A Authority is involved in all aspects of PPP including identifying projects, requesting proposals, selecting the proponent, negotiating the contract and monitoring contract compliance. It is fair to say that the P3A carries all functions of a PPP unit in policy guidance, promotion, and procurement management. The P3A has developed a list of candidate/priority PPP projects in schools, rails, roads, social infrastructure, airport, and water facilities. By 2013, there were two projects with total value of $3.7 billion, the PR Highways (long-term lease, $1.44 billion) and the Tren Urbano Rail (DB, $2.25 billion).

3.12 Texas – Strategic Projects Division
Texas is one of the top four states using PPP; as of 2013, it had 13 projects at a value of $12.9 billion. Some of the projects developed include: LBJ Managed Lanes (DBFOM, $2.6 billion), North Tarrant Express (DBFOM, $2.04 billion), SH130 Segment 5-6 (DBFOM, $1.36 billion), Grand Parkway (DBFOM, $1.04 billion), and North Tarrant 3A/3B (DBFOM, $1.4 billion).

Texas DOT established the Strategic Projects Division to oversee procurement policies, right-of-way acquisition and to support activities for public-private partnership agreements known as Comprehensive Development Agreements (CDAs). It is fair to say that the Division is a PPP Guidance, Coordination, Promotion, and technical assistance (procurement management) office. PPP procurement management will still be done by the DOT internal resources, e.g. planning, finance, construction, and procurement.

Moving beyond transportation, in 2011 Texas enacted the Public and Private Facilities and Infrastructure Act (S.B. 1048) which provided for using PPP in nearly all public facilities (e.g. transit, power generation,
water/waste water facility, or other similar facility needed for public use). This will be managed by the Texas Facilities Commission, which is the real estate representative of the State of Texas in the purchase of buildings, grounds and property. However, still no dedicated PPP unit.

3.13 Virginia - Office of Transportation PPP (Virginia P3)

In 2010, Virginia Office of Transportation Public-Private Partnerships (Virginia P3) was created following a review of Virginia’s Public-Private Transportation Act (PPTA) of 1995. Virginia P3 is a dedicated public PPP unit, responsible for developing and implementing a statewide program for transportation PPPs. Virginia P3 is located within the Virginia Department of Transportation (VDOT) and reports to and works with the Secretary of Transportation. Virginia P3 has ten members and augmented by consultants in two groups: business management services and financial services. The Secretary of Transportation funds it.

Virginia P3 works through the PPTA Implementation Manual and Guidelines. At the program level, it is responsible for overseeing the P3 program including outreach and stakeholders coordination. At the project level, Virginia P3 works collaboratively with other state transportation and aviation agencies using a four-stage PPP project, namely project identification, screening, development, and procurement. For example, during project screening, Virginia P3 conduct detailed screening and makes recommendation to the procuring agency to make a final decision; if approved, they both submit a recommendation to the PPTA Steering Committee to make a final recommendation on whether a project should advance or not. During project development, it works with Agency in assessing a procurement strategy, conducting initial value-for-money analysis, and developing procurement documents. Along with working with the procuring agency administrators, Virginia P3 works with the PPTA Steering Committee and the Oversight Boards. With the support of Virginia P3 on the issues/terms of PPPs, the agency administrators have several decision points during the process as they represent the final authority for a project.

By 2013, Virginia is another one of the top four states that have more than 10 PPP projects; it had 12 projects at a value of $11.6 billion. A number of recent projects include 595 Express Lanes ($1.9 billion), 95 Express Lanes ($925 million), and the Midtown Tunnel ($2.1 billion). Virginia P3 is a successful step toward streamlining PPPs in Virginia; it does the common functions of PPP units while the responsibility for the PPP projects is still with the procuring agencies. The unit is for the transportation infrastructure; the state has yet to investigate if it would have other units for the different types of infrastructure.

3.14 Washington State – Transportation Partnerships Office (TPO)

WSDOT has an authority to engage in agreement of PPPs. The agency’s office to do that is the TPO. In addition to WSDOT, however, the 2005 PPP law authorized a process called Transportation Innovative Partnership (TIP) program to evaluate the potential transportation PPPs but restricted the use of private finance. The Washington State Transportation Commission (WSTC) has an oversight role over the TIP program and a final approval authority of such PPPs. WSTC provided WSDOT’s TPO to carry out the TIP program’s functions and responsibilities. In summary, TPO has activities that include consultation and advisory services, analysis and assessment, project development, and liaison and representation. TPO, however, has a limited budget (less than $350,000/yr) that funds the office’s three members and all other activities. Since the 2005 law, there were no significant transportation PPPs reported by the state. It is fair to say that TPO is a PPP Guidance and Coordination office supported by internal WSDOT resources.

4 CONCLUSION AND RECOMMENDATION

PPP units are becoming an important vehicle to implement PPPs. A unit can have one or more functions including, policy formulation and guidance, procurement management and technical support, promotion and capacity building (including training), and quality assurance/control against PPP statutes/regulations.

PPP units can be established as a centralized unit under a finance or treasury department where it can work with all other government departments. It can be an independent public agency that report to a treasure or a higher level council. With these two locations, the unit can work at a full or partial scale performing all the functions including procurement management. At the minimum, a PPP unit can be just an office under a department of transportation or another relevant department. In this case, the unit/office
would have limited functionality and a necessity to rely on internal resources (another government office such as construction, finance, and procurement) for PPP procurement management.

Among the international units reviewed in this research, Partnerships BC stands as an excellent example of a unit that performs most of the functions of a PPP unit, particularly procurement management and technical support. Its location as an independent agency gives PBC flexibility in managing its own portfolio without being under political pressures, while still being a public agency owned by the BC Treasurer, and can be self-sustained without a government budget line. In UK, the several years of experience under PFI/ PF2, guidance documents, and hundreds of PPP projects, sufficient PPP knowledge base has been established at the different levels of government. This has provided for Partnerships UK to be another good example of a PPP unit, however, with mixed private and public ownership. Infrastructure UK came to merge the roles of Partnerships UK, and other finance and policy units. With the maturity of PPP in UK, it is expected that Infrastructure UK will emphasize more on the roles of policy formulation, quality assurance, and technical assistance rather than procurement management. Partnerships Victoria was another good example of a unit that has roles in policy guidance and review/quality assurance while leaving procurement management to the procuring agencies.

The survey of PPP units/offices in the United States revealed that most of the PPP-enabled states rely on the internal resources of the departments of transportation. Fourteen states have PPP offices/units. All of such PPP offices provides, partial or full, policy guidance, coordination, and promotion roles, and only five of them have real PPP procurement management and technical support roles.

It is no surprise that the best states using PPPs are those that also have PPP units that do partial/full procurement management along with the regular guidance, coordination, and promotion duties. These states include Florida, California, Texas, Virginia, and Colorado. California and Florida had dedicated offices for innovative project financing, and this should have added significant capacity in financing to pursue more PPP than other states.

It is also found that nearly all the PPP-enabled states have their PPP offices in the Department of Transportation and that they do not have the authority to approve projects that are given to the upper administration. A significant finding was that Florida, Puerto Rico, and Texas are expanding their PPP implementation (new acts made) beyond transportation to include schools, hospitals, water facilities, and other facilities and public projects. This also signifies that the more a state becomes familiar with PPPs, the more it is likely to expand it beyond transportation facilities.

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A SIMULATION FRAMEWORK FOR EX-ANTE ANALYSIS OF SAFETY AND PRODUCTIVITY IN CONSTRUCTION PROJECTS

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Abstract: Safety hazards are one of the major challenges facing construction industry across the globe. Despite a growing literature on assessment of construction safety, the majority of the existing studies are descriptive in nature, do not capture the specific conditions of construction operations and provide one-size-fits-all strategies for enhancing the safety of construction projects. On the other hand, productivity improvement is also a main concern in construction projects. However, the research effort addressing both safety and productivity improvement concerns is still missed in the construction industry. Among different tools used for construction project planning and productivity improvement, discrete event simulation is a well-known tool which has been widely used for analyzing and improving complex construction operations. In this research, for the first time, we are proposing a simulation based framework which concurrently follows safety and productivity improvement in construction projects.

1 INTRODUCTION

Job safety and productivity improvement are main interests in many construction projects. There is a growing literature in construction industry for enhancing safety in projects (e.g., Jannadi and Almishari 2003, Seo and Choi 2008, Zhou et al. 2011, Hinze et al. 2013, Votano and Sunindijo 2014). Improving productivity of construction projects has also been a big concern for many scholars (e.g., Maloney 1983, Arditi 1985, Roseefeld et al. 1992, Han et al. 2008, Zhai et al. 2009, Gouett et al. 2011, Borg and Song 2014). Despite the large number of research efforts done for enhancing safety and productivity in construction projects, construction industry is still missing the research efforts addressing simultaneous improvement of the both aspects. The need for this type of research efforts is more felt when we see mutual impacts that safety and productivity can have on each other in construction jobsites. For example the chance of job hazard is increased when improvement in work productivity amplifies jobsite congestion. Cumbersome safety systems, on the other hand, restrain work productivity and increase the costs of construction jobs. As a matter of fact, there is a big resistance from many construction managers to acquiesce to the safety regulation and enforce safety codes in the construction sites as they see it a non-productive and expensive part of the job and assume it a break on the work progress; this is especially the case in developing countries where construction jobsites are not frequently inspected by safety officers. Increased number of hazards and decreased productivity in construction jobsites are outcomes of this single-dimensional view to the work safety and productivity.
Among the different tools used for improving construction projects productivity, as a result of its capabilities to capture operation details, discrete event simulation (DES) has been widely used in the construction industry. DES capability for modeling complex construction operations has been proven by applying it in a variety of construction operations such as earthmoving (e.g., Farid and Koning 1994), lifting (e.g., Nam et al. 2002), piling (e.g., Zayed and Halpin 2004), pipeline construction (e.g., Lou and Najafi 2007), excavation (e.g., Marzouk et al. 2010) and road construction operations (e.g., Mostafavi et al. 2012). In this research we have introduced a new framework which uses capabilities of DES for modeling construction operations and has exploited it to concurrently model and evaluates safety and productivity levels of different operation scenarios. The framework enables construction project managers to select a scenario which fulfills safety and productivity concerns in the best way. Proposed framework has been tested by modeling a fabricated example of roof tile installation operation; safety and productivity levels of six different operation scenarios have been evaluated and compared in this example and the most suitable scenario has been identified.

2 SAFETY EVALUATION OF CONSTRUCTION OPERATIONS

Safety enhancement is not possible without obtaining a robust safety evaluation method which points the improvable parts of the job. Though, depending on the time and the scope of evaluation, safety evaluation itself can be done in different directions. After a review of safety evaluation research efforts done for construction projects, we identified four main directions for them.

1. Safety performance evaluation: These research efforts are focused on defining safety performance indicators using different project safety outcomes such as the number of accidents, the number of first aids and medical aids, the number of injuries and the time lost. Project safety improvement in this type of research efforts is sought by trending and analyzing values of safety performance indicators.

2. Safety system evaluation: This type of safety evaluation follows a holistic view to the safety, similar approach safety standards such as OHSAS18001, ILO-OSH 2001 and Z1000 pursue. Safety system evaluations or audits in this point of view to safety evolution, is done by direct inspection of different parts of the company to check the compliance of different parts of the organization to the safety procedures, codes and regulations. (e.g., Griffith 2011, Alvanchi and Kanerva 2012).

3. Safety evaluation of job site condition: In these research efforts the safety condition of the job site and its relation to specific job hazards are evaluated. (e.g. Huang and Hinze 2003. Sacks et al. 2012)

4. Project safety risk assessment: Project safety risk assessment is a widely used safety planning method in construction projects. In this method likelihood and severity of possible hazards (or hazard potentials) are estimated based on the project condition. Proper responses are suggested to prevent, control, or transfer risk of hazards during the course of the project. (e.g., Jannadi and Almishari 2003, Mitropoulos and Namboodiri 2010, Lee et al. 2012)

Among these four directions, in the first two directions researchers have based their evaluation methods on the implementation or construction phase of the project and use implementation records for safety evaluation; these approaches pursue a passive perspective to the safety improvement, i.e., improve wherever deficiency has occurred. In the third direction researchers follow a general view to the jobsite safety condition rather than evaluating and improving a specific safety project. Direction four refers to the safety evaluation methods done for a project during the planning phase. Therefore, in terms of safety evaluation method, our ex-ante approach to the safety hazards follows this direction of safety evaluation.

Accuracy in estimation of hazard potentials is a major concern in the research efforts done for safety planning. For example, Jannadi and Almishari in 2003 developed a computerized safety assessment program which bases its estimation on the historical data collected for injuries occurred in different construction activities. This research, however, disregards dynamic nature of construction jobsites, i.e., result of historical data collected from different construction sites, with their specific work conditions, are not necessarily applied to another construction project with its unique work condition; the safety level estimated in this research contains a level of bias depending on the variation of the work condition. In
Identify hazardous operations

Operation assessment

Simulation model of operation

Evaluation of safety and productivity of scenarios

Figure 1. Different parts of the framework

4.1 Identify hazardous operations

Although in recent years simulation software packages have been improved a lot and development of simulation models has become much more easier for model developers, but still development of simulation models requires more efforts compared to traditional planning tools such as CPM or EVM; we need to make sure that we are going to do the simulation modeling for the operations that are in our priorities for safety improvement. In fact, there might be operations which are not considered as hazardous operations, based on the organization past experiences. So, the first part of the framework is to identify most hazardous operations within the project. This can be done by a team of project manager, HSE team members, project planners and any other key project participant at the project manager’s discretion (namely project team) via review of past records, jobsite condition and the project’s priorities.

4.2 Operation assessment

Every operation which is going to be simulated needs to be analyzed in two main aspects including 1) alternative scenarios and 2) possible hazards and influential factors.
4.2.1 Alternative operation scenarios

Alternative operation scenarios are formed by deviations in activities and/or resources. These deviations can cause change in the operation’s safety and productivity levels for different scenarios. In fact, in many cases (e.g., Lamptey 2010, Namboodiri 2010, Dikmen, 2012, Liu, 2005) one of the main concerns construction managers are dealing with during the planning phase is to find scenarios with the most suitable combination of safety and productivity levels. So, simulation of construction operations, which is the main approach for evaluating safety and productivity levels of hazardous operations in this research, is basically the case if there is more than one alternative scenario for an operation. To be able to develop simulation models of construction operation scenarios, orders and durations of activities done in an operation as well as the number and types of resources required should be estimated. These estimations are usually based on past records and project expert judgement.

4.2.2 Possible hazards and influential factors assessment

Possible operation hazards as well as influential factors affecting those hazards should be recognized and quantified to be able to incorporate them in the simulation model. First, we need to assign relative weights to different hazards; this relative should be assigned by project team considering past hazard experiences. Then, we need to measure the impact of changes in values of influential factors on hazard potential. The quantification process itself can be a challenging process; moving from one company to the other or even from one project to the other within a company can change the extent of influential factor impact on hazards. It should be considered that organizational and environmental factors, such as workers skill, climate condition, geographical condition, safety equipment used and past experiences, play significant roles in hazards and influential factors quantification (Mitropoulos et al. 2009). For example working in a windy region might cause more concern for the height falling hazard during steel installation operation while working in a hot region might create more concern for workers dewatering threat during the job. In fact, many safety quantification data collected for a project operation are only valid for that specific project; a mechanism through which safety measurement data is collected and validated for a project is required.

At the first step of influential factor assessment it is suggested that a list of possible influential factors be prepared. As proposed by Mitropoulos et al. (2009), to be able to better recognize a variety of influential factors better, we divide influential factors into three main categories including: task factors, environmental factors and work behavior factors. Activity factors are influential factors affecting activity condition and can increase/decrease hazard potentials during activity. Activity height, distance to the edge, equipment specifications, and material movement distance are some examples for activity influential factors. Environment factors return to the environmental condition in which work is done such as wind, light, temperature, humidity and topography. Operation factors refer to the work congestion and concurrency of different operations. Shared workspace, shared equipment and equipment speed in an adjacent operation are some examples for operation factors. It is recommended for every operation a table, presenting different hazards and related influential factors, is drawn as the output of the first step. The table is going to be completed in next two steps.

The Second step of influential factor assessment is to set thresholds and range of values of influential factors. For example working within 1.8 meter distance to the edge can create a more hazardous condition than beyond 1.8 meter. Safety codes and standards, past hazard reports and team members’ past experiences are the main assets for this step. The output table at step one is more completed by writing down different ranges next to each influential factor. At the third step, the extent of the impacts of different values of influential factors on hazard potential is determined by the project team. The use of a three level rating method proposed by Mitropoulos and Namboodiri (2010) in TDA method, as discussed in section 2, is recommended here. At this step team members evaluate impact of every value range of each influential factor by assigning 1 (low impact), 3 (moderate impact) or 9 (high impact) ratings. Team members are encouraged to use output table from the second step to assign proper rates to the value ranges of influential factors. Table 1 presents a sample output from implementation of three steps of hazard and influential factor assessment.
Table 1: A sample hazard and influential factor assessment for steel erection operation

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Influential factors</th>
<th>Factor impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to the edge</td>
<td>0 m to 1 m, 1m to 3 m, Beyond 3 m</td>
<td>High, Moderate, Low</td>
</tr>
<tr>
<td>Height falling</td>
<td>0 m to 1.6 m, 1.6 m to 4 m, Beyond 4 m</td>
<td>High, Moderate, Low</td>
</tr>
<tr>
<td>Steel element weight</td>
<td>0 kg to 5 kg, 5 kg to 20 kg, Beyond 20 kg</td>
<td>Low, Moderate</td>
</tr>
</tbody>
</table>

4.3 Simulation model of operation

Productivity evaluation of construction operations is a common output from DES models (Martinez 2010). But, the use of DES models for evaluation of safety level is a new approach we are proposing in this research. To be able to evaluate safety levels of different operation scenarios we need to make sure the model can trace changes in hazard influential factors, especially when they pass their thresholds. For calculating safety level of an operation scenario, Mitropoulos and Namboodiri (2010) were videotaping the operation and manually changing ratings of influential factors when their values cross thresholds. In our approach, however, DES model traces change in value of influential factors over time and automatically calculates the level of each hazard at a given time by multiplying rates of its different influential factors. Total safety level of an operation is then calculated by considering relative weights of different hazards. In addition, work productivity level of an operation is calculated simultaneously by calculating cost of workers and the equipment (and material, if it is a source of deviation in scenarios) used in the operation. In our simulation based approach when the model of a base scenario is developed, development of other scenarios (usually) requires minimal efforts by simply deviating DES model elements from the base model. So, capacity of the proposed framework to easily evaluate outcomes of different work scenarios is an advantage of the framework compared to the TDA method proposed by Mitropoulos and Namboodiri (2010). For detailed explanation on DES model development and simulation processes please refer to Banks et al. (2005).

4.4 Evaluation of safety and productivity of scenarios

Dimensionless values of safety levels and dollar values of productivity levels measured are main outputs of an operation simulation model. In cases where a scenario scores the minimum cost and hazard potential, simply this scenario is considered the best scenario. However, it will not happen in most cases. So, to be able to compare results achieved in different scenarios properly and select the most suitable scenario we need a comparison method which works for all situations. Our suggestion is a normalization method in which safety and productivity values are transferred to the range of 0 to 100. More explanation for the proposed normalization method follows.

4.4.1 Normalization of safety

The safety results calculated for scenarios represent hazard potentials of scenarios, i.e., lower values are more favourable. The normalization method is in a way that can address our two main concerns. First, we aimed to be able to distinguish major and trivial safety value differences in different scenarios; it is very important to avoid giving extra credits to trivial safety improvements and degrading substantial safety improvements. Second, we were interested in setting higher values as higher priorities, as a prevalent approach used in grading. Our proposal for addressing the first point, again, is to refer to the project team and ask them to set a desirable value of safety or hazard potential improvement (namely SDV); it is going to be set in percent. For example, while 3% safety improvement, as a result of organizational culture and past experiences, can be assumed a desirable improvement for a project team, another project team might consider 10% safety improvement as a desirable improvement. It is important that improvements close to the desirable value can be easily seen by comparing different scenarios. We also do not expect to receive much higher improvements than desirable improvement, during comparing safety results.
Furthermore, as improvements get more distance from the desirable value (i.e., are reduced) their level of significance decreases and we need to see this reduction in improvement level.

In our normalization method, we assume 0 to 100 represents a range equal to twice of the desirable safety improvement value (DSV). Suppose SSb represents the scenario with the best (or minimum) hazard potential score, SSw is the scenario with the worst (or maximum) hazard potential score. We set the middle value (SSm) as formula below:

\[ SS_m = \frac{(SS_w + SS_b)}{2} \]

In the normalization method SSm or middle value reflects value of 50 (at the range of 0 to 100). But depending on the improvement achieved SSw is normalized to a point between 0 and 50 (namely SNw) and SSb is normalized to a point between 50 and 100 (namely SNb). However, their transferred points are symmetric about 50. If SSi represents hazard potential score of its scenario, its normalized value or SNi is calculated as formula below:

\[ SN_i = 50 - \left(\frac{SS_i - SS_m}{SS_w / DSV}\right) \times 50 \]

To calculate normalized values for the best and the worst scenarios, simply replace SSi with them. For example if hazard potential values for an operation with 3 scenarios have been calculated as 25, 27 and 31 with desirable safety improvement of 10% set by the project team, normalization calculations, using formulas 1 and 2 are:

SSm = (31 + 25) / 2 = 28

SN1 = SNb = 50 – (25 – 28) / 31 / 10% * 50 = 98.4
SN2 = 50 – (27 – 28) / 31 / 10% * 50 = 66.1
SN3 = SNw = 50 – (31 – 28) / 31 / 10% * 50 = 1.6

**4.4.2 Normalization of Productivity**

The Similar approach followed for normalization of safety is followed for productivity too. The only difference here is that the values scored for each scenario here have monetary unit. With similar approach and different notation for the desirable productivity improvement value of DPV, scenario with the best productivity value of PSb, scenario with the worst productivity value of PSw, middle value of PSm, productivity value for its scenario of Psi and its normalized value of PNi, related formulas are:

\[ P_S_m = \frac{(PS_w + PS_b)}{2} \]

\[ P_N_i = 50 - \left(\frac{PS_i - P_S_m}{PS_w / DPV}\right) \times 50 \]

**4.4.3 Scenario comparison**

Combining normalized safety and productivity values achieved, for example, by assigning priority or weight to them, is possible but it is a challenging issue. At its simplest way, we can ask project team to set weights for safety and productivity and simply calculate final values of different scenarios to be able to select the best scenario. However, at this stage we propose a colour coded two dimensional X-Y diagram, with productivity values represented on the X axis and safety values represented on the Y axis (Figure 2). The diagram has been divided into four areas by intersection of middle values (i.e., 50):

- Area 1 or green area: Holds scenarios with high safety and productivity levels
- Area 2 or yellow area: Scenarios with high safety and low productivity levels fall into this area
- Area 3 or orange area: Scenarios with high productivity and low safety are seen in this area
- Area 4 or red area: Holds scenarios with low safety and productivity levels
In general, scenarios within area 1 are more desirable. However, depending on the project team’s priority, scenarios within area 2 (with project team priority on safety) and area 3 (with project priority on productivity, might be selected as well. Distance to the middle values is also another effective factor. It is likely that a project team rejects scenarios within area 1, but very close to middle point and accept a scenario within area 2 with high standing in safety and minor distance to the middle value of productivity.

5 FRAEMWORK IMPLEMENTATION

To test different features of the proposed framework, different steps of the framework have been applied to a fabricated roof tile installation operation. Since this is a fabricated operation rather than an actual project, in this test we skip step one to “identify hazardous operations”. Furthermore, a group of authors have played the role of project team with inputs from literature.

5.1 Operation description

In this operation there is one worker on the ground that loads and hoists roof tiles to the top. Another worker works on the roof top that, first, depots tiles on the roof and, then, installs them. Main specifications of the roof are:

- Roof pitch is 1 to 3
- Roof area is 9 m long and 4 m wide
- Roof has a fall protection guard on the width but is not protected on the length
- Tiles have dimension of 25 cm to 35 cm; with tiles overlapping the effective dimension is 20 cm to 30 cm

5.2 Operation scenarios

Six different scenarios are evaluated and compared in this example. Different scenarios are created as a result of using different depot arrangements and different types of hoists with different capacities and working speeds. Figure 3 illustrates the roof specifications and two main depot arrangements types on the roof used in different scenarios. Table 2 presents main characteristics of different work scenarios.
5.3 Influential factors assessment

Falling hazard is the hazard identified for this operation. Three influential factors are identified for this hazard including: the roof pitch, the distance to the not-protected edge and the workers movement. Table 3 presents influential factor assessment for the roof tile installation operation.
Table 3: Influential factor assessment for roof tile installation

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Influential factors</th>
<th>Factor impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof pitch*</td>
<td>Flat below 5:12 below 5:12</td>
<td>Low (1) Low (9)</td>
</tr>
<tr>
<td>Height falling distance to the not-protected edge</td>
<td>On the roof ridge beyond 1.8 m</td>
<td>Moderate (3) Low (9)</td>
</tr>
<tr>
<td>workers movement</td>
<td>No movement forward movement</td>
<td>Low (1) Moderate (3)</td>
</tr>
<tr>
<td></td>
<td>Backward movement</td>
<td>Low (9)</td>
</tr>
</tbody>
</table>

* There is no change on the roof pitch during the operation and its value is considered constant.

5.4 Simulation model assessment

Simulation models are developed in Anylogic simulation program. For productivity calculations based on Iran’s construction market, equivalent hourly rate of 2.5 US$ is considered for the hoist operator and equivalent hourly rate of 5 US$ is considered for the tile installer. In addition hourly rate of hoist rental for bucket sizes of 10, 15 and 20 tiles are respectively considered as 2 US$, 2.5 US$ and 3 US$. Table 4 presents raw and normalized results achieved for productivity and safety level of each scenario. Desirable improvement for both productivity and safety levels is set as 10%. A comparison between results is also illustrated in colour coded diagram in Figure 4.

Table 4: Safety and productivity results achieved in simulation models

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Hazard potentials</th>
<th>Normalized Safety level</th>
<th>Productivity rate (total tile installed)</th>
<th>Normalized productivity level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.69</td>
<td>73</td>
<td>97</td>
<td>62</td>
</tr>
<tr>
<td>2</td>
<td>8.74</td>
<td>70</td>
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<td>75</td>
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<tr>
<td>3</td>
<td>8.46</td>
<td>84</td>
<td>106</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>9.81</td>
<td>16</td>
<td>93</td>
<td>81</td>
</tr>
<tr>
<td>5</td>
<td>9.78</td>
<td>17</td>
<td>95</td>
<td>71</td>
</tr>
<tr>
<td>6</td>
<td>9.46</td>
<td>33</td>
<td>103</td>
<td>33</td>
</tr>
</tbody>
</table>

* This price is related to the cost of hoist rent and Labors.

Figure 4. Colour coded diagram presenting normalized result achieved for scenarios
Among different scenarios, scenario 3 has scored the lowest hazard potential value and has the best safety level with normalized value of 84. In regard to the productivity scenario 4 has the lowest cost and highest productivity level with normalized value of 81. At a fast glance to the colour coded diagram, scenario 2 in area 1, with a relatively high safety and productivity levels, is the first scenario to be selected. However, final scenario selection can be changed due to the project team priority.

6 CONCLUSION

Safety and productivity improvement is a day after day concern of construction project managers. Although many research efforts have been done to improve safety and productivity of construction projects, the research efforts addressing these two aspects of construction projects are still missed. In this research we proposed a new simulation based framework to concurrently evaluate safety and productivity levels of construction operations. The framework helps construction project managers to select most suitable alternative operation scenarios, especially for hazardous operations within a project. It involves project team members in different steps; it uses their related past experiences and incorporates their concerns during the decision making process. In this perspective the framework tries to model and evaluate the work condition as realistic as possible. To assess different features of the framework we applied the framework to a fabricated example of a roof tile installation operation. However, more validation efforts for applying the framework to real construction projects are still in progress.

References


ASSESSMENT OF NETWORK-LEVEL ENVIRONMENTAL SUSTAINABILITY IN INFRASTRUCTURE SYSTEMS USING SERVICE AND PERFORMANCE ADJUSTED LIFE CYCLE ANALYSIS

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Abstract: Managing environmental impacts of civil infrastructure systems is critical for fostering sustainable development. However, despite the growing body of literature, an integrated methodology that captures the specific traits of infrastructure systems for a network-level environmental impact assessment is still missing. The objective of this paper is to propose a novel methodology [called Service and Performance Adjusted Life Cycle Assessment (SPA-LCA)] for addressing the limitations of the traditional LCA in environmental assessment of infrastructure networks. The SPA-LCA methodology adopts a service-based accounting approach to enable aggregation of the impacts pertaining to assets with different functions and service life expectancies at the network level. In the proposed SPA-LCA methodology, first, through conducting traditional asset-level LCA, life cycle inventories for the assets are determined. Second, the life cycle inventories are disaggregated to performance-sensitive and non-sensitive impacts. Then, using a hybrid mathematical/agent-based simulation model, the levels of service and performance are simulated for different assets in the network across the analysis horizon. Finally, the environmental impacts are determined for each year based on the levels of service and performance. The application of the proposed SPA-LCA method is demonstrated in environmental assessment of a road network. The results highlight the capabilities of SPA-LCA in providing better insight regarding environmental performance of infrastructure networks.

1 INTRODUCTION

With the growing awareness of environmental protection, decision makers are increasingly interested in careful assessment of the environmental impacts associated with civil infrastructure networks. However, the majority of the existing environmental assessment studies are based on asset-level models, which cannot fully capture the environmental impacts at the network level. There are fundamental differences between asset-level and network-level environmental assessment of infrastructure (Öberg et al. 2012):

1. Asset-level impacts mostly depend on technical solutions (Vanier 2001). For instance, the environmental performance of a single road depends on a technical plan that determines the design specifications and identifies the timing and type of future maintenance/rehabilitation activities. However, at the network level, non-technical considerations (such as financial plans corresponding to allocation of resources among several assets with competing maintenance needs) also affect environmental performance (Zhang et al. 2012).
2. Environmental impacts of an asset are assessed within the service life of the asset (i.e. from construction to demolition and reconstruction of the asset). However, infrastructure networks do not have a definite life cycle. Instead, at the network level, the objective of network management determines the analysis horizon. Objectives may be related to short-term operational, mid-term tactical, and long-term strategic planning horizons (Vanier 2001).

3. Management of a single asset is mainly consisted of decisions made at the time of asset design. However, the management of infrastructure networks is an ongoing process involving multiple stakeholders whose adaptive decision-making processes and behaviors affect the environmental impacts of these networks over time (Osman and Nikbakht 2014; du Plessis and Cole 2011).

4. Asset-level infrastructure management is solely focused on “objects” (i.e. projects or facilities). However, at the network level, the focus is on objects and their interdependencies (functional, budgetary, and resource) (Öberg et al. 2012; Vanier 2001).

Life Cycle Assessment (LCA) is a widely used environmental impact assessment method which was initially developed for assessment of manufactured products (ISO 14040 2006). Due to its unique capability in compilation and evaluation of the potential environmental impacts, LCA has now become a dominant method for assessment of environmental performance in infrastructure. However, LCA has certain methodological limitations that affect its reliability for network-level environmental assessment. First, LCA provides a lump sum assessment of environmental performance by compiling the potential environmental impacts of a product throughout its expected service life (ISO 14040 2006). Such analysis assumes that the performance of the product is uniform throughout the analysis horizon which is contradictory with the varying nature of service and performance in infrastructure networks. The lump sum outcomes of LCA are most useful for manufactured products for which decision making is usually a single task done during the design or procurement of the product. However, in infrastructure networks, decision making is an ongoing process, which has significant implications particularly in use/operation phase when decisions about timing and type of maintenance and rehabilitation of infrastructure are made. Second, LCA is a static method in which the dynamic changes in the level of service and performance are not considered. The level of service and performance in infrastructure networks is affected by the decision-making processes and behaviors of stakeholders. LCA is not capable of capturing these dynamic behaviors affecting the performance and level of service in infrastructure networks. Finally, LCA has been developed based on the premise that a sustainable approach is the one that minimizes the environmental impacts per functional unit for a product. This approach is valid when the life cycle is definite and functional unit is unique. However, infrastructure networks have a continuous service life and serve multiple performance functions. Hence, for infrastructure networks, a sustainable approach is the one that provides the longest service life and greatest performance with the lowest environmental impacts. Hence, an appropriate methodology for assessment of environmental impacts in infrastructure networks should consider the following: (i) Continuous service life of networks; (ii) Dynamic changes in the level of service and performance of networks affecting the environmental impacts; and (iii) The decision making processes of stakeholders affecting the level of service and performance in infrastructure networks.

An integrated methodology that captures the requirements of network-level environmental assessment in infrastructure is missing in the existing literature. The objective of this research is to address this gap in the body of knowledge by creating a network-level environmental assessment methodology that considers the specific traits of infrastructure networks.

2 BACKGROUND

The majority of the existing environmental assessment methodologies are based on an environmental accounting principle in which the environmental events are recognized at the time when emission occurs or natural resources are depleted. This accounting principle is prone to shifting burdens from one location to another (Hoekstra and Janssen 2006), or from one stage of life cycle to another stage (ISO 14040 2006) [e.g., by postponing the required maintenance of a road and creating a need for earlier reconstruction]. Life cycle assessment has successfully solved this problem for asset/product-level environmental assessment by taking all the impacts related to the entire service life of the asset/product.
into consideration (ISO 14040 2006; ISO 14044 2006). However, when it comes to network-level environmental assessment, individual assets have different start/finish dates of life cycles. Hence, when LCA is used for a network-level environmental impact assessment, it only captures the emissions during the analysis horizon and does not capture the emissions related to activities (such as maintenance and rehabilitation activities) prior and after the analysis horizon. Therefore, using LCA for a network-level assessment leads to the same burden shifting problem of emission-based environmental accounting.

We propose that changing the accounting principle for environmental assessment from emission-basis to service-basis accounting can both prevent burden shifting and provide flexibility regarding the length of analysis. To this end, we make an analogy between the environmental accounting and financial accounting. In business and finance literature, two distinctive types of financial accounting are used: i) cash-based accounting in which revenues and expenses are recorded when the cash is transferred. The existing emission-based environmental accounting is similar to cash-based financial accounting in which the release of pollutants or consumption of resources play the role of cash flows; and ii) accrual accounting in which economic events are recognized at the time of transaction rather than when a payment is made (or received). Accrual accounting has shown to be more reflective of the impacts of managerial decisions and the financial conditions of a company because it takes both current and expected future cash flows into consideration (Kwon 1990). Using an analogy to accrual accounting approach (Figure 1), we propose a service-based environmental accounting principle in which the impacts are recognized when the service is provided rather than when emission is made. For example, the huge impacts created during the construction of a new road, are not recognized at the time of construction. Instead, these impacts are attributed to each year of the service life based on proportion of total expected service offered in that year. The service basis principle enables consideration of both current and future impacts of a network on a yearly basis, thus providing a measure for evaluation of the environmental performance of the network during any desired analysis horizon.

<table>
<thead>
<tr>
<th>Financial Accounting</th>
<th>Environmental Accounting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cash basis Accounting</td>
<td>Emission basis Accounting</td>
</tr>
<tr>
<td>Events are recognized at the time of payment.</td>
<td>Events are recognized at the time of emission.</td>
</tr>
<tr>
<td>Accrual Accounting</td>
<td>Service Basis Accounting</td>
</tr>
<tr>
<td>Events are recognized at the time of transaction.</td>
<td>Events are recognized at the time of service.</td>
</tr>
</tbody>
</table>

Figure 1: The proposed service-basis accounting is analogous to accrual accounting in financial studies.

3  SERVICE AND PERFORMANCE ADJUSTED LIFE CYCLE ASSESSMENT (SPA-LCA)

The proposed service-based accounting for environmental assessment of infrastructure networks requires determination of levels of service and performance in a network during the analysis horizon. Hence, a simulation-based approach is needed for dynamic modeling of the service and performance. To this end, the proposed SPA-LCA methodology consists of two modules to capture the specific requirements of network-level environmental assessment in infrastructure systems (Figure 2). The module of network performance simulation is comprised of a hybrid mathematical/agent-based simulation framework to model the complex dynamic interactions between the conditions of assets, the demand pattern, and the managerial decisions regarding preservation of the network. The outcomes of the simulation model include the level of service and performance of each asset. Given an inventory of relevant energy and material inputs and environmental releases, the simulated service and performance of the assets are then used in network environmental assessment module to calculate network-level. The network performance simulation module is based on the methodology proposed by Batouli and Mostafavi (2014) for dynamic modeling of agency-asset-user interactions in infrastructure systems. The level of
service and performance in infrastructure networks is an emergent property as a result of the interactions between the conditions of assets, the extent of demand, and the decision making processes in administrating agency (Batouli and Mostafavi 2014). The decision making processes are modeled in the asset management component of the proposed framework. The asset management component uses agent-based modeling to abstract and simulate the decisions regarding the timing and type of maintenance and rehabilitation (M&R) activities considering the current condition of the assets as well as the underlying policies and availability of funding (Mostafavi et al. 2013). The service model simulates the level of demand on each asset based on the historical information and the conditions of assets. The conditions of assets are in turn identified in asset performance model using dynamic mathematical simulation. The performance of an asset is a function of the level of service it provides and the preservation (i.e., maintenance or rehabilitation) it receives. Detailed information related to the components of network performance simulation module can be found in Batouli and Mostafavi (2014).

The service and performance of all assets are used as inputs to the network environmental assessment module to calculate the network-level environmental impacts. An inventory of relevant energy and material input/output flows is created similar to the traditional LCA (ISO 14040 2006; ISO 14044 2006). However, in the asset-level life cycle inventories (LCI) of the SPA-LCA methodology, the inventory items are divided into two categories based on the sensitivity of the inventory item to the performance of the asset. Disaggregation of LCI to performance sensitive and non-sensitive items is required for translating the lump-sum environmental impacts in traditional LCA into a dynamic environmental profile in SPA-LCA methodology.

The items whose quantities vary based on the performance of the asset fall into the performance sensitive category. The flows that impose a fixed amount of impact regardless of the performance of the asset are attributed to performance non-sensitive category. For example, in analyzing the environmental impacts of a pavement network, items related to the use phase of the pavements belong to the performance sensitive category. That is because fuel consumption and pollutant emissions of vehicles depend on the roughness of the pavement as well as the travel time (Yu and Lu 2012). However, the impacts related to the construction of the pavement are independent from the pavement performance and hence they fall into the non-sensitive impact category. In the SPCA-LCA model, a Performance Adjustment Factor (PAF) is defined to modify the quantities of performance-sensitive items based on the simulated levels of performance. The PAF is defined based on historical information regarding the correlation between environmental impacts and performance of infrastructure assets.

The impact values of performance adjusted inventory items are then summed up with the values of non-sensitive items to form an adjusted life cycle inventory. Finally, the adjusted life cycle impacts of each asset are attributed to different years of the asset’s expected service life based on the level of service at each year (obtained from the network performance simulation model). Attributing the impacts based on the level of service is consistent with the service-based accounting principle explained in previous section. Application of the proposed framework is elaborated in next section using a case study pertaining to a road network.
4 NUMERICAL EXAMPLE

Global warming potential (GWP) associated with the service life of pavements pertaining to twelve sections of a road network are analysed over a 40 year analysis horizon to demonstrate the application of the SPA-LCA methodology. The information related to the network characteristics are obtained from The ICMPA7 Investment Analysis and Communication Challenge for Road Assets (Haas 2008) and are summarized in Table 1. The network includes roads with flexible (F), rigid (shown as CP (Concrete Pavement) in Table 1), and Composite (C) pavements. Roads are either rural (R) or interstate (I) highways. The initial traffic on each road is represented by Equivalent Single Axle Load (ESAL) in Table 1.

<table>
<thead>
<tr>
<th>Section Name</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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<th>I</th>
<th>J</th>
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<td>I</td>
<td>R</td>
<td>I</td>
<td>I</td>
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<td>F</td>
<td>F</td>
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<td>CP</td>
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<td>41.0</td>
<td>37.4</td>
<td>42.7</td>
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<td>46.6</td>
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<td>6</td>
<td>4</td>
<td>4</td>
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<td>6</td>
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<tr>
<td>ESAL/ Day</td>
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<td>1185</td>
<td>1645</td>
<td>1756</td>
<td>864</td>
<td>688</td>
<td>1142</td>
<td>1785</td>
<td>1785</td>
<td>1185</td>
<td>1479</td>
<td>1756</td>
</tr>
</tbody>
</table>

4.1 Module of network performance simulation

This module includes three components: asset management model, performance model and service model. The interaction between these three components determines the level of service and performance of assets during the analysis horizon.

The performance model uses dynamic mathematical simulation to model the deterioration of the pavements given the initial conditions of the roads, traffic demand, environmental conditions, and the timing and type of M&R treatments. Present Serviceability Rating (PSR) is used as a metric for measuring pavement performance and is quantified using an empirical equation proposed by Lee et al. (1993) as shown in Equation 1:

\[ PSR = PSR_i - A \cdot F \cdot a \cdot STR^b \cdot Age^c \cdot CESAL^d + MR \]
In Equation 1, \( PSR_i \) denotes the initial value of PSR for a given link right after construction. This value is 4.5 according to Chootinan et al. (2006) and Lee et al. (1993). Cumulative Equivalent Single Axle Loads per day (CESAL) and STR (existing structure of pavement) capture the impact of traffic load and structural design of the pavement, respectively. CESAL is mathematically calculated in the service model based on the historic traffic data and projections of future traffic growth. An adjustment factor (A.F.) is used for considering the effect of climate conditions. Finally, \( a, b, c \) and \( d \) are empirically-based coefficients whose values depend on the type of pavement (Lee et al. 1993).

The improvements in pavement condition due to maintenance/rehabilitation activities are incorporated in Equation 1 with the denotation \( MR \). The value of \( MR \) is calculated in asset management model. The asset management model uses agent based modeling to simulate the decision making behavior of the administrative agency regarding the timing and type of M&R activities. Four types of M&R activities are considered in this case study: routine maintenance, surface treatment, overlay, and rehabilitation. Each of these activities leads to a certain level of improvement in performance depending on the age of the pavement (Chootinan et al. 2006). For preservation of the network, the administrative agency follows a “worst-first” strategy in which the roads with lowest performance are prioritized for allocation of M&R funding. A maintenance and rehabilitation (M&R) activity is implemented only if it can restore the pavement to an excellent condition; otherwise, if an adequate funding is not available for the required M&R, repair activities are deferred to the next period. Details related to the agent-based modeling of the agency decision processes can be found in Batouli and Mostafavi (2014) and Batouli et al. (2014).

The outcomes of the network performance simulation model include the level of service and performance of pavement assets, the expected service life of each asset, and the type and timing of M&R activities. The expected service lives of individual pavement assets are determined based on the threshold values of PSR to determine the need for reconstruction. These threshold values are considered to be 2.2 and 2 for urban and rural roads, respectively (Elkins et al. 2013). Once a road reaches this threshold PSR value, it is considered to be irremediable by maintenance activities, and hence, it should be reconstructed. The outcomes of simulation model are used in the module of SPA-LCA to calculate the global warming potential of the network at each year of service.

4.2 Module of network environmental assessment

The cradle-to-grave life cycle inventories related to different types of pavements, based on average conditions in the United States, are obtained from Loijos et al. (2013). The data includes greenhouse gas emissions created during all stages of pavement life cycle from materials production to construction, use, M&R, and end of life. However, the LCI inventory provided in Loijos et al. (2013) is developed using traditional LCA methodology. This inventory information needs to be adjusted to be used in the SPA-LCA model. To this end, the life cycle inventory was divided into three categories of inventory items:

The impacts associated with the materials production, construction and end of life are not sensitive to the level of service and performance. The inventory items related to this category are kept unchanged in the adjusted LCI of SPA-LCA model.

The impacts related to M&R activities directly depend on the type and frequency of M&R treatments. For example, a typical preservation plan during the service life of a pavement asset may include 3 routine maintenances, one surface treatment, and one rehabilitation. However, in reality, budget constraints and agency priorities may result in deferring or changing the planned maintenance. Similarly, accelerated deterioration of the pavement may lead to the need for an additional overlay treatment. Hence, the impacts related to M&R activities are determined based on the outcomes of the simulation model, which determines the timing and type of M&R activities. The unit emission for each of these M&R activities is extracted from the LCI inventory and is multiplied by the simulated number of each type of treatment during service life of an asset.

The quantity of GWP generated during use phase of a pavement highly depends on the rate of fuel consumption of vehicles traveling on the pavement. On the other hand, the fuel efficiency of the vehicles is a function of pavement performance. To incorporate the impact of the pavement roughness on the
overall GHG emissions related to the use phase, the adjustment factors suggested by (Barnes and Langworthy 2003) are used in this study. According to Barnes and Langworthy (2003), when PSR value of a road is between 3 and 3.5 the fuel consumption is 5% greater than fuel consumption on pavements with excellent condition. For PSR values in the range of 2.5-3.0, fuel consumption increases 15%.

The first two categories of inventory items are independent from the level of performance of pavement assets, while the last one is performance sensitive. Calculations of impacts for performance sensitive and non-sensitive impacts are explained below.

1. Calculation of performance non-sensitive impacts

The performance adjusted inventory impacts are used in the service basis accounting model to distribute the life cycle impacts of a pavement asset over its service life. For performance non-sensitive items, the impact at each year is calculated using Equation 2:

\[
X_{ij} = NS_{ij} \cdot \frac{ESAL_{ij}}{ESAL_{av}}
\]

Where:
- \(X_{ij}\): The GWP related to performance non-sensitive impacts of road \(j\) in year \(i\) (in Mg Co2 equivalent)
- \(NS_{ij}\): Total GWP related to performance non-sensitive impacts of road \(j\) during the life cycle that contains year \(i\) (in Mg Co2 equivalent)
- \(ESAL_{ij}\): Total equivalent single axle traffic load on road \(j\) in year \(i\)
- \(ESAL_{av}\): Total equivalent single axle traffic load on road \(j\) during its service life

In Equation 2, the fraction \(\frac{ESAL_{ij}}{ESAL_{av}}\) is a service adjustment factor that determines what proportion of the total service of road \(j\) is provided in year \(i\).

The outcomes of the network performance simulation model is used to determine the level of service, performance condition, number and timing of M&R activities, and service life of individual assets in the network. This information is used in calculating the performance non-sensitive impacts in Equation 2. For example, the simulation model shows that road A reaches its end of life at year 7 of the analysis horizon, and hence, it is reconstructed at year 8. Year 8 is the beginning of a service life for road A. This service life lasts for 41 years. During this service life, based on the simulated conditions and the worst-first preservation strategy, road A will receive two surface treatments, three overlays, and one rehabilitation. Each surface treatment, overlay and rehabilitation of road A creates a total of 24, 71 and 141 Mg of CO2 eq. GWP, respectively. Therefore, during this service life (from year 8 to year 49) a total of 402 Mg CO2 eq. (2×24+3×71+1×141=402 Mg CO2 eq.) impact will be created due to M&R activities. In addition, the materials production, construction and end of life of road A create 6508, 123 and 1175 Mg CO2 eq. global warming potential, respectively. Thus, a total of 8208 Mg CO2 eq. GWP of performance non-sensitive impacts is created during the service life of road A.

For distributing the impacts to each year, total impacts are multiplied by the service adjustment factor. For example, the simulation model shows that the traffic on road A in year 10 is 0.1442 ESAL. The total traffic load of Road A during this life cycle (i.e., year 8 to 49) is 10.70157 ESAL. Therefore 1.3% of the total service is provided in year 10. Based on the service basis accounting principle, 1.3% of the total life cycle impacts of road A (approximately 110.6 Mg CO2 eq. GWP) is due to the service in year 10.
2. Calculation of performance sensitive impacts

In order to consider the impacts of pavement performance on the fuel consumption of the vehicles, the impacts of use phase are adjusted based on the simulated pavement roughness (measured using in PSR) using Equation 3.

\[ Y_{ij} = TS_j \frac{ESAL_{ij}}{ESAL_{av}} \times PAF \]

Where:
- \( Y_{ij} \): The GWP related to performance sensitive impacts of road \( j \) in year \( i \) (in Mg Co2 equivalent)
- \( TS_j \): GWP related to use phase impacts of road \( j \) considering excellent road conditions
- \( PAF \): Performance Adjustment Factor
- \( ESAL_{ij} \): Total equivalent single axle traffic load on road \( j \) in year \( i \)
- \( ESAL_{av} \): Total equivalent single axle traffic load on road \( j \) during its service life

For example, under excellent roughness condition, 2150 Mg CO2 eq. GWP is created due to use of road A during this life cycle (i.e., years 8-49). However, the performance of road A is not excellent in year 10 (PSR=3.36), and hence, impacts will be worse. To account for the additional impacts, the use impact of road A is multiplied by a PAF of 1.05 (associated with PSR of road A in year 10). Thus, the use impact in year 10 is calculated as follows: 2150×1.3%×1.05= 29.35 Mg CO2 eq. GWP. Accordingly, the total environmental impacts of road A in year 10 can be calculated by adding the performance sensitive and non-sensitive impacts. A similar process is conducted for all assets in the network for the 40 year analysis horizon. The results are shown in Figure 3. In Figure 3, the decreases in GWP values are related to reduction of the service due to partial or complete road closures for applying M&R treatments.

![Figure 3: Asset-level SPA-LCA GWP impacts.](image)

Another advantage of SPA-LCA for the network-level environmental assessment is that it facilitates aggregation of asset-level impacts into network-level environmental performance. The results of traditional LCA are based on the aggregation of the life cycle of individual assets. However, the aggregated lump-sum impacts of individual assets could be misleading. For example, a planning strategy might lead to lower aggregated lump-sum impacts at the network level; however, it might reduce the service life of the network and raise the need for major reconstruction projects after the analysis horizon. However, in the SPA-LCA method, the impacts are not presented as a lump sum value for the total life cycle of an asset. Instead they are calculated for each year, and thus, the impacts at network-level are obtained by aggregating the asset-level impacts in each year during the analysis horizon. Hence, using this approach, the need for defining a definite service life for the network is eliminated, and the analysis could be performed for any desired analysis horizons. Figure 4 depicts the network-level impacts for the case study network. As shown in the figure, the network-level impacts increase with time. This is due to
two reasons. First, the traffic growth rate is positive in this network which basically means there will be accelerated deterioration and increased fuel consumption in future. Second, with the current preservation strategy on this network, the average PSR of the network decreases over time from an initial value of 4.1 to a final value of 3.55. This results in increased fuel consumption at the later stages of the life cycle of these assets, which leads to greater GWP impacts. This implies that, for networks with expected demand growth, a sustainable approach is to adopt more durable materials and pavement types to slow down the rate of deterioration and eliminate the need for frequent M&R treatment.

![Figure 4: Network-level SPA-LCA GWP impacts.](image)

4. CONCLUSION

This study proposed a new methodology for assessment of environmental impacts of infrastructure systems at the network level. From a theoretical aspect, the underlying premise of the proposed methodology introduces a new paradigm for assessment of environmental sustainability in infrastructure networks. While the traditional LCA fails to recognize the level of service and performance in conceptualizing sustainability in networks, the proposed method defines a sustainable approach to be the one that provides the longest service life and greatest performance with the lowest environmental impacts. From a methodological perspective, the proposed methodology addresses the limitations of the traditional LCA methods for network-level assessment of infrastructure systems by: (i) capturing the complex interactions affecting the level of service, performance, and environmental performance of infrastructure networks; (ii) eliminating burden shifting through recognizing environmental impacts at the time of service; and (iii) considering the continuous service life of networks by determining the environmental impacts for each year, and thus, eliminating the need for defining a global life cycle for the network. From a practical aspect, the proposed method enables evaluation of environmental impacts associated with various operational (e.g., prioritizing M&R activities for funding allocation) and strategic (e.g., corridor planning) decisions.

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NEW MULTIMEDIA SAFETY EDUCATION PROGRAM: IMPACTS ON EMOTIONS, RISK PERCEPTIONS, AND LEARNING

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Abstract: Safety training is a vital component of any construction organization’s safety program. Training offers an opportunity for the transfer of explicit and tacit knowledge of safe work practices. Often, safety training focuses on core issues faced by the specific organization and links to desired worker behaviour. Unfortunately, the typical delivery modes involve PowerPoint presentations, written safety protocols, and classroom-style settings. Such teaching modes do not facilitate active, inductive, context-based learning that is essential for effective andragogy (i.e., adult learning) and, therefore, often fail to achieve their desired objectives. This study tests the hypotheses that a new method of risk-free safety training, Live Safety Demos, increases engagement through emotional response to training activities. The technique involves demonstrating the cause and effect of actual injuries to human hands, which are the most commonly injured body part in construction. The delivery of the demos include the following key components: (1) biologically-realistic replicas of human hands that include flesh, bones, and blood networks; (2) in-person demonstrations of common injuries to worker’s hands (e.g., pinch-points between sections of pipe); (3) videos showing injuries to the replicas recorded at over 2100 frames per second to show detail; and (4) worker-led activities to design work practices that would prevent each injury type. The research was achieved with a team that included one faculty member, three students, a senior manager from the owner organization, four safety managers, and an English-to-Spanish translator. To test the aforementioned hypothesis, the research team used field-validated methods from experimental psychology to measure emotional response to the training program. Using a longitudinal A+B experiment, the demos were tested over the course of a one-week period with approximately 1,200 workers who belonged to approximately 100 crews. The results indicate a very strong emotional response to the Live Safety Demos with statistically significant changes in almost every emotion category. There was a significant increase in negative emotions, which is known to increase risk perception and decrease risk tolerance. Increase in induced activating emotions lead to a more engaged learning commitment during safety training, which increases the ability of workers to recognize more hazards. Thus, this research shows that live safety demos, although resource-intensive, has the potential to transform safety training in the construction industry. Future research is suggested to broaden the sample population and to test additional elements such as retention levels, duration of these induced emotions, communication networks, and ability to respond ad hoc to new safety environments.
1 INTRODUCTION

Carter and Smith (2006) and the Center for Disease Control and Prevention (CDC 2012) suggest that construction workers lack the necessary skill set to correctly identify potential hazards at the job-site. This is a valid claim because, despite constantly improving industry standards and years of extensive research to reduce injuries, there were 4,405 fatal work-related injuries during 2013 (Bureau of Labor Statistics 2013). Furthermore, although there was a modest decline in injury rates between 2011 and 2013, there was an overall increase in fatality rates and a dramatic 7% increase in injuries and fatalities to Hispanic workers (Bureau of Labor Statistics 2013). These trends imply that the industry could benefit from more engaging safety-training that heightens awareness of potential hazards and addresses andragogical principles of learning (Wilkins 2011).

There has been extensive research conducted to understand how people learn in occupational contexts. For example, Baddeley (1992) suggested that the working memory uses both verbal and visuals channels to process and retain information. Hence, in contrast to generic presentation-based training programs, multimedia styles of learning are theoretically more effective as they engage both visual and verbal channels. Moreover, adults seek engaging learning approaches with significance to everyday life as a motivation for learning (Lindeman 1956). This study involved the development and empirical testing of Live Safety Demos, an experiential learning program built upon the principles of Generative Theory of Multimedia Learning (Mayer 1997). As Mayer (1997, p.4) suggests, "multimedia instruction affects the degree to which learners engage in the cognitive processes required for meaningful learning within the visual and verbal information processing systems." The Live Safety Demos were designed within this theoretical context.

The Live Safety Demos included realistic simulations of commonly occurring injuries and a concurrent explanation of the cause and effect of those injuries. To enhance andragogy, the demos involved biologically accurate replications of human hands, realistic simulation of injuries on the artificial hands, a high-speed video of the injury to illustrate detail, and in-depth conversations with the workforce. To test the effectiveness of this new form of safety training, the research team aimed to measure the extent to which the participant’s emotions change as a result of the training program. There has been substantial research that suggests that emotions play a major role in a person’s decision-making process and, thus, affect an individual’s risk perception and tolerance (Clore et. al. 1994; Keller et. al. 2006). This is the first investigation to measure emotional response to an experiential safety program despite the empirical connections between emotional response, learning, and safe work behaviour.

2 LIVE SAFETY DEMONSTRATION CREATION AND DELIVERY

Researchers have found that the only major factor that affects an individual’s risk tolerance is previous personal injury history (Hallowell 2010). That is, a past injury or witnessing a severe injury to a close co-worker is the only factor that has been shown to decrease risk tolerance. Unfortunately, the implication of this finding is that someone must be injured in order for risk tolerances to change. A major objective of this research was to create a hyper-realistic demonstration of an injury that gives participants the experience of an injury without the negative consequences. In this study, we gauge change in emotional response to measure the change in the risk perception/tolerance. Drevets and Raichle (1998) showed that blood supply to brain decreased near the risk-based decision-making sections during acute induced emotional moments and Loewenstein et. al.’s (2001) research found that specific emotions sway human response in adverse situations. Previous studies have shown that people with positive emotional state have more affinity for risk (Isen and Patrick 1983). This implies that if the demonstrations induce a negative emotional state, it should lower the participant’s affinity towards risk.

An important component of the Live Safety Demos was the creation of a hyper-realistic demonstration of an injury. To achieve the goals artificial hands were created that look, feel, and respond like actual human hands (Figure 1). The hands were built using life-casting techniques primarily found in dentistry and prosthetics and include flesh with the exact properties of a human hand, an internal blood bladder and
blood network, and bones. To illustrate the level of realism achieved in the creation of the hands, Table 1 provides a complete comparison between the fabricated hand and the average adult human hand according to the Oxford Handbook of Clinical Medicine (Longmore et al. 2014). As one can see from Table 1 and Figure 1, the hands were sufficiently accurate to serve as a realistic proxy for a worker in dangerous situations.

![Image of artificial hands for Live Safety Demonstration](image)

**Figure 1: Artificial hands for Live Safety Demonstration**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Fabricated Hand</th>
<th>Actual Human Hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.07 g/cc</td>
<td>1.067 g/cc</td>
</tr>
<tr>
<td>Hardness</td>
<td>10 A</td>
<td>10 A</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>475 psi</td>
<td>421 psi</td>
</tr>
<tr>
<td>Elongation at Tear</td>
<td>364%</td>
<td>245%</td>
</tr>
<tr>
<td>Die B Tear Strength</td>
<td>102 pli</td>
<td>100 pli</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>&lt;0.001 in/in</td>
<td>&lt;0.001 in/in</td>
</tr>
<tr>
<td>Bone Shear Strength</td>
<td>70 Mpa</td>
<td>52 Mpa</td>
</tr>
<tr>
<td>Bone Breaking Force</td>
<td>280 lbs</td>
<td>267 lbs</td>
</tr>
</tbody>
</table>

To accompany the fabricated hand in a training demonstration, a video was created where the hand was injured in two modes: a falling concrete chisel and a pinch point between two sections of three inch steel pipe. A brief description of the two demonstrations is provided below.

**Falling Concrete Chisel:** This demonstration aimed to replicate an actual disabling injury where a carpenter dropped a one-kilogram concrete chisel when stripping concrete formwork. The falling chisel struck another worker who was working below the formwork and punctured his hand. Ultimately, there were three broken phalanges and nerve damage, which resulted in limited use of the hand. The first part of the demonstration involved educating the workers of the speed that the chisel was falling at time of impact (approximately 43 kilometers per hour), the impact area of the chisel (0.30 cm²), and the overall pressure on the hand (48 MPa). To achieve a memorable mnemonic, a discussion related to speed, sharpness, and weight was held among the workers as prompted by the instructors. Following this discussion, the resilience of the human hand was described. Specifically, the human hand can withstand approximately 1 MPa without significant damage. Given the load on and resistance of the hand, the
workers were asked to predict what would happen to a gloved and ungloved hand. Once this discussion was complete, a high-speed video was shown with both a gloved and ungloved hand, illustrating dramatic differences in outcome. The first demonstration session concluded with a discussion of the safe work practices for the type of work demonstrated.

**Pinch Points between Two 3-Inch Steel Pipes:** The second demonstration focused on an injury where a worker was in the process of connecting a 3-inch steel pipe to a pipe couple when the pipe sling shifted and the worker’s hand was pinched between the pipe and the couple. The result of the injury was a deep flesh wound and nerve damage. Similar to the falling chisel demo, the first step of the demonstration was to present the physics behind the injury. This included the momentum of the moving pipe, the contact area of the pipe, and the overall pressure on the hand. Once the resistance of the hand to pressure (1 MPa), the workers predicted the outcome for a gloved and ungloved hand and the associated videos were shown that depicted both scenarios. Also, a discussion was held regarding the potential outcomes of a heavier, sharper, or faster moving pipe. The session also concluded with a discussion of safe work practices for installing steel pipe.

![Screen capture of a gloved hand being struck by a falling concrete chisel.](image)

**Figure 2:** Screen capture of a gloved hand being struck by a falling concrete chisel.

### 3 RESEARCH METHODS

As previously indicated, our research goal for this study was to measure emotional response to the active, experience-based demonstrations that incorporated theory of andragogy. In order to achieve this goal, we delivered the demos to 1,200 construction workers in a one-week period in Kenedy, Texas through sixteen different sessions (average of 75 workers per session). The same delivery technique and the same instructors were used in each session to ensure consistency. Additionally, a set script was followed to enhance reliability and replicability of the study and all instructors followed a set script.

In order to measure emotional response, we implemented a before and after (AB) experimental design where Rottenberg et al.’s (2007) emotional polarity questionnaire was used to survey workers before and after the Live Demos. On this questionnaire, the participants were asked to rate their emotions on 8-point scale. In addition to Rottenberg et al.’s (2007) questionnaire, we considered various alternative methods to gauge the emotional response such as the Balloon Analogue Risk Task (BART), which is a laboratory based computerized self-reporting risk assessment tool (Lejuez, C. W., et al. 2002). We decided to pursue the paper form of the Rottenberg et al. (2007) questionnaire because of our sample size and time and resource constraints in the field. The emotion questionnaire was quantitative with one optional qualitative question, which requested comments or other emotions.
Out of the 1200 workers, 489 (40%) participated in the surveys as participation was voluntary and uncompensated. The surveys were administered in paper form and all the participants were provided sufficient time and resources to complete the surveys both times. Surveys were provided to the participants immediately before and immediately after the Live Demonstrations and no more than a 3-minute time lag was allowed as suggested by Verduyn et. al. (2009 & 2011).

The following protocol was implemented when delivering the live safety demos and collecting data:
1. Introduction to the topic and welcome
2. Emotions survey with demographics
3. Delivery of dropped object demo or pinch point demo
4. Delivery of the second demo (one not delivered in step 3)
5. Emotions survey and open-ended qualitative question
6. Closing remarks

As previously indicated, all demos were delivered to workers in Kenedy, Texas. Subjects involved had no knowledge of the demos prior to the session. Some work crews in this region were Spanish-only-speaking while others were English-only-speaking. We delivered the demonstrations in both English and Spanish, as members of the research team were bilingual. The participants were allowed to choose between the English or Spanish session. Seventy-five percent of the participants attended English sessions and 25% attended Spanish sessions.

To ensure anonymity, the participants were not required to enter their names or any direct identification. Instead, workers used a personal password that was not linked to their name, trade, or employer. For demographic questions, we also offered participants the opportunity to decline to answer a question if they felt uncomfortable providing the information. In our sample, 69% were married, 50% had witnessed a severe injury first-hand, 23% had been injured (recordable injury), 6% have a bachelor’s degree or more, 32% have some college education, 57% completed high school, 4% have no education, 70% were Hispanic, and 30% were Caucasian. The average age of the participants was 38 years and, interestingly, less than 5% of the workers were female. Figure 3 illustrates the overall research process including development, data collection, statistical comparisons, and conclusions.

4 RESULTS

In order to study the emotional responses, the data were analyzed using paired t-tests. Paired t-tests were used because we have two nominal variables and one measurement variable (McDonald, J.H. 2014). One nominal variable represents the participant and other is the “pre” and “post” emotional state recorded via their responses. Table 2 shows the results of the emotional change for the entire sample. We considered the change to be significant at 95% confidence (p <0.05). Based on the results shown in Table 2, there was a large and statistically significant change in the following emotions: confusion, disgust, guilt, fear, happiness, joy, love, pride, sadness, surprise, and unhappiness. The greatest change occurred in fear and surprise. We can also say here that the ‘negative’ emotions or those associated with being serious, sombre, and vulnerable increased significantly.

Table 3 shows the emotional response of Caucasians and Hispanic workers separately. It also shows that Caucasians showed a significant change in confusion, fear, happiness, joy, love, pride, sadness, shame, and surprise whereas Hispanic workers had a significant change in anger, confusion, fear, guilt, happiness, joy, love, pride, sadness, surprise, and unhappiness. This is further discussed in the next section in the context of this paper.
Table 2: Changes in Emotional State due to Live Safety Demo

<table>
<thead>
<tr>
<th>Emotion</th>
<th>Average Before</th>
<th>Average After</th>
<th>Difference</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amusement</td>
<td>4.06</td>
<td>4.16</td>
<td>2%</td>
<td>0.319</td>
</tr>
<tr>
<td>Anger</td>
<td>1.65</td>
<td>1.53</td>
<td>-7%</td>
<td>0.154</td>
</tr>
<tr>
<td>Anxiety</td>
<td>1.82</td>
<td>1.94</td>
<td>7%</td>
<td>0.092</td>
</tr>
<tr>
<td>Confusion</td>
<td>1.68</td>
<td>1.45</td>
<td>-14%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Disgust</td>
<td>1.44</td>
<td>1.62</td>
<td>12%</td>
<td>0.044</td>
</tr>
<tr>
<td>Embarrassment</td>
<td>1.52</td>
<td>1.45</td>
<td>-4%</td>
<td>0.401</td>
</tr>
<tr>
<td>Fear</td>
<td>1.45</td>
<td>2.13</td>
<td>47%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Guilt</td>
<td>1.36</td>
<td>1.54</td>
<td>13%</td>
<td>0.013</td>
</tr>
<tr>
<td>Happiness</td>
<td>5.68</td>
<td>4.05</td>
<td>-29%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Interest</td>
<td>6.11</td>
<td>6.00</td>
<td>-2%</td>
<td>0.322</td>
</tr>
<tr>
<td>Joy</td>
<td>5.43</td>
<td>4.07</td>
<td>-25%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Love</td>
<td>5.29</td>
<td>3.73</td>
<td>-29%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Pride</td>
<td>5.61</td>
<td>4.33</td>
<td>-23%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sadness</td>
<td>1.51</td>
<td>2.15</td>
<td>43%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Shame</td>
<td>1.57</td>
<td>1.69</td>
<td>7%</td>
<td>0.277</td>
</tr>
<tr>
<td>Surprise</td>
<td>2.66</td>
<td>3.91</td>
<td>47%</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Unhappiness</td>
<td>1.47</td>
<td>1.74</td>
<td>18%</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Note: The plus and minus sign represent the increase and decrease of that particular emotion.
# Table 3: Results from English and Spanish Surveys

<table>
<thead>
<tr>
<th>Emotions</th>
<th>Average Before (Caucasian)</th>
<th>Average After (Caucasian)</th>
<th>Difference (%)</th>
<th>P-value</th>
<th>Average Before (Hispanic)</th>
<th>Average After (Hispanic)</th>
<th>Difference (%)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amusement</td>
<td>3.97</td>
<td>3.79</td>
<td>-5%</td>
<td>0.80</td>
<td>4.10</td>
<td>4.29</td>
<td>5%</td>
<td>0.20</td>
</tr>
<tr>
<td>Anger</td>
<td>1.64</td>
<td>1.59</td>
<td>-3%</td>
<td>0.91</td>
<td>1.63</td>
<td>1.45</td>
<td>-11%</td>
<td>0.04</td>
</tr>
<tr>
<td>Anxiety</td>
<td>1.85</td>
<td>2.01</td>
<td>9%</td>
<td>0.13</td>
<td>1.78</td>
<td>1.64</td>
<td>4%</td>
<td>0.40</td>
</tr>
<tr>
<td>Confusion</td>
<td>1.65</td>
<td>1.38</td>
<td>-16%</td>
<td>0.009</td>
<td>1.44</td>
<td>2.20</td>
<td>-12%</td>
<td>0.01</td>
</tr>
<tr>
<td>Disgust</td>
<td>1.50</td>
<td>1.71</td>
<td>14%</td>
<td>0.17</td>
<td>1.38</td>
<td>1.53</td>
<td>11%</td>
<td>0.15</td>
</tr>
<tr>
<td>Embarrassment</td>
<td>1.36</td>
<td>1.28</td>
<td>-6%</td>
<td>0.42</td>
<td>1.57</td>
<td>1.46</td>
<td>-7%</td>
<td>0.36</td>
</tr>
<tr>
<td>Fear</td>
<td>1.31</td>
<td>2.25</td>
<td>72%</td>
<td>&lt;0.001</td>
<td>1.49</td>
<td>2.04</td>
<td>36%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Guilt</td>
<td>1.26</td>
<td>1.39</td>
<td>10%</td>
<td>0.12</td>
<td>1.37</td>
<td>1.57</td>
<td>14%</td>
<td>0.04</td>
</tr>
<tr>
<td>Happiness</td>
<td>5.52</td>
<td>3.85</td>
<td>-30%</td>
<td>&lt;0.001</td>
<td>5.78</td>
<td>4.23</td>
<td>-27%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Interest</td>
<td>6.00</td>
<td>5.96</td>
<td>-1%</td>
<td>0.77</td>
<td>6.19</td>
<td>6.05</td>
<td>-2%</td>
<td>0.31</td>
</tr>
<tr>
<td>Joy</td>
<td>4.90</td>
<td>3.58</td>
<td>-27%</td>
<td>&lt;0.001</td>
<td>5.66</td>
<td>4.40</td>
<td>-22%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Love</td>
<td>5.00</td>
<td>3.31</td>
<td>-34%</td>
<td>&lt;0.001</td>
<td>5.41</td>
<td>3.95</td>
<td>-27%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Pride</td>
<td>6.12</td>
<td>4.80</td>
<td>-22%</td>
<td>&lt;0.001</td>
<td>5.40</td>
<td>4.15</td>
<td>-23%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sadness</td>
<td>1.52</td>
<td>2.11</td>
<td>39%</td>
<td>0.004</td>
<td>1.48</td>
<td>2.08</td>
<td>40%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Shame</td>
<td>1.30</td>
<td>1.68</td>
<td>30%</td>
<td>0.004</td>
<td>1.66</td>
<td>1.66</td>
<td>0%</td>
<td>0.62</td>
</tr>
<tr>
<td>Surprise</td>
<td>2.28</td>
<td>3.89</td>
<td>71%</td>
<td>&lt;0.001</td>
<td>2.76</td>
<td>3.97</td>
<td>44%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Unhappiness</td>
<td>1.54</td>
<td>1.69</td>
<td>10%</td>
<td>0.28</td>
<td>1.40</td>
<td>1.67</td>
<td>20%</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Key takeaways from the data are that emotions such as anger, anxiety, confusion, disgust, embarrassment, fear, guilt, happiness, joy, pride, sadness, love, surprise, and unhappiness showed a fluctuation in the same direction. Both Hispanic and Caucasian workers registered an aggregate decrease in their positive emotions such as happiness (-29%), joy (-25%), love (-29%), and pride (-23%) and an increase in negative emotions unhappiness (18%), fear (47%), surprise (47%), and sadness (43%). When viewed separately, Caucasian surveys showed statistically significant change in 'fear' and Hispanic surveys showed statistically significant change in 'anger' and 'fear' (activating).

The implications of the observed emotional changes on learning are significant. Pekrun (2006) explains that negative emotions increase extrinsic motivation to learn and avoid failure. Specifically, Pekrun et. al. (2002, p.97) claims that "Emotions may trigger, sustain, or reduce academic motivation and related volitional processes." They also suggest that changes in positive emotions (happiness, joy) and negative emotions (anxiety, anger) can be activating and may facilitate learning. Bless et. al. (1996) further proposed that negative emotions lead to more detail-oriented and cautious approach towards solving problems, which could be preferable to construction safety. Thus, it can be concluded that Live Safety Demos is an improvement over the current training style for the construction crews because workers will be more detail-oriented and cautious as they troubleshoot safety problems and plan for safe work.

In addition to enhanced learning, the changes in emotions are linked to decreased risk taking. As mentioned in the introduction, it is overwhelmingly accepted that negative emotions lead to a less affinity towards taking risk (Öhman and Mineka 2001; Clore et. al. 1994; Keller et. al. 2006). Taylor and Brown (1988) claimed that “false optimism” leads to a fake sense of security towards any situation thus, making them less cautious and oblivious to hidden risks. Additionally, it should be noted that negative emotional states are strongly associated with an increase in risk perception (i.e., workers perceive greater risk in their environment) and reductions in risk-taking behaviour (Gruber et. al. 2011). Results in Tables 3 and 4 also show that there is a significant decrease in joy and interest emotions, which leads a decrease in safety valuations of situations (Izard 1977). Based on these established theories, we believe that the Live Safety Demos makes construction workers perceive more risk, which should decrease sense of false optimism and risk taking behavior.

There were some interesting differences in the emotional reactions between Hispanic and Caucasian workers. Firstly, Caucasian workers experienced greater increases in anxiety, fear, surprise, shame, and disgust than their Hispanic counterparts. Hispanic workers, on the other hand, experienced greater relative changes (increase) in amusement unhappiness, and guilt. Hispanic workers were less angry and less happy while Caucasian workers were much more fearful and surprised. Matsumoto et. al. 1988 showed that there are cultural differences in self-reporting of any emotional experience, which include intensity, control, and duration of emotion. However, these induced emotions though varying in intensity, need to correlate positively with cognition among these workers. Since the changes in emotions are all in the same direction, there is no indication that the differences in emotional response would have any serious implications for risk taking or safety learning. Figure 4 outlines some of the major changes due to Live Safety Demos on the participants and the implications of those changes.
Figure 4: Major Implications of the Results from Live Safety Demos

The findings mentioned above come with limitations. As discussed briefly in the research methods section, the survey responses are never quite accurate for various reasons. First, there was an inherent discomfort observed among the participants even if surveys are anonymous that they could be traced back to them. Second, there was also some conversations among the participants as they filled the surveys out which might have also affected their answers. Third, and most importantly, it has been documented that people are sometimes incapable of understanding our own emotions. Finally, there is a clear male bias in the sample.

Other studies can further these results by analyze how long did the induced emotions last among the participants after the demos and what is the level of emotional intelligence among construction workers. It will be interesting to also research if ethnicity impacts. More importantly, emotional intelligence examination might allow us to judge whether self-reporting questionnaire form is a good choice or not among construction workers. In conclusion, this paper shows that current safety training programs are inefficient and monotonous. Live Safety Demos is an effective multi-media safety-training program, which embraces the andragogical principles and increases risk perception by inducing a sombre and cautious emotional response among construction workers. These demos will by-pass the need to introduce new and more stringent rules by improving participants’ hazard recognition and the risks associated with it.

Acknowledgements

The authors would like to thank Conocophillips for the opportunity to conduct this research on their site in Kenedy, TX. In particular we would like to thank David Wulf, Dwayne Beadle, Pedro Oronia, Bobby Bourque, and the many workers who participated in the Live Demos. We would also like to thank Sofia Hafdan for her assistance with statistical analyses

References


A DECISION-MAKING ALGORITHM FOR SELECTING BUILDING INFORMATION MODELING FUNCTIONS

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Abstract: Due to a lack of common financial benchmarking for various BIM functions, decisions regarding adopting BIM functions are usually made based on market pressure or a manager’s intuition. While larger firms can afford such a trial and error process, the cost burden on small- to medium-sized firms is significant. Therefore, there is a need to assemble the tacit knowledge of BIM users into a simple algorithm that can aid new users in understanding the advantages and disadvantages of implementing BIM functions in a project. This study aims to develop a decision-making algorithm that helps practitioners choose BIM functions for their project to maximize success. Some of the independent variables that were considered are project category, project size, delivery method, and time of involvement of different parties. A questionnaire was developed to measure the importance of these variables on using different BIM functions. The survey was sent out to 3,017 owner representatives, architects, and project managers. In total, 119 individuals responded to the survey of which 81 were BIM users. The analysis of the data resulted in a decision matrix and an algorithm that provides guidance for decision makers regarding adopting different BIM functions. Most of the respondents worked in the building and commercial construction sector, which likely influenced the respondents. The findings of the study have contributions to both academia and practice. The results can be used by researchers as a benchmark for future studies and practitioners can use the decision-making algorithm to select an appropriate BIM function for their projects.

1 INTRODUCTION

The potential of building information modeling (BIM) to unify the traditionally fragmented AEC industry has contributed to BIM gaining wide acceptance in the North American market (Bynum et al., 2013). BIM has fostered closer collaboration by enabling interaction and aiding collective understandings of projects (Grilo and Jardim, 2010; Hanna et al., 2013). In doing so, BIM has been simultaneously expanding and advancing in its applications. The Smart Market series (McGraw-Hill, 2008; 2009; 2012) provides a comprehensive understanding of the adoption pattern of BIM among various construction sectors and disciplines in the AEC industry. Per the McGraw-Hill report (2012), the industry adoption rate of BIM in North America has shown a noteworthy increase, from 28% in 2007 to 71% in 2012. The report also indicates that there has been a steady increase in BIM adoption within various disciplines, especially among mechanical, electrical, plumbing, and structural engineers. However, despite BIM enabling the construction industry to merge via a virtual process (Azhar, 2011), limitations and challenges to the expansion of this approach still exist.
The ongoing challenges to BIM mainly exist in the realms of technical, contractual, and personal relationships among construction professionals (Hamdi and Leite, 2014). BIM-enabled projects continue to be organizationally divided (Dossick and Neffe, 2009), and on average 25% of construction industry professionals refuse to use BIM for various reasons. Some reasons contributing to lower usage of information and communication technologies (ICT’s) like BIM are identified in literature review as technical and financial problems, attachment to conventional ways of conducting business (Doherty, 1997; Samuelson, 2002), and the lack of an effective tool for the entire construction market (Egbu and Botterill, 2002). Another challenge encountered by BIM is the low adoption rate among small and medium enterprises (SME’s). Studies indicate that despite ICT’s being a means for instant knowledge transfer, few SME’s can use such innovations to their full capacity (Acar et al., 2005) and most SMEs fail to adopt and implement them (Blackley and Shepard, 1996; Acar et al., 2005). These findings are reflected in the fact that the adoption rate of BIM is only 49% among small firms as compared to 91% in large firms (McGraw-Hill Report, 2012).

Very few studies—McGraw-Hill series reports (2008; 2009; 2012) and Krieder et al., (2010)—have attempted to evaluate the value and the frequency of use of various BIM functions across disciplines and project phases. Due to a lack of common financial benchmarking for various BIM functions (Becerik-Gerber and Rice, 2010), decisions regarding adopting BIM functions are usually made based on market pressure or a manager’s intuition. While larger firms can afford such a trial and error process, the cost burden on small- to medium-sized firms is significant. Therefore, there is a need to assemble the tacit knowledge of BIM users into a simple algorithm that can aid new users in understanding the advantages and disadvantages of implementing BIM functions in a project. To address this need, this study aims to develop a decision-making algorithm that helps practitioners choose BIM functions for their project to maximize their success.

This study begins by conducting a literature review to identify relevant BIM functions and independent variables that can be used in the decision-making process when selecting which of these functions to use in early stages of a project. An online survey is conducted to gather the tacit knowledge of existing BIM users. Descriptive statistics are then used to present the findings. An easy-to-use algorithm is developed based on the independent variables. The results of this study project a novel tool that can be further enhanced for accuracy. This study will benefit future researchers seeking to understand the factors contributing to the implementation of BIM functions. It will also aid construction professionals in the decision-making process while they select the appropriate BIM functions.

2 LITERATURE REVIEW

The wide acceptance of BIM could be partly accredited to the growing number of applications that appeal to various disciplines in the construction industry. Therefore, an extensive list of BIM functions can be found in literature. Since inception, collaboration has been one of the key characteristics of BIM (Eastman et al., 2011). 3D visualization and clash detection are two major functions of BIM that aid effective communication and interdisciplinary understanding among multiple disciplines (Eastman et al., 2011). Apart from these two functions, BIM has shown high potential for use in several other construction processes and has rapidly advanced in its number of applications in the past decade. Currently, BIM encompasses the most integral processes in construction, namely scheduling, constructability analysis, structural analysis, the shop drawing process, cost estimation and quantity takeoff, facility space planning and logistics, material-tracking delivery and management, stakeholder engagement, project turnover and closeout, code validation, energy analysis, and facility management.

Prior to use of BIM, studies (e.g., Chau et al., 2004) presented a 4D visualization model by linking 3D geometric model with scheduling data. Chau et al. (2004) presented the potential benefits of 4D visualization as a means of facilitating site planning and management, predicting the occurrence of any potential site problems, and streamlining site management practices. Even though 4D visualization models presented several advantages over the traditional 2D CAD process, the process remained tedious and lacked the significant feature—change management—that BIM later introduced. Tulke et al.
(2008) suggested integrating construction scheduling in a collaborative, BIM-based design process by establishing quantity takeoff as a model-based central approach prior to scheduling and cost estimation. However, even though benefits of BIM were well-documented for construction-management work—like scheduling—the application’s use was reported as infrequent (Goedert and Meadati, 2008).

Another important process in construction benefited by BIM is constructability analysis. Constructability analysis is a preconstruction process that identifies potential obstacles during construction and thus helps prevent delays and cost overruns (Pulaski and Horman, 2005). Sulankivi et al. (2014) discusses six promising ways of using BIM to improve constructability: visual examination of BIM, clash detection using a combined model, BIM-based construction planning, visualization in 3D or 4D, BIM as a tool for cooperation, and BIM-based checking, analysis, appraisal, and measurement of safety or constructability. Despite the benefits named in literature, very few studies have investigated the use of BIM for constructability.

In contrast to the inadequate research regarding several BIM functions, in the past few years, two BIM functions have been extensively discussed namely facility management and energy analysis. Facility management has evolved from being a practice to a profession. As defined by IFMA (2004), facility management is a multidisciplinary profession that integrates people, places, processes, and technology during the operations and maintenance (O&M) phase to assure the smooth functioning of the built environment. The O&M phase demands extensive information from multiple disciplines (Caldas et al., 2005). This information is provided by contractors to the facility managers in the form of a pile of project documents in various formats (William East et al., 2013), all of which need to be manually fed into the maintenance management software. BIM has the capability to eradicate this cumbersome process. Becerik-Gerber et al. (2012) identified ten potential application areas for BIM in facility management: locating building components, facilitating real-time data access, visualization and marketing, checking maintainability, creating digital assets, space management, planning and feasibility studies for non-capital construction, emergency management, controlling and monitoring energy, and personnel training and development. However, along with the numerous potential application areas, implementation of BIM for facility management also faces numerous challenges. Seven barriers to implementing BIM in facility management—as identified by Becerik-Gerber et al. (2012)—are: unclear and invalidated benefits of BIM, increase in the amount of work, lack of interoperability, lack of demand by owner community, lack of clarity about responsibility in contracts, lack of standardization in facility management tools, and lack of experience in using BIM. Even though there has been a lot of research related to BIM and facility management, to-date, the adoption of BIM in facility management is slow (Brooks and Lucas, 2014).

Energy analysis is another application discussed extensively in the literature, likely due to the increasing importance of sustainable construction. Considering buildings' huge share in energy consumption, having an efficient energy analysis tool that is easy to run and easy to understand could empower designers to make more energy-conscious decisions during the early design phase (Kim and Anderson, 2013). BIM has been found to have the potential to aid energy analysis to ensure optimized, sustainable building designs (Krygiel and Nies, 2008; Azhar et al., 2011; Kim and Anderson, 2013; Bynum et al., 2013). However, upon investigating the perceptions of designers and constructors on using BIM for sustainability, Bynum et al. (2013) found that most of their survey respondents believed that sustainability was not a primary application of BIM; they also found that problems with interoperability continue to persist among the various BIM applications in the industry.

Our literature review concludes that although several studies have investigated the role of BIM functions individually and have offered unique objectives as part of their investigations, very few studies have attempted to evaluate the advantages and disadvantages of implementing BIM functions in a project.

3 METHOD OVERVIEW

To achieve the objective of the study, first the study attempted to explore factors impacting the decisions of using BIM functions within the construction industry. An in-depth literature review was conducted to identify fourteen relevant BIM functions shortlisted after expert opinion. The identified BIM functions
formed the basis of inquiry for each of the independent variables investigated. A comprehensive questionnaire was developed and distributed to 3017 construction professionals via an e-mail that contained the project description and a link to the survey. The e-mail addresses of contacted individuals were extracted from the publically accessible member lists of Associated General Contractors (AGC) and Associated Builders and Contractors (ABC) organizations from eleven states of North America (Iowa, Illinois, Hawaii, New Mexico, Nebraska, Washington, Florida, Arkansas, Arizona, New York and Maine); though the limited public access added a geographical limitation to the findings of the study. In an attempt to reach maximum audience, the participants of the 2012 Design-Build Institute of America (DBIA) conference were also approached. The questionnaire link was also posted on the LinkedIn page for the American Society of Civil Engineers. Participation in the survey was voluntary.

The objective of the questionnaire was to understand whether BIM is required for all projects and whether project-delivery method and team selection impacts the decision to use BIM in projects. For those projects in which BIM is required, this questionnaire also examined which functions should be used based on the project’s size (Refer Table 1) and objectives (i.e., cost, time, quality, and owner satisfaction). The questionnaire contained two sections. First, a personal experience and information section that sought to identify the participant’s professional background; to increase participation and encourage open expression of opinion, this section did not require any contact information (e.g., name, e-mail addresses). The first section ended with a key question regarding whether or not the participant had used building information modeling for their projects. In the second section—the BIM users’ section—participants were provided with a description of every BIM function. The Likert scale ranging 1 (low) to 6 (High) was used to inquire about frequency, difficulty, and perceived value for each BIM function. The scale also provided an option called ‘I don’t know’ for respondents unfamiliar with a certain function or unknowledgeable about a question. The survey was conducted for a period of one month, during which time two reminders were sent to each of the recipients. This study uses descriptive statistics to present the findings. Based on these findings, the study develops a decision matrix and an algorithm that provides guidance for decision makers regarding adopting different BIM functions. Based upon the independent variables, this study uses descriptive statistics to present the findings and develops an easy-to-use algorithm to translate the findings into a tool for new BIM users.

<table>
<thead>
<tr>
<th>Table 1: Project Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Size</td>
</tr>
<tr>
<td>Very Small (VS)</td>
</tr>
<tr>
<td>Small (S)</td>
</tr>
<tr>
<td>Medium (M)</td>
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<tr>
<td>Large (L)</td>
</tr>
<tr>
<td>Very Large (VL)</td>
</tr>
</tbody>
</table>

4 RESULTS

Of the 158 responses received, all partial responses were excluded from the analysis to maintain consistency in results. This yielded a response rate of 3.9% with 81 responses from BIM users and 37 from BIM non-users.

4.1 Participant Background

The analysis indicated participation of all targeted divisions of construction professionals in the survey. In total, 69% of respondents were BIM users and 31% were BIM non-users. Majority of respondents held a managerial position (87%) with the average work experience of participants as 26 years. Among BIM users, majority of the participants indicated their project categories as medium and large; and employed design-bid-build and design build as the project delivery method for most projects on average. Among BIM non-users, majority of the participants indicated their project categories as small and medium; and employed design-bid-build as the project delivery method for most projects on average. Most of respondents among BIM users (30%) stated to be multi role organizations with half the respondents identifying as DB+CM/GC, while majority of respondents among BIM non-users (39%) stated to be owners. The findings indicate that a total of 72.5% of respondents think that BIM is not required for all the
projects which highlights the importance of developing decision making algorithm for selecting right BIM function for a project.

4.2 Descriptive Statistics

The project delivery methods used in construction projects determine the organizational relationships and have been found to influence project outcomes and processes (Beard et al. 2001). To investigate the role of project delivery methods in facilitating successful adoption of BIM, the questionnaire asked respondents to provide a rank order for each. The Design Build (DB) delivery method was found to play the most significant role in facilitating successful adoption of BIM followed by Integrated Project Delivery (IPD) method. Design Bid Build (DBB) was ranked at the bottom. For project procurement methods, 2-Stage RFP was ranked at the top in facilitating successful adoption of BIM, followed by Pre-Qualified Bid, Sole Source, 1-Stage RFP and Low Bid (Refer Table 6). Upon inquiring about prefabrication, respondents indicated that on average a minimum of 24% of prefabrication is required in a project to benefit from BIM.

The questionnaire inquired about the minimum project size required for implementation of each of the listed BIM functions. The findings indicate that a total of 72.5% of respondents think that project size impacts the decision of using BIM functions. As shown in Table 2, more than 75% of participants believe that the minimum project size for employing 3D visualization, clash detection, constructability analysis, structural analysis, cost estimation and quantity take off and; stakeholder engagement is 1 million to 10 million (Medium size project). While more than 50% participants believe that minimum of medium size project is required for employing any of the fourteen BIM functions listed.

| Table 2: Minimum project size required to have a significant impact on project success |
|---------------------------------|---------|------|-----|-----|------|--------|
|                                 | VS      | S    | M   | L   | VL   | Number of users |
| 3D Visualization                | 21%     | 52%  | 86% | 100%| 100% | 80      |
| Clash Detection                 | 9%      | 30%  | 80% | 98% | 100% | 75      |
| Facility Space Planning and Logistics | 15%   | 23%  | 67% | 94% | 100% | 47      |
| Code Validation                 | 14%     | 21%  | 67% | 93% | 100% | 17      |
| Constructability Analysis       | 12%     | 32%  | 80% | 96% | 100% | 56      |
| Structural Analysis             | 10%     | 27%  | 75% | 98% | 100% | 35      |
| Cost Estimation & Quantity Take-off | 8%   | 30%  | 76% | 98% | 100% | 50      |
| Scheduling (4D Animation)       | 4%      | 10%  | 50% | 96% | 100% | 45      |
| Energy Analysis                 | 7%      | 20%  | 74% | 98% | 100% | 27      |
| Shop-drawing Process            | 9%      | 28%  | 72% | 87% | 100% | 55      |
| Material Tracking, Delivery and Mgt. | 4%   | 13%  | 48% | 85% | 100% | 17      |
| Stakeholder Engagement          | 20%     | 35%  | 84% | 98% | 100% | 50      |
| Project Turnover & Closeout     | 6%      | 19%  | 66% | 94% | 100% | 39      |
| Facility Management             | 9%      | 13%  | 67% | 98% | 100% | 21      |

More than half (59.26%) of the respondents indicated that project objective impacts the decision of using BIM functions. Four project objectives were investigated in this study - reducing project cost, reducing project time, improving quality and; improving owner’s satisfaction (Table 3). Findings indicated that clash detection was the only BIM function among the fourteen BIM functions investigated that had a high impact on all four project objectives.

5 ALGORITHM FOR SELECTING BIM FUNCTIONS

Using the results of the study, an algorithm is developed to aid practitioners choose BIM functions for their project to maximize success. The algorithm is limited to the fourteen BIM functions discussed in this
study and is based on the following assumptions: (1) decision to use/not use BIM in a project is a function of the project delivery method and team selection; (2) selecting different BIM functions depends on the project size and project objectives; (3) the project objectives that determine applicability of a BIM function are cost, schedule, quality, and owner’s satisfaction. Based on these assumptions, the research team developed a decision making algorithm that consists of four major steps. These steps are explained in more details below.

### Table 3: Impact on reducing project cost and time and; improving quality and owner’s satisfaction*

<table>
<thead>
<tr>
<th>BIM functions</th>
<th>Reducing Cost</th>
<th>Project Time</th>
<th>Project Quality</th>
<th>Owners Satisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Visualization</td>
<td>4</td>
<td>4</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>Clash Detection</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Facility Space Planning and Logistics</td>
<td>4</td>
<td>4</td>
<td>4.5</td>
<td>5</td>
</tr>
<tr>
<td>Code Validation</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Constructability Analysis</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Structural Analysis</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Cost Estimation &amp; Quantity Take-off</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Scheduling (4D Animation)</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Energy Analysis</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Shop-drawing Process</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Material Tracking, Delivery and mgt</td>
<td>3</td>
<td>5</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>Stakeholder Engagement</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Project Turnover &amp; Closeout</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Facility Management</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

* Impact measured by a Likert Scale, with 1 = Very low and 6 = Very High

### Step 1: Project delivery and procurement method

Studies have found project procurement and project delivery methods to have varying impact on success of BIM (Becerik-Gerber and Rice, 2010). Integrated project delivery (IPD) (Becerik-Gerber and Rice, 2010; Azhar, 2011) and Design-Build (DB) are cited as the most effective project delivery methods in facilitating the use of BIM (Bynum et al., 2013). Also, procurement methods are found to be crucial in identifying the key issues while developing a BIM contract (Chunduri et al., 2013). Thus, in the first step of the algorithm we identify combinations of project procurement and project delivery methods eligible for achieving BIM benefits. The research team suggests that for the following combinations of the project delivery method and team selections, BIM provides the most benefits for project stakeholders: DB and 2-Stage RFP; DB and Pre-Qualified Bid; DB and Sole Source; CMR and 2-Stage RFP; CMR and Pre-Qualified Bid; IPD and 2-Stage RFP; IPD and Pre-Qualified Bid; and IPD and Sole Source. In the first step, the decision maker checks whether the project has any of the above mentioned delivery and team selection combinations. If the combination is right, using BIM would be beneficial for the final project success.

### Step 2: Project size

While selecting a BIM function, the most frequent question raised by a novice BIM user is about the project size (Won et al., 2013). Upon investigating whether or not the project size impacted the decision of BIM implementation, 72.5% respondents complied. The findings also indicated that the ratings for BIM functions differed as per project size. Thus, in the second step, the algorithm classifies the use of BIM function as per project size. The results of the survey indicated that BIM functions are not required for very small projects. On the other hand, BIM functions can be beneficial for large and very large projects. Therefore, the size of a project can be differentiator when one is comparing a small ($100,000 to $1Million) and medium ($1Million to $10Million) size project. In the algorithm proposed in this study, the ratings provided by experts for project size will be used as modification factor for the contribution of a BIM
function \( M_j \). For example, 3D Visualization potential contribution into a small size project should be multiplied with 52% while in a medium size project it should be multiplied with 86% (Table 4).

Step 3: Project objectives
Another factor that plays a significant role in determining the applicable BIM function for a project is the relative weight of project objectives \( W_k \). These weights will be used later to be multiplied with the contribution of a BIM function to achieve the objective \( S_{kj} \) obtained from the survey and summarized in Table 3. The ratings scale from Table 3 is converted to percentage for uniformity (Table 4).

<table>
<thead>
<tr>
<th>BIM functions</th>
<th>Cost (1)</th>
<th>Time (2)</th>
<th>Quality (3)</th>
<th>Owners Satis. (4)</th>
<th>S(5)</th>
<th>M(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Visualization</td>
<td>67%</td>
<td>67%</td>
<td>92%</td>
<td>100%</td>
<td>52%</td>
<td>86%</td>
</tr>
<tr>
<td>Clash Detection</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>83%</td>
<td>30%</td>
<td>80%</td>
</tr>
<tr>
<td>Facility Space Planning and Logistics</td>
<td>67%</td>
<td>67%</td>
<td>75%</td>
<td>83%</td>
<td>23%</td>
<td>67%</td>
</tr>
<tr>
<td>Code Validation</td>
<td>50%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>21%</td>
<td>67%</td>
</tr>
<tr>
<td>Constructability Analysis</td>
<td>83%</td>
<td>83%</td>
<td>83%</td>
<td>67%</td>
<td>32%</td>
<td>80%</td>
</tr>
<tr>
<td>Structural Analysis</td>
<td>83%</td>
<td>83%</td>
<td>83%</td>
<td>67%</td>
<td>27%</td>
<td>75%</td>
</tr>
<tr>
<td>Cost Estimation &amp; Quantity Take-off</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>67%</td>
<td>30%</td>
<td>76%</td>
</tr>
<tr>
<td>Scheduling (4D Animation)</td>
<td>67%</td>
<td>83%</td>
<td>67%</td>
<td>83%</td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td>Energy Analysis</td>
<td>67%</td>
<td>50%</td>
<td>83%</td>
<td>83%</td>
<td>20%</td>
<td>74%</td>
</tr>
<tr>
<td>Shop-drawing Process</td>
<td>67%</td>
<td>83%</td>
<td>83%</td>
<td>67%</td>
<td>28%</td>
<td>72%</td>
</tr>
<tr>
<td>Material Tracking, Delivery and mgt</td>
<td>50%</td>
<td>83%</td>
<td>58%</td>
<td>67%</td>
<td>13%</td>
<td>48%</td>
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<tr>
<td>Stakeholder Engagement</td>
<td>83%</td>
<td>67%</td>
<td>83%</td>
<td>100%</td>
<td>35%</td>
<td>84%</td>
</tr>
<tr>
<td>Project Turnover &amp; Closeout</td>
<td>67%</td>
<td>50%</td>
<td>67%</td>
<td>100%</td>
<td>19%</td>
<td>66%</td>
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<tr>
<td>Facility Management</td>
<td>67%</td>
<td>50%</td>
<td>67%</td>
<td>100%</td>
<td>13%</td>
<td>67%</td>
</tr>
</tbody>
</table>

Step 4: Prioritizing BIM functions
After identifying the weight of project objectives, one can calculate the potential contribution that each function can provide for the project using the following equation:

\[
C_j = \sum_{k}^{\text{objectives}} (W_k \times S_{kj}) \times M_j
\]

In which \( C_j \) is the contribution of a BIM function \( j \) to the overall success of the project; \( W_k \) is the relative weight of objective \( k \) for the project; \( S_{kj} \) is the contribution of a BIM function to the objective \( k \) (Table 4; columns 1 to 4); \( M_j \) is the modification factor related to project size (i.e. medium and small) for BIM function \( j \) (Table 4; columns 5 and 6). By calculating the potential contribution of each BIM function, one can select most beneficial BIM functions for a project. Flowchart of the proposed process is shown in Figure 1.

To demonstrate practicality of the process, one can consider a project with the following characteristics: assume that the a medium size DB project is procured using 2-Stage RFP and cost and quality are the main project objectives with relative weights of 0.80 and 0.20 respectively. The potential contribution of BIM functions are presented in Table 5 and sample calculations for the contribution of clash detection is provided below:
As one can see in Table 5, clash detection (contribution score = 80%), stakeholder engagement (contribution score = 70%), constructability analysis (contribution score = 67%), structural analysis (contribution score = 63%), and 3D Visualization (contribution score = 62%) have the highest priority to be implemented in the project.

As one can see in Table 5, clash detection (contribution score = 80%), stakeholder engagement (contribution score = 70%), constructability analysis (contribution score = 67%), structural analysis (contribution score = 63%), and 3D Visualization (contribution score = 62%) have the highest priority to be implemented in the project.

6 CONCLUSION

The benefits provided by Building information modeling are frequently documented in literature (Becerik-Gerber and Rice, 2010; Meadati et al., 2011; Azhar, 2011; Bryde et al., 2013). However, small- to medium-sized firms fail to adopt and implement BIM as there is no common financial benchmark for making decisions regarding adoption of BIM functions. As an attempt to solve this problem, we conducted a survey to gather the tacit knowledge of BIM users. It was found that 72.5 % respondents believed that...
BIM is not required for all the projects. As far as project delivery and procurement methods are concerned, Design-Build (DB) and 2-Stage RFP procurement method were ranked at top for facilitating successful BIM adoption. In addition, most BIM users (72.5%) believed that project size impacts the decision in using BIM and more than half (59.26%) of the respondents indicated that project objective impacts the decision of using BIM functions.

Using these findings, a decision making algorithm was developed that can aid new users in understanding the advantages and disadvantages of implementing BIM functions in a project. The project provides significant contribution to the body of knowledge; however, there are some limitations that need to be mentioned. First, to develop the algorithm we assumed that the decision to use or not to use BIM in a project depends on project delivery method and team selection. Future studies should be conducted to identify other influential variables on making decision to use BIM in a project. Second, we assumed that selecting different BIM functions can be determined mainly based on project size and objectives. However, other variables can also be critical in using BIM functions such as availability of skillful personnel in a company. Third, large number of respondents were from design-build firms; this can explain why structural analysis and energy analysis were adopted more than expectations among respondents. Finally, the developed algorithm needs to be validated by conducting real cases studies.

7 REFERENCES


MEASURING CONSTRUCTION WORKERS’ ATTENTION USING EYE-TRACKING TECHNOLOGY

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Abstract: Although there are several studies that have highlighted the importance of attention in reducing the number of injuries in the construction industry, few studies have attempted to empirically measure the attention of construction workers. One of the techniques that can be used to measure workers’ attention is eye-tracking. Eye-tracking is widely accepted as the most direct and continuous measure of attention given that where one looks is highly correlated with where a person is focusing his/her attention. Thus, with the fundamental objective of investigating hazard identification abilities and the visual attention of construction workers, this study pioneers the application of eye-tracking technology to the realm of construction-safety practices. The study conducts a pilot test to examine the pattern of participants’ eye movement and attention distribution when shown a hazardous situation in a construction site. To achieve this objective, thirty-five pictures that include multiple areas of interest were shown to ten participants, and their eye movements were recorded using a head mounted EyeLink-II system (SR Research). Then, the absolute duration heat maps were generated and the fixation/gaze-related and saccade-related metrics were calculated for each area of interest. The results of the analysis revealed that some people failed to fixate on hidden hazards or even a danger sign. The findings of the study exhibit the immense potential of using eye-tracking technology for improving construction site safety.

1 INTRODUCTION

The U.S Bureau of Labor Statistics reported 845 fatalities within the construction industry in 2013 (U.S Bureau of Labor Statistics 2015). Even though the number of injuries have decreased significantly in the past couple of decades (Esmaeili and Hallowell 2012), accidents continue to take place. One of the main causes of accidents is the lack of attention and the failure of workers to identify hazards. If workers are distracted, they cannot identify and properly respond to a hazard. Therefore, it is rewarding to study attention and to identify ways for improving it. Although there are several studies that have highlighted the importance of attention in reducing the number of injuries in the construction industry, few studies have attempted to empirically measure the attention of construction workers.

One of the scientific ways for studying attention is to use eye-tracking technology. Eye-tracking is widely accepted as the most direct and continuous measure of attention given that where one looks is highly correlated with where a person is focusing his or her attention (Hoffman and Subramaniam 1995). In the past decade, use of eye-tracking has been flourishing in studies related to human computer interaction (Jacob and Karn 2003, Jaimes and Sebe 2007), usability research (Poole and Ball 2006), advertisement
To address this knowledge gap, the present study employs eye-tracking technology to investigate the visual attention of workers. The objective of the study is to identify the hazard identification patterns that participants demonstrate while performing a task-based search. To achieve this objective, a pilot test was conducted wherein eye movements were recorded using a head mounted Eye Link-II system (SR Research) and eye movement patterns were generated using the EyeLink® Data Viewer tool. The paper is organized into four sections. In the first part, the study presents the relationship between eye movement and attention, followed by a brief history of eye-tracking research, its application areas, and eye-tracking metrics. The second part explains the research method employed to conduct the pilot test. The third section includes findings of the study that are presented using absolute-duration heat maps and various eye-tracking metrics. Finally, the study concludes by providing a list of suggestions for using eye-tracking technology in future research.

2 LITERATURE REVIEW

2.1 Eye movement and attention

Humans eyes have finite capabilities and cannot attend to everything in their surroundings at once (Nilsson 1989). To be able to focus our vision on an area of interest, we have to move our eyes continuously, inspecting the field of view using brief fixations. Very often, our attention is directed toward the point we are looking at. This inextricable link between perception and attention was found by Yarbus in 1967. In a series of experiments that provided evidence for the relationship between human eyes and cognitive goals, Yarbus demonstrated that human eyes fixate longer on elements that project more information of interest to the observer. The experiments also implied that the analysis pattern (or eye movement path) of the scene under observation differs depending on the purpose of the observer (Yarbus 1967). The relationship between eye movement and attention mechanisms led to the vast use of eye-tracking research in the fields of neuroscience, psychology, ergonomics, advertising, and design (Richardson and Spivey 2004). By observing eye movements and the proportion of time spent looking at areas of interest, researchers attempt to infer which portions of a scene capture the participant’s visual attention and which portions are ignored.

2.2 History of Eye-Tracking Research

Historically, eye-tracking research was conducted to reveal what individuals look at, where they are look, or how they investigate an object of interest. Throughout the past century, several other concepts have emerged regarding the evolution of the eye-tracking technology, all of which have led to a wider scope for application areas (Duchowski 2007). Richardson and Spivey (2004) presented a commendable chronological account of various eye-tracking methods developed in the past century. They traced the history of eye-tracking back to the study of Louis Emile Javal in 1879. Javal (1879) used mirrors to observe the reader’s eye movements and was the first to observe that eye movements were not smooth. Later, to gain more insights about eye movements, Delabare (1898) simultaneously succeeded in inventing the first eye-trackers. Although the first eye-trackers provided valuable information for conducting reading studies, these tools were criticized for being invasive. To provide a non-invasive approach, Dodge and Cline (1901) invented a device that used photography for recording eye movements. With advancements in technology, researchers such as Buswell (1922) were able to use the reflection of light for recording eye movements on a film that enabled the production of some of the first two-dimensional scan paths.

The early 1970’s marked the onset of digital technology and image processing, which enabled Young (1970) to suggest scanning the image of the eye for the limbus. Due to the difficulty faced in scanning the limbus and vertical eye movements with Young’s technique, an alternative approach of scanning for the lack of reflectance from the pupil (“dark-pupil” tracking) was proposed. The limitation to dark pupil tracking was the low contrast between the black circle and brown irises. Therefore, Merchant et al. (1974)
suggested the bright-pupil tracking technique, wherein the pupil is lit directly from the front so that the light bounces off the back of the retina and appears very bright and is easily detected while scanning. The same technique was used to find the smaller, brighter corneal reflection that is seen in the contemporary systems. Over years, eye-tracking devices have been improved to achieve higher-precision records of observers’ points of regard, which allow for natural head and body movements (Richardson and Spivey 2004). Currently, eye-tracking technology exhibits a robust capability to aid in visual attention studies related to construction safety and can provide invaluable insights for further improvement.

2.3 Application Areas of Eye-Tracking

Although early eye-tracking research mainly focused on investigating the process of reading, the relationship between cognitive goals and eye movements opened gates for the use of eye-tracking in neuroscience, psychology, and behavioral research (Richardson and Spivey 2004). The application areas of eye-tracking research include diagnostic as well as interactive purposes. Considering the research objective of this study to be diagnostic in nature, we will limit the discussion of related eye-tracking research to diagnostic purposes only.

In the past decade, the use of eye-tracking has been flourishing in studies related to human-computer interactions and usability research (Jacob and Karn 2003, Poole and Ball 2006) and it has also been applied to transportation (Suh et al. 2006, Yao et al. 2011), driving (Recarte et al. 2008, Palinko et al. 2010), aviation (Sarter et al. 2007), marketing (Pieters 2008), nuclear power control rooms (Ha and Seong 2009), medicine (Zheng et al. 2011) and petrochemical control rooms (Ikuma et al., 2014). The use of eye-tracking in the above listed fields has been mostly related to estimating cognitive loads, analyzing user behavior, revealing differences in aptitude and expertise, and diagnosing neurological disorders. Even though eye-tracking is being applied in an increasing number of fields, it remains unexplored in the field of construction safety.

2.4 Heat Maps

A heat map is one of the most frequently used techniques for the visualization of data in eye-tracking studies. Heat maps can be described as graphical representations of eye movements over a scene. Major advantages of using heat maps include that they are easy to create and interpret because they graphically represent data using a color scale that relates to temperature, they provide a quick view of existing patterns, and they reveal a huge amount of data that would otherwise require more mental effort if presented in numerical formats (Bojko 2009). Therefore, heat maps are found to be widely used in web usability studies (Cutrell and Guan 2007, Buscher et al. 2009). Heat maps are limited in their representation of data—i.e. they only show density-based representation and heat maps lack information about the sequential order of eye movements. Thus, understanding the different types of heat maps, their limitations, and their purpose of use is necessary prior to their implementation (Bojko 2009).

2.5 Eye-Tracking Metrics

A large number of eye-tracking metrics have been used in previous studies to analyze human cognitive processes. The most common measurements used in eye-tracking research are “fixations” (relatively stationary eye positions over minimum duration) and “saccades” (quick eye movements). In order to explore the determinants of ocular behavior, a multitude of derived metrics that stem from these basic measures are incorporated into eye-tracking studies as dependent variables. Fixation-related and saccade-related metrics identified from literature are described in Table 1.

3 POINT OF DEPARTURE

Eye-tracking research has been flourishing widely in various fields of study. Even though the key characteristic of eye-tracking research—namely, that eye-tracking is the only direct measure of attention—provides immense potential for investigating, understanding, and improving construction workers' attention, eye-tracking remains unexplored in the field of construction safety. This study addresses this gap in knowledge and pioneers the application of a widely developed technology to the realm of construction-safety practices.
4 METHODOLOGY

A pilot test was mandatory for this research since no study had previously investigated using eye-tracking technology to explore the hazard identification abilities of construction workers. The pilot test was designed to examine participants’ viewing behaviors and attention distribution when shown a hazardous situation in a construction site. The experiment tested participants’ search-efficiency skills when required to use cognitive processing to determine whether or not a hazard is present in a given situation.

Eight male and four female graduate students at the University of Nebraska–Lincoln participated in the experiment as paid volunteers. All of them had normal or corrected-to-normal vision and had been prohibited from drinking coffee on the day of the experiment. Participants were invited to the study by responding to an invitation flyer. Eye movements were recorded using a head mounted Eye Link-II system (SR Research) with a sampling rate of 500 Hz and an instrument spatial resolution of 0.01°. The construction site images were displayed on a square 19’ computer screen. Participants used a video-game remote control to complete the task. The EyeLink® Data Viewer tool was used to generate eye movement patterns and variables.
Following the guidelines provided by Pernice and Nielson (2009), the experiment was performed in a lab setting. The lab was well lit and equipped with a dual screen setup, with the eye-tracking monitor placed behind the participant to avoid distracting him or her from the assigned task. The study strictly followed a well-drafted research protocol based on literature and expert advice. The experiment consisted of a single task wherein each participant was shown thirty-five construction site images ordered randomly on a computer screen while wearing the eye-tracker and was told to identify whether or not the situation in the image presented a hazard. Each image was displayed for a maximum of 20 seconds. The research assistant observed the participants’ eye movements on the eye-tracking monitor. The participants had to answer whether or not they found any hazards with the use “A”—Yes—or “B”—No—buttons on a video-game remote control. No specific information was provided regarding the type of hazard to look for.

After conducting the experiment and collecting the data, the first step for analyzing the relationships between eye movement parameters and dependent measures was to define areas of interest (AOI) in each picture. AOI(s) are visual environments of interest defined by the research team (Jacob and Karn 2003). For example, in marketing-related studies, specialists might be interested to know about the total time each observer views the desired target (brand area) on home page (Goldberg et al. 2002). In this study, because we aim to find out how participants scan a picture to identify hazards, we defined AOI(s) as visual environments of interest in pictures that include a hazard. The research team specified areas in each picture, and two examples are shown in Figure 2.

![Figure 2: Picture I and II’s Areas of Interests](image)

After conducting the experiment, to graphically represent the data, an absolute fixation duration heat map was generated for each picture. The results were also analyzed using different eye movement metrics such as time to the first fixation on target, average gaze percent (time) on each AOI, average number of fixations per AOI, average run count, saccade/fixation ratio, and average saccade amplitude.

5 RESULTS

The experiment was conducted on twelve participants and data were collected according to the established protocol. The data of two participants were omitted from the analysis because acceptable levels of calibration on the eye-tracker could not be achieved. Then, the EyeLink® Data Viewer was used to extract data and perform the analysis. To compare visual representations of participants’ eye movements with their hazard identification abilities, heat maps were created and compared with the number of hazards identified by each participant. Then eye movement metrics were analyzed to determine which areas of interest (areas that contain a hazard or a hint to identify a hazard) were identified fastest, which areas of interest were perceived more important, and how the participants searched and scanned pictures.

5.1 Hazard Identification and Heat Maps

The results of the pilot test conducted on ten students at the University of Nebraska-Lincoln confirmed that most of the hazards in a construction site can be easily missed or not considered to be a hazard by
individuals. Although all of the thirty-five images shown to the participants had multiple hazards varying in safety risk, the number of hazards identified by participants for all pictures ranged from 11 to 29 with a median of 22.5. The results can be alarming because working in an environment with latent hazards drastically increases the risk of an incident (Laurence 2005, Sneddon et al. 2004).

The absolute duration heat maps were generated by combining data from all ten participants to provide a quick view of average existing viewing patterns. To demonstrate the potential application of eye-tracking technology for measuring construction workers’ attention, a heat map for one of the images is shown in Figure 3. By looking at heat maps, one can visually understand which objects captured participants’ attention in a scene. While the absolute duration heat maps generated by combining data from all ten participants illustrates existing viewing patterns on average, the heat maps developed per participant for each image shed light on another aspect of the individual’s visual attention. In one of the pictures, five out of ten participants did not fixate on a person standing at a height without any fall-arrest protection systems. In another example, participants missed a danger sign, raising doubts as to the effectiveness of the signboards in catching peoples’ attention.

![Heat Maps for Pic I](image)

Figure 3: Heat maps for Pic I - (a) Original picture, (b) Heat map

### 5.2 Eye-Tracking Metrics

The metrics provided in Table 1 are calculated by analyzing the two-dimensional eye movement patterns of participants. The two-dimensional eye movement analysis starts by measuring the visual angle of pairs (or more) of data points in a time series—i.e., \( (x_i, y_i) \)—and also, the distance between successive data points—i.e., \( (x_{i+1}, y_{i+1}) \) (Duchowski et al. 2002). Using this concept, the following eye-tracking metrics were calculated for all AOI(s) in each image: the time to the first fixation on an AOI; the average proportion of gaze duration on each AOI based on time; the average number of fixations per AOI; and the average run count. The results for two pictures (out of 35 pictures) are shown in Table 2. Using these metrics, one can answer the following questions: How long does it take for a participant to see an AOI for the first time? On average, how long does a participant fixate on an AOI? In a given time, how many times does a participant fixate on an AOI? How many times does a participant come back to an AOI?

<table>
<thead>
<tr>
<th>Picture(s)</th>
<th>AOI(s)</th>
<th>Time to the first fixation on target (ms)</th>
<th>Gaze % (time) on each AOI-Avg</th>
<th>Number of fixations per AOI_Avg</th>
<th>Run count Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pic I</td>
<td>AOI 1</td>
<td>1336.57</td>
<td>9.05</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>AOI 2</td>
<td>2337.5</td>
<td>13.58</td>
<td>2.5</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>AOI 3</td>
<td>1789.6</td>
<td>25.97</td>
<td>3.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Pic II</td>
<td>AOI 1</td>
<td>2953.33</td>
<td>5.84</td>
<td>2.1</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>AOI 2</td>
<td>260</td>
<td>37.16</td>
<td>6.4</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>AOI 3</td>
<td>1318.8</td>
<td>19.52</td>
<td>3.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>
In picture I, the time of the first fixation in three areas of interests shows that the lack of guardrails placing around walking/working surface (AOI 1) captured people’s attention quicker than other areas of interest. This is an important finding, as previous studies related to graphical user interfaces showed that a lower first-fixation time indicates that the target better captured one’s attention (Byrne et al. 1999). In addition, the results of the analysis illustrate that participants spent more time on the AOI 3 (larger gaze proportion, number of fixations, and run count). In the AOI 3, a person is looking down a third floor of a building without any fall protection. This is against OSHA regulations as an employer has to provide some type of fall protection for workers who are working more than six feet above the lower surface. The highest run-count and proportion of gaze duration looking at the AOI 3 indicate the importance of this hazardous situation for participants.

In picture II, the AOI 1 was a danger sign that received only 5.84% of the proportion of gaze duration. This means that, on average, participants paid little attention to this part. Further analysis revealed that seven out of 10 participants did not even look at the sign. On the other hand, the AOI 2, which included a human figure, grabbed more attention (37.16% of proportion of gaze duration). This was expected as previous studies found that participants mostly tend to fixate preferentially and rapidly on human figures (Wilkinson and Light 2011, Thiessen et al. 2014). In the construction safety domain, it can be concluded that participants can identify areas with an imminent danger to a person faster than those areas that include a dormant hazard. The AOI 3 was also important because it showed that the worker standing on an elevated lift did not use the personal fall-arrest system properly: while he was wearing the body harness with attached lanyard, he anchored himself to the elevated lift in way that created a swing-fall hazard. According to the OSHA regulations, the anchorage point must support the force of a person falling and the worker should be tied off to an anchor in such a way that if he fell, he would not swing into an obstruction. The AOI 3 was the second most important area viewed by participants.

In addition to metrics per image, one can calculate mean value of eye-movement variables per participants to further investigate each person’s search strategy. These values are summarized in Table 3. Larger saccade/fixation ratios reflect that a person was more careful to scan pictures and search for hazards. Also, larger average saccade amplitudes indicate that a person could find the hazards more rapidly according to his/her experience. These values can help a researcher divide participants into multiple groups based on certain characteristics (e.g., age, gender, hazard-identification ability, risk perception, previous training, etc.) and test related hypotheses to compare their visual attention. Due to the low number of participants in this pilot test, the results of this analysis are not shown here.

5.3 Scanpath

Scanpath is a compelling visualization of eye movements that shows the sequence of saccade-fixate-saccade. Figure 4 depicts a scanpath obtained from one of the participants for Picture II. An optimal scanpath is a straight line eye movement to desired targets and a short fixation on targets (Jacob and Karn 2003, Pole and Ball 2005). Different quantitative measures and statistical analyses are used to analyze scanpaths—these analyses are outside of the scope of this study. Previous studies investigated scanpath variability between multiple webpage designs and found that visual complexity contributes to eye movement behavior. Similar studies can be conducted in the construction industry to measure the impact of crowded jobsites in distracting workers.

6 CONCLUSION

One of the root causes of accidents is human error (Abdelhamid and Everett 2000), i.e., the lack of attention and failure of workers to identify hazards. Given that hazard identification plays a crucial role in construction safety (Holt and Lampl 2006), the use of eye-tracking technology to investigate hazard identification abilities can aid in reducing construction worksite injuries. This paper presents a novel approach to improving construction-site safety by employing the eye-tracking technology that has been widely accepted as the most direct and continuous measure of attention. As a first step towards exploring the use of eye-tracking technology for construction safety, this study conducted a pilot test aimed at investigating patterns of participants’ eye movements when performing a task-based search. To analyze
the results, heat maps were created for data visualization, and gaze/fixation-related and saccade-related metrics were calculated.

![Figure 4: Pic II Scanpath](image)

Table 3: Mean values of eye movement variables per person

<table>
<thead>
<tr>
<th>Pictures</th>
<th>Participants</th>
<th>Fixation duration mean</th>
<th>Saccade amplitude-Avg</th>
<th>Number of fixations</th>
<th>Number of saccades</th>
<th>Saccade/fixation ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pic I</td>
<td>P #1</td>
<td>233.89</td>
<td>5.39</td>
<td>55</td>
<td>54</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>P #2</td>
<td>293.00</td>
<td>4.25</td>
<td>12</td>
<td>11</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>P #3</td>
<td>334.95</td>
<td>3.75</td>
<td>19</td>
<td>19</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>P #4</td>
<td>220.33</td>
<td>2.54</td>
<td>12</td>
<td>11</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>P #5</td>
<td>292.00</td>
<td>4.27</td>
<td>18</td>
<td>17</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>P #6</td>
<td>324.00</td>
<td>2.03</td>
<td>11</td>
<td>10</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>P #7</td>
<td>386.46</td>
<td>3.22</td>
<td>13</td>
<td>12</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>P #8</td>
<td>312.00</td>
<td>3.23</td>
<td>6</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>P #9</td>
<td>134.67</td>
<td>3.83</td>
<td>21</td>
<td>20</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>P #10</td>
<td>325.79</td>
<td>2.94</td>
<td>38</td>
<td>38</td>
<td>0.34</td>
</tr>
<tr>
<td>Pic II</td>
<td>P #1</td>
<td>199.48</td>
<td>3.18</td>
<td>31</td>
<td>30</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>P #2</td>
<td>306.42</td>
<td>3.16</td>
<td>43</td>
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<tr>
<td></td>
<td>P #3</td>
<td>287.81</td>
<td>4.10</td>
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<tr>
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<td>P #4</td>
<td>240.00</td>
<td>2.44</td>
<td>5</td>
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<td>0.05</td>
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<tr>
<td></td>
<td>P #5</td>
<td>300.23</td>
<td>3.89</td>
<td>35</td>
<td>34</td>
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<td></td>
<td>P #6</td>
<td>229.07</td>
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<td>418.53</td>
<td>1.93</td>
<td>19</td>
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<td></td>
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<td>5.57</td>
<td>7</td>
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<tr>
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<td>P #9</td>
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<td>15</td>
<td>14</td>
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<tr>
<td></td>
<td>P #10</td>
<td>255.60</td>
<td>4.26</td>
<td>30</td>
<td>29</td>
<td>0.48</td>
</tr>
</tbody>
</table>

The findings of this study provide a proof-of-concept and indicate the immense potential for using eye-tracking technology to improve construction-site safety and to attempt to facilitate more detailed
investigations in future research. As implied above, eye-tracking can be utilized for innumerable purposes inclined towards achieving safer working conditions, such as identifying hidden hazards, measuring situational awareness of workers, and improving the effectiveness of safety-training programs. With advancements in technology, eye-tracking equipment is available at lower costs, allowing for higher flexibility in use and providing a higher precision record for observer’s eye movements. There is no doubt that investments in eye-tracking technology will prove beneficial in academic as well as professional fields, thereby unveiling invaluable findings for improving construction-site safety.

References


CLOSING THE CONTRACTUAL CIRCLE: INVESTIGATING EMERGENT SUBCONTRACTING APPROACHES

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Abstract: The Architecture-Engineering-Construction (AEC) industry is shifting away from the traditional paradigm, one that places users, planners, designers, and contractors in different silos during professional practice. Other contractual schemes, which rely on contractual integration at lower contractual tiers, are emerging. These schemes close the contractual framework at lower tiers by having multiple upper-tier contractors subcontracting work to the same lower-tier entity. In these instances, subcontractors have contractual relationships with more than one other upper-tier party in the same project. A previous study on Building Information Modeling (BIM)-enabled projects revealed the emergence of these types of contractual relationships. To date, however, little is known on these emergent approaches, their diffusion, criteria for adoption, or expected utilities. This research proposes a methodology to analyze the benefits of these emergent models, then applies this methodology to recent projects to quantify outcomes, and finally develops a holistic framework of integrated contracting to assess its impacts on project efficiency. The specific objective of this research is to identify and delineate new lower-tier organizational relationships in today's construction practice. Preliminary results are included in the paper. Use of these emergent models for building contractors was assessed using a survey instrument. Data collection involved contractors in Washington State. After initial screening, several contractors were selected and interviewed regarding the nature of the adopted emergent subcontracting practices, the purpose for using them, and their perceived outcomes. This research contributes to a greater understanding of the occurrence, reasons, and advantages and disadvantages of these emergent contractual schemes. A discussion of their impact on overall project performance is included.

1 INTRODUCTION

Engaging subcontractors is an essential part of any construction project. While the Integrated Project Delivery (IPD) method aligns all the team members through a multiparty contract, other contractual schemes, which rely on contractual integration at different contractual tiers, are also emerging. Although procurement practices of subcontractors come in many forms and may be custom to various organizations, to date the literature lacks studies on the practices of lower-tier subcontracting.

According to Ndekugri (1988), on many individual projects, the level of subcontracting can be up to 80-90%. While general contractors hold the direct relationship with the client, they are usually not the only party involved to ensure successful completion of the works. Subcontractors are often engaged to assist
general contractors address difficulties due to the necessity to secure special expertise, resources and finances to the project (Elazouni and Metwally 2000). According to Shimizu and Cardoso (2002), subcontractors are specialist agents in carrying out a specific job, supplying manpower, besides materials, equipment, tools or design. Subcontractors act as representatives of the production system of the contractor company and are responsible only for the executed part of the workmanship.

The concept of supply chains is progressively becoming more significant to improve performance in the construction industry (London and Kenley 2001). Construction supply chain management (CSCM) refers to the coordination of distinct quantities of material delivered to specific construction projects.

Obrien et al. (2009), understanding the implications of supply chain management, to improve the effectiveness in the construction project execution. In particular they recognizes the importance of considering arrangements between the different firms involved in designing, procuring, and assembling construction, and reviews various perspectives to understanding and improving organizational issues in the supply chain. Also, they provide an overview of a range of information technologies that can contribute to supply chain performance, as well as examples of effective use.

Cox (2004) highlights the importance project managers develop different sourcing relationships depending on the different situation they are involved.

Additional impacts of subcontracting often include the spread of project risk and financing burdens across contractual parties. For example, to allow subcontractors to overcome project complexity, economical and efficiency problems, they frequently sublet a portion of their contract to other specialized firms. These specialized firms are commonly known as lower-tier subcontractors or sub-subcontractors. Engaging these specialized contractors enable them to perform their work at a quicker pace and lesser cost due to the availability of the resources as compared to general contractors. However, subletting parts of a subcontract to a lower tier subcontractor also provides an added complexity. When there are multiple levels of contractors involved in a project, the communication links between the parties - particularly the client and subcontractors - are weakened. The clients do not communicate directly with some of the firms that actually perform the work as they often do not know the identity of the lower-tier subcontractors (Choudhry et al. 2012; Arditi and Chotibhongs 2005). There are many forms of relationships between general contractor and subcontractors. Partnering is a common relationship between contractual parties at large, but partnering with subcontractors has different connotations from traditional owner-contractor forms of partnering. Hsieh (1998), affirms that more than 80% of general contractors prefers to create a durable working relationship with a particular subcontractor and material seller, also known as strategic partnership (Li et al 2000). Anyway, general contractors have a preference with a financial autonomy more willingly than any type of joint ownership. Most of the general contractors preserve a durable working relationship with an average of three subcontractors and two material vendors for any specified trade. Considering the prevalence of durable working relationship, a small number of general contractors engage new subcontractors except when forced by public procurement laws. If there is a new engagement, general contractors are influenced by the recommendations of other firms basing most of the weight of their decision on subcontractor’s references and track record. Differently to ordinary conviction, financial capability and equipment ownership are not much take into account for selecting subcontractors.

Partnering has also been considered as an avoidance technique in the form of alternative dispute resolution. A variety of reasons have been brought forward as consideration prior to the decision for partnering. According to Kumaraswamy and Matthews (2000), prime contractors and subcontractors believe that there are benefits in developing partnering arrangements between prime contractors and key subcontractors.

According to Tommelein and Ballard (1997), the coordination of the specialty contractor management by the general contractors affects the quality of production management on projects. Only knowing the appropriateness of the power regime perspective on sourcing and relationship management, the coordination can be appropriate.
According to Burr and Jones (2010) and Kelly (2014), project and system complexity, coupled with piece-meal design specialization has resulted in the need for greater collaboration among project participants in order to avoid cost overruns and other negative project outcomes. A widespread lack of trust, respect and honesty in the American, Australian and European construction industries has been credited as one of the main drivers toward the adoption of partnering concepts (Kumaraswamy and Matthews, 2000).

In the last years several forms of relational contracts, contracts in recognition to the commercial “relationship” between the parties to the contract, have been implemented in the architectural, engineering, and construction (AEC) industries to improve project performance by reducing schedule duration and increasing participants collaboration (Colledge, 2005).

Building upon transaction cost economic theory, Winch (2001) propose a conceptual framework for governing processes in the construction industry. While studying the impact of BIM-enabled design on project delivery, Clevenger and Khan (2014) highlighted that there are several organizational similarities and differences with regard to the contractual relationships between the relevant parties of the projects. Similar to Integrated Project Delivery (IPD) where the main parties of a construction project are contractually linked (at minimum the Client, Consultants and the General Contractor, but often also subcontractors and vendors), there are also circumstances where the lower tier subcontractor closes the contractual circle.

This research analyzes the preliminary results of emergent subcontracting approaches in the US improving the knowledge of the occurrence, reasons, and advantages and disadvantages of these emergent contractual schemes. The outcomes develop a holistic framework of integrated contracting to assess its impacts on project efficiency.

2 RESEARCH METHODOLOGY

This research was conducted in two steps: a) an online survey was performed to provide a current overview of emergent contracting practices among building contractors in Washington. The survey was mainly used to identify and screen potential candidates for follow-up interviews; b) on-site interviews were conducted to discuss reasons and results of these emerging contracting practices. The survey was completed in fall 2014 while the interviews were completed in winter 2015.

2.1 Online survey

The online survey was created using a web-based service (questionpro.com). The target audience included contractors and subcontractors in Washington State. Prior to conducting the survey, a pilot survey was carried out with students and faculty of the construction management department in University of Washington (UW) with experience in subcontracting practices. The questionnaire was modified to incorporate feedback from the pilot survey, to adapt it for the construction industry. The questionnaire was sent to registered firms with the Associated General Contractors of America of Washington (AGC-WA) and The UW Construction Industry Advisory Council (CIAC).

The survey consisted of three parts. The first part focused on the individual's background and personal experience in the construction industry, referring to the contractor's current position in the company and the value of the largest construction contract over the last 3 years. The second part addressed information on the individual's company, such as the general size of the company, the estimated average annual revenue (in US dollars) during the last 3 years and the company's main role, either as a General Contractor or as a Specialty Contractor. This was used to provide a better understanding of the size of the company and size of the projects they deal with. In addition, the participants were asked their level of involvement in the administration of subcontracts. The last part of the survey was used to collect data regarding the delivery methods commonly used in the projects, the factors that can influence the selection of subcontractors, and, in particular, if any subcontractors have signed contracts with other any project team members.
2.2 On-site interviews

The authors decided to select as first interviewee, an individual with significant knowledge of industry practices who also serves as instructor for short-courses on contracting practices for industry organizations in Washington State. This interview was used to “calibrate” our interview guide, including our tentative list of subcontracting models. The following list includes all the subcontracting models that resulted from this first interview. They were shown and explained to all the later interviewees.

- **Traditional Subcontracting (TS):** Figure 1a reflects the traditional contracting approach where the Owner (O) engages the General Contractor (C) and the Designer (D). The Designer refers to the lead consultant, and may be the Architect or the Engineer depending on the project type; D will then engage their own sub-designers (SD), C will engage their own subcontractors (SC). There are no mandated functional relationships between SD and SC.

- **Traditional Subcontracting with Design Assist (TS-DA):** Figure 1b is similar to the traditional approach except for the presence of a mandated “Design Assist” functional relationship between SD and SC.

- **Design-Build Subcontracting (DBS):** Figure 1c refers to O engaging D and C at an early stage known an Early Contractor Involvement (ECI) and only C engages SC in a Design Build contract for the design and construction phases.

- **Integrated Design-Construction Subcontracting (IDCS):** Figure 1d refers to O engaging D and C who then engages the same SC; D engages SC for design work while C engages SC for construction work. Therefore, SC holds a contractual relationship with both D and C. However, this is unlike IPD where there is a cross of contractual relationship between every party involved. It is also noteworthy that D & C do not hold a contractual relationship.

- **Integrated Specialty Work Subcontracting (ISWS):** Figure 1e is similar to the traditional approach at the upper tier. However, in this case, C engages 2 different SC. One of these SC sublets a portion of their work to the other SC in the same project.

These subcontracting models were diagrammed as shown in Figure 1. This figure was shown and explained to all the contractors who were interviewed thereafter.

![Organization chart](image)

**Figure 1: Organization chart**

On-site interviews were conducted with selected survey participants to study in greater detail the different subcontracting approaches adopted in Washington State. In addition, the interviewees were asked if they encountered multiple roles in a project, the influence of the Project Delivery Method and Procurement Method on the decision, the advantages, disadvantages, opinion and consideration on such practices. A special focus was given to identify situations where subcontractors have contractual relationships with more than one other party in the project.

3 SURVEY DATA AND ANALYSIS

Data collection involved contractors and subcontractors in Washington State. The questionnaire was sent to a total of 271 participants using the contact list extracted from AGC and CIAC. Out of the 271 questionnaires sent out, there was a 33.9% response rate for a total of 92 respondents. Among the respondents, 65 were executives, 15 were project managers, 10 were estimators and 2 were superintendents. In particular, data indicated that 68% of the respondents worked for general contractors, 25% for specialty contractors, and 7% for suppliers. This response rate suggests the results are deemed reliable. In fact, Owen and Jones (1994) suggested that 20% would be an acceptable response rate whereas Black et al. (2000) leaned toward 30% as an acceptable response rate.
Figure 2 shows the results regarding Individual’s Background. Figure 2(a) shows that contractors with at least 15 years of construction experience (senior contractors) are the largest percentage of the participants (88%). No contractors with less than 2 years’ experience participated. Figure 2(b) shows that 40% of the respondents had stayed with the same company for more than 15 years, while 39% had maintained the same position for a period between a period of 5 and 15 years. This suggests that most of the respondents are well experienced in the construction industry and with their employer’s practices.

![Pie chart showing years of experience in the construction industry and years in the same position with the company](image)

(a) Years of experience in the construction industry  (b) Years in the same position with the company

Figure 2: Individual’s Background results

Figure 3 shows the results regarding the Individual’s Company. Figure 3(a) shows that 47% of the respondents have been fully involved and somewhat involved in the subcontracting administration, and 5% are aware but not involved. One respondent was removed from the data analysis, as the individual was not aware and not involved in the process. Figure 3(b) shows that the respondent’s company acts primarily as a prime contractor for 71% of the respondents, while it acts as a subcontractor for 29% of the respondents.

![Pie chart showing administrative involvement in subcontracted work and major business role of the company](image)

(a) Administrative involvement in subcontracted work  (b) Major business role of the company

Figure 3: Individual’s Company results

Figure 5 shows the percentages of respondents who were aware of situations where a subcontractor shared contractual relationships with multiple parties in a single project.
Last, survey participants were asked if they were willing to participate in follow-up interviews. Out of 92 respondents, 61 agreed to participate in the follow-up. Among all those who were willing to be interviewed, we selected only those who were familiar with the situation where a subcontractor shares a contractual relationship with more than another party in the project (Yes in Figure 5) or were unsure about this fact (Unsure in Figure 5).

4 INTERVIEW DATA AND RESULTS

Twenty-four respondents were invited for follow-up interviews, including 19 prime contractors and 5 subcontractors. In the end, the authors conducted 14 interviews with 11 prime contractors and 3 subcontractors. Job titles included 10 executives, a retired executive, a project manager, an estimating manager and a safety manager. Each interview lasted approximately 45 minutes. One of the interviews, a prime contractor, did not produce meaningful data because we discovered during the interview that the interviewee only had a limited involvement in subcontracting. Interviewee No.1 helped the research team to refine the list of subcontracting models, which aided in drawing Figure 1. Later interviewees were shown diagrams in Figure 1. They were asked to describe which contractual strategies were most commonly used under which circumstances.

4.1 Traditional Subcontracting (TS)

All the interviewees described the model represented in Figure 1.a as the most traditional form of procuring subcontractors and sub-consultants where the owner will hire a designer and a general contractor and they will hire their own sub designer and subcontractor respectively. According to the interviewees, this model is used commonly in public projects particularly for lump sum contracts awarded to the lowest bidder. While it may seem inefficient from a communication standpoint, most contractors curb this inefficiency by communicating directly to other contractual parties by requesting and organizing joint meetings.

4.2 Traditional Subcontracting with Design Assist (TS-DA)

All the interviewees agreed that the model represented in Figure 1.b is the most common. This is particularly true for private projects where the subcontractor and the sub designer will share a functional Design Assist relationship. According to the interviewees, this is particularly true when the contractor is on board at a later stage, which requires the sub designer to produce preliminary drawings to be included in the bidding documents for the general contractor. This general contractor will then require the subcontractor to establish a Design Assist relationship with the sub designer with the purpose of facilitating collaboration on the production of detailed design documents. This is the most preferred approach for all contractors regardless of trades. One of the interviewees also said that it works well for subcontractors who do not employ individuals who are qualified to be engineers of record, and, therefore, cannot use the Design-Build subcontracting model.
According to most of the interviewees (8 of 13), the Design-Build Subcontracting model shown in Figure 1.c is not as common as those represented in Figures 1.a and 1.b. While all (13 of 13) interviewees encountered it, they have suggested this subcontracting model is used only for specific specialty trades, such as precast concrete structures for parking, curtain walls or Mechanical, Electrical and Plumbing (MEP) works. This model is also commonly used for smaller projects where a sub designer is typically not needed. At least three interviewees explained a variation where even the consultant designer is under the general contractor, which ultimately makes it a traditional design-build contractual strategy. Figure 1.c is also a growing trend and is getting more common in the industry, particularly in projects with early contractor involvement.

The Design-Construction Integrated Subcontracting model shown in Figure 1.d describes a contractual structure where both the general contractor and the designer select the same subcontractor to perform a scope of work that integrates design and construction services. However, different from Design-Build Subcontracting, this subcontractor holds two separate contracts with the general contractor and the designer. According to 9 of 13 interviewees, this approach is rarely adopted, but it is present in the industry. At least four interviewees explained that the general contractor may have a contract with the subcontractor, similar to Figure 1.c, but the subcontractor may share a functional relationship with the designer. At least six interviewees have faced this situation. This situation happens, however, only on highly specialized projects where there is a large scope for the subcontractor.

Those interviewees (7 of 13) who had never faced this situation were asked to provide their feedback and opinions based on their personal experience. All the interviewees stated that an MEP contractor would be one who could be part of this contractual strategy. Apart from the general contractor, an MEP contractor could be contracted either by the owner or the architect or in some cases, the structural engineer. At least five interviewees stated that the next most common trade was the curtain wall or shop front contractors. Some other trades include the Structural Steel, Precast, Surveyor, Quality Assurance and Quality Checks, Kitchen Equipment, Data Cabling and Door Hardware. The majority of interviewees (9 of 13) suggested this method is commonly used for private projects rather than public ones due to its flexibility. In cases where the interviewee had experience with this situation, the decision to contract the same subcontractor is usually a joint decision between the designer and the general contractor, to provide the best solution for the project. This is where the designer will contract the subcontractor to do the design work, and the general contractor will contract the subcontractor for the construction work.

The decision to use this contract strategy is usually weighed by the relationships the different parties share. For example, the designer and the contractor agree to use the same subcontractor when they share a strong relationship with each other as well as the subcontractor. In this way, a strong relationship is necessary to carry out this strategy. It also depends on the complexity of the project. It is encouraged for proprietary or specialized works where the engineer or architect is not familiar with the system and would require a high level of expertise. The project delivery method used by the project also impacts this decision. In a Design-Build project, the parties have a greater flexibility in using this approach as compared to traditional Design-Bid-Build projects. In General Contractor/Construction Manager (GC/CM) however, it varies depending on the complexity of the project, as it is more likely to proceed with Design-Build Subcontracting (Figure 1.c).

The interviewees were asked about the advantages of the Design-Construction Integration model (Figure 1.d). The advantages suggested by the interviewees included, but were not limited to the followings:

- **Triggers economic efficiencies** in terms of cost and resources because it encourages labour and cost efficiency due to the sharing of resources;
- **Promotes communication efficiencies** because it forces good communication between the parties due to the contractual binding. It is more efficient as it eliminates the “back and forth” communication between the subcontractor and the designer; it also eliminates the learning curve to working together.
while generating detailed design due to the specialty designer having a better knowledge of the construction phase, as they are essentially the same team with the specialty contractor;

- **Facilitates lean construction**, as the designers are more knowledgeable and takes constructability into consideration when designing;
- **Provides consistency** in the project, as the party who is designing is also doing the installation and construction. There are lesser chances of scope gap as one party will be in charge of the whole system and they can highlight if there are any gaps found;
- **Improves price prediction** as all parties have a better understanding of the construction and installation process;
- **Improves project quality** by reducing amount of design and construction rework;

The interviewees also raised some concerns and provided some disadvantages of this subcontracting model. The disadvantages suggested by the interviewees included, but were not limited to the followings:

- **Misalignment between designer and general contractor**: The subcontractor may be subject to discording instructions from the designer and the general contractor due to the different expectations and intent. For example, the contractor will be focused on cost driven approaches while the designer will expect better design quality. Whose instructions take precedence? There is also potential for the subcontractor to be bias towards one party, usually the one who they share a better relationship with. Therefore, influence over the subcontractor is less as it is split between two parties. Interviewees identified this risk factor as high;
- **More paperwork and risk of contractual complication**: "who pays for what" issue between the contractor and the designer. There is also a liability issue, as there is less control over design. If a part of the project is not designed right, besides the subcontractor, who will be responsible contractually? Will it be the designer or the general contractor? There is a risk of blaming the other party;
- **Internal coordination failures**: Potential of a subcontractor who has different teams to do the design and construction within the same company and they may not coordinate as expected; therefore, the expected results may not be achieved.

While all interviewees mentioned one or more of these disadvantages, eight of the interviewees felt that these issues can be overcome through the establishment of a collaborative team that shares a trusting relationship involving trust. This strategy works well if the contractual implications are explicit in the contract and all the parties have a clear understanding of the objectives, intents and risks involved in this strategy.

Eight of the interviewees highly encouraged this model as long as there is no increased risk. This depends on having the right team with good, honest and collaborative relationships with everyone being clearly aware of the contract and the factors involved in the contractual strategy. Some interviewees feel that having the owner fully aware of the situation benefits the project while some feels that it is better for the owner to not be involved. Three of the interviewees felt that it was not ideal, as a single point of contract is preferred to avoid liability issues. These interviewees feel that there is a need to have one responsible party to be in charge of the on goings of the project rather than split responsibility. To the rest (2 of 13) of the contractors, the approach doesn’t matter as long as everyone is fully aware of their scope and responsibilities.

**4.5 Integrated Specialty Work Subcontracting (ISWS)**

This model was found to be very common between subcontractors where a subcontractor on a project engages another subcontractor on the same project to complete part of their works. This is usually a small portion of the works and interviewees suggested there are plenty of occasions where the subcontractors do not share a contractual relationship with each other, and the works are done on a trust basis. In such a scenario, subcontractor ‘A’ helps subcontractor ‘B’ on a project, and subcontractor ‘B’ returns the favour on another project they work with together. Whether or not these subcontractors share a contractual relationship, most general contractors encourage this approach as it shows a collaborative relationship between their subcontractors, which in turn provides a better quality project. It also ensures
that the subcontractors with the right set of skills and resources are doing the right work. A common example from the interviewees is the electrical contractors who will engage either the earthwork or utility contractor to do trenching works for them.

This strategy is very situational where some interviewees prefers contract involvement to deal with payment and warranty issues while some interviewees feel that the lack of contracts provide less paperwork to deal with, which in turn saves time. When interviewing the subcontractors, some prefer having a change order by the general contractor rather than add on another contract, while some prefer to share the resources without getting the general contractor involved. When interviewing the prime contractors, some prefer the subcontractors to manage the contract on their own without their involvement to avoid any conflicts and additional paperwork due to change orders. However, there are some prime contractors who prefer to have control over their subcontractors.

5 CONCLUSIONS

Based on the surveys and interviews completed to date, the authors found that the subcontracting model used on a project is primarily situational, and that there are many factors involved in the decision of selecting a contractual strategy. The interviewees confirmed that all of the subcontracting models presented to them are used in Washington State. All models are relatively common except for the Integrated Design-Construction Subcontracting (Figure 1.d). Such results expand upon previous findings of Clevenger and Khan (2014) that have first identified the occurrence of ICDS. Since that previous study had linked this model to the increasing use of BIM, we explored this issue with our interviewees. When asked about the impact of Building Information Modeling (BIM), it was found that although BIM does not have a direct impact on the changes of the contractual strategies over the years, it does play a role and accelerates the changes in contractual strategies found. The general consensus of the interviewees (9 of 13) is that BIM is just another tool used in construction yet it forces collaboration and a functional relationship between the project team members involved, and that BIM provides an overall advantage to the industry.

The authors delved into the reasons, benefits and barriers of ICDS, while comparing it against the remaining models. With regards to the remaining models, such approaches have been used under different circumstances depending firstly on whether the project is a public or private project. While most public projects are less flexible, there are exceptions where the owner is willing to test out alternative contracting strategies. The project team involved, the complexity of the project and the type of building (residential, commercial etc.) also determines the strategy used.

The use of ICDS relies on many factors. One major factor is the trade of the subcontractor, which may be involved in this model. For example, while the bigger trades like MEP and curtain wall frequently practices this approach, trades with less complex scope of work, such as concrete, do not. Another factor is the complexity of the project, and a larger, more complex project is more likely to explore the different strategies as compared to smaller, “cookie cutter” projects. It was also found that while most interviewees encourage the approach of closing the contractual circle on the lower levels, its success depends a collaborative team with a good relationship, and a clear contract.

Some limitations faced by this research was that the data set is only collected based on contractors located within a 45 mile radius of the University of Washington, Seattle. It was also noted during the interviews that some contractors felt that the designers may have a resistance towards ICDS.

To externally validate the research, the authors had concurrently conducted a smaller study with contractors in Colorado. Based on the set of 13 surveys completed, three were shortlisted for an interview. An interview will be conducted to validate the responses of the existing interviewees. Based on these responses, the authors will develop a survey instrument addressed to a larger nationwide pool of participants to provide an extensive data set. We will also consider expanding the data set further by including designers and developers as part of the research to fully understand the acceptance and resistance of this contractual approach.
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References


AN EXPLORATION OF IMAGE-BASED WALK THROUGH TECHNOLOGIES

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Abstract: Construction sites contain vast amounts of information. Recent advances in image-based visualization techniques enable monitoring construction progress using interactive and visual approaches. Photographs capture construction information in great detail while allowing the user to absorb as much information as they need. Construction as-built images captures great detail yet excludes portions of the site which may become of interest to the project participants. To overcome limitations of existing image-based monitoring techniques, this research focuses on an image-based virtual walk-through visualization approach to monitor construction sites. The use of a 3D model to create a virtual walk-through enables a comprehensive record and delivers the information in an intuitive manner. A pilot study is conducted to create several as-built 3D models from construction photographs. Then these 3D models are visualized in a 3D walk-through model. Within such an environment, the as-built construction objects are visualized to generate the status of construction progress. The study shows that this 3D image-based walk-through system introduces an advanced model that enables the user to have a realistic understanding of the construction site.

1 INTRODUCTION

Research has been conducted on image-based walk-through virtual reality technologies for monitoring construction projects (Rankohi et al. 2013). Dang et al. (2011) proposed a panorama-based semi-interactive 3D reconstruction framework for indoor scenes. Their framework overcomes the problems of limited field of view in indoor scenes and has the desired properties of: robustness, efficiency, and accuracy. Bradley et al. (2005) present a system for virtual navigation in real environments using image-based panorama rendering. Roh et al. (2011) proposed an object-based 3D walk-through model for interior construction progress monitoring.

Virtual Reality Documentation or VR Doc (www.vrdoc.ca) records construction progress through high resolution 360 degree panoramas (Rankohi et al. 2014). An intuitive VR Doc user interface allows the user to view panoramas from a specific date and location. Although VR Doc panoramas provide great detail through zoom capability, items out of view may become important as construction progresses. Therefore, increasing VR Doc coverage beyond predetermined locations creates a comprehensive photographic record of construction which is of value to the entire construction team. Moreover, using VR panoramas to capture an entire construction site would result in an overwhelming amount of data and
requires a significant amount of time to capture and process. Using photogrammetry techniques to compile site photographs into a single 3D walk-through environment provides a simple method of displaying and navigating a large and detailed data set.

The walk-through is seen as a “global” tool to be used at all levels of management and through all stages of construction. Before construction even begins the walk-through could assist with site planning and disaster management. During construction, inspectors would be able to perform quick assessments of the work being performed. Safety personnel could perform routine safety audits. Subcontractors would better predict their schedule by checking on the status of the work preceding them. Use also continues long after construction is complete by leveraging the ability to locate hidden items when planning upgrades and renovations. The technology could even be expanding to perform measurements, incorporating surveying and material quantity calculations. This paper investigates generating a low resolution walk-through model, which retains sufficient detail to visualize and document progress that would complement current features. To reach this goal, different software and photography techniques have been tested and the results are compared. Finally based on the achieved results, a first person Walkthrough model of an interior hallway is developed.

2 GOPRO CAMERA

A GoPro camera (www.gopro.com) was chosen to incorporate 3D model photography into the existing VR Doc workflow. The GoPro Hero 2 is an 11 megapixel camera capable of capturing both HD video and still images. The camera measures 42 mm x 60 mm x 30 mm, and has many mounting options that allow attachment to your body, helmet and various other objects or vehicles. The lens provides a 170 degree horizontal field of view which is captured by a 1.0160 cm CMOS sensor. The size and ease of portability makes it ideal to integrate into current VR Doc workflow. A time lapse option lets the user specify a capture interval of 0.5, 1, 2, 5, 10, 30 or 60 seconds. An interval of 2 seconds was chosen as it allows sufficient time to pass at a walking pace between images. Using this mode, the camera could be mounted to the photographer during VR Doc capture to simultaneously capture 3D model data.

Using the GoPro for photogrammetry purposes poses some problems. While able to capture a large field of view and minimize the number of photographs to cover a scene, the lens produces images with significant optical imperfections that affect the construction of a 3D model. The most visible imperfection is barrel distortion. Overlapping images are difficult to match as objects become different shapes in each image. Figure 1 compares the barrel distortion produced by the GoPro to an image taken with a Canon EOS 60D (a 17.9 megapixels camera with a 22.3 × 14.9 mm (1.6x crop factor) sensor). Corrections were applied to help reduce imperfections found in the GoPro images. Table 1 summarizes corrections applied using Dxo OpticsPro 10 (www.dxo.com).

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3 BUILDING A 3D MODEL

3.1 Photography

A 3D model generated from photographs has different photography and post processing requirements than VR Doc panoramas. While capturing the twelve photographs for a VR Doc panorama the camera
remains in a fixed position as it rotates about the nodal point of the lens. The objects in the scene may be
distilled or moving in non-overlapping regions and overlapping regions should contain objects with texture and
contrast. Post processing identifies and matches key points in overlapping regions, stitching the images
together.

To generate a 3D model, photographs of the entire scene must be captured with the camera changing
position between images. Overlapping regions are significantly larger than in VR Doc panoramas; some
images may overlap 100 percent. Key points are extracted and matched over the entire photograph,
therefore texture and contrast must be present over the entire scene. Objects should also be stationary
during photography. The photography process which has performed well for uncluttered interiors involves
taking photographs perpendicular to the surface of interest with subsequent photographs of the same
surface continuing on the same camera plane. When approaching a corner, the camera should follow a
smooth curved path, avoiding abrupt changes in angle. This ensures sufficient overlap is achieved and
that key points will be detected and matched. After photography is complete many post-processing steps
are required to produce the final model.

3.2 Post Processing

Several different software packages were evaluated to build the 3D model. Agisoft Photoscan
(www.agisoft.com) was found to be the most suited to large unordered photo collections. The post-
processing described in this section pertains to Photoscan although the steps are similar across all
software evaluated.

![Figure 1: Barrel distortion correction: Cannon 60D image (a) before and (b) after correction; GoPro image (c) before and (d) after correction](image)

After adding the photographs to Photoscan, they must be aligned. The alignment process involves
identifying and matching key points across images. Setting the accuracy to high provides the best
solution but takes significantly longer to process. Disabling pair selection allows each image to be
matched across all others which provides better results for large unordered photograph collections.
Processing time varies with the accuracy chosen and the number of photographs used. Aligning the
photos creates a point cloud which is the first step in creating the 3D model. Building the geometry is
performed after the point cloud is generated which creates a mesh connecting the points together using
polygons. Photoscan has some basic mesh editing capabilities and if more editing is required the mesh
can be exported for refinement in third party software and re-imported. At this point the model resembles
the captured scene. The final process is to apply a texture to the mesh. Build textures feature creates a
texture which is overlaid on the mesh by incorporating the images used in the model. The textured model
completes the processing performed in Photoscan which is exported to create the virtual walk-through.
3.3 **Virtual Walk-through**

A first person walk-through is an intuitive method to explore the model in detail. The user is free to move around the model as if they were walking on foot with control of the direction of view as well as forward and backward and side to side movement. Many video games employ this type of viewpoint which is achieved using a video game engine. The video game engine is used to design and publish multiplatform video games, where in this case, the video game is simply the 3D model.

The Unity (www.unity3d.com) game engine was chosen to build the walk-through as it has a free version with sufficient capabilities. After building the model in Photoscan, it is exported in .fbx format with textures exported as .png. These two files are then imported into a Unity project. Before adding the model to the scene, picture normal vectors were set to calculate; otherwise the model was displayed inside out. Colliders were also enabled to form a rigid surface over the entire mesh, creating boundaries on floors, walls and objects. Textures are a separate component from the model and must be applied to the mesh. Unity has many options to apply a texture and introduce artificial lighting. For this application we wish to preserve the original scene and use the unlit texture option. Once rendered, the walk-through can be exported as a standalone executable file to be viewed on a personal computer. There is also a web delivery option which would facilitate delivery to a client.

3.4 **Description of Variables/Challenges**

Various challenges were encountered during the photography stage. Errors typically only become evident after photography is complete when building the 3D model. It is also difficult to determine the exact cause of the error as they tend to produce similar results; therefore it is important to pay close attention to all details during photography. Table 2 highlights the main challenges and expected solutions associated with photography.

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model will not build or contains holes or is severely distorted</td>
<td>Increase number of photos</td>
</tr>
<tr>
<td></td>
<td>Avoid moving objects in scene</td>
</tr>
<tr>
<td></td>
<td>More photos from other angles</td>
</tr>
<tr>
<td></td>
<td>Photograph objects with texture</td>
</tr>
<tr>
<td>Low detail in model</td>
<td>Increase photo resolution</td>
</tr>
</tbody>
</table>

The number of photographs required to build a 3D model depends on the size of the scene, the lens used and the amount of overlap between images. A wide angle lens is recommended for interior photography in order to obtain sufficient overlap while minimizing the amount of images. A wide angle lens also aids in scenes with low texture, providing more opportunities for key point detection. Holes will appear in the model if portions are not sufficiently covered during photography. In extreme cases entire sections of the model will be left out or multiple sub-models will be created if there is not enough information to link sections together. Distortions or holes will also be created if objects move or if the scene contains repeating patterns. Repeating patterns have similar key points that can be confused during matching.

Several camera settings influence the outcome of the model. Interiors typically have lower light levels than exteriors and require increasing the ISO. High ISOs introduce noise into the image making key point identification difficult. Wide apertures are also often used in low light and have a large impact on the depth of field. Many photography factors contribute to a sharp image including: ISO, shutter speed and focus point. A sharp image is critical to key point identification and therefore attention to focus point and shutter speed is essential, especially while hand holding the camera. A properly photographed scene will proceed through post processing with little difficulty. Another challenge in post processing is the time required to build the model. Projects which contain hundreds of images with high quality settings can take upwards of twelve hours to process. More processing resources would reduce this time and allow more trials to be performed. Post processing related challenges encountered are identified in Table 3.
Table 3: Post processing challenges

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low key point matching</td>
<td>Apply distortion correction</td>
</tr>
<tr>
<td></td>
<td>Reduce noise in images</td>
</tr>
<tr>
<td></td>
<td>Check focus point</td>
</tr>
<tr>
<td></td>
<td>Increase shutter speed</td>
</tr>
<tr>
<td></td>
<td>Decrease ISO</td>
</tr>
<tr>
<td>Slow processing</td>
<td>Use a faster computer</td>
</tr>
</tbody>
</table>

4 MODEL BUILDING SOFTWARE

The following section examines each variable independently using panoramas taken in a laboratory setting. Each variable has a base image with which the effects of the variable are compared. Base images were taken in Room H135 Head Hall using artificial overhead lighting with one window providing exterior light. The software that have been used in this pilot study are Agisoft PhotoScan, Photomodeler, Autodesk 123D Catch, Visual SFM, and Unity 3D.

Agisoft Photoscan (www.agisoft.com) is a fully automated commercially available software package. Photoscan is also a complete 3D model building package creating 3D point clouds, meshes and textured models. Limited tools are available for point cloud and mesh editing, although it is possible to export either for further refinement. Photoscan performs very well with large unordered photo collections.

Similar to Photoscan, Photomodeler (www.photomodeler.com) is a complete 3D model building package. Photomodeler provides the user a great amount of control throughout the building process. Large unordered photo collections of the interior of a building were not one of Photomodeler’s strengths. The models generated were very distorted. Photomodeler appears to be better suited to stereo pair photography with the use of coded targets. While it is possible to create dense point clouds without targets, this type of work is largely seen in aerial imagery.

Autodesk 123D Catch (www.123dapp.com/catch) is a free web based service provided by Autodesk. As many as seventy images, three mega pixels or larger can be uploaded to their servers where all of the processing takes place. Model construction is fast as local computing resources are not a limiting factor. Poor results were obtained when building 3D models of interiors. Models were very distorted, incomplete, and many of the photos were unable to be matched.

Visual SFM (www.ccwu.me/vsfm) is an open source program which facilitates the use of a collection of scripts developed by various researchers by incorporating a GUI. There are no limitations on the number of images although the largest dimension must be no greater than 3,200 pixels. Once a point cloud is created it can be exported for further processing or for use in other software to continue with 3D model generation. Unity 3D (www.unity3d.com) was the only video game engine tested and produced satisfactory results. Standalone and web based delivery options are possible and fit well with the current workflow of VR Doc.

5 PILOT STUDY

5.1 Initial Model Testing

Testing was originally performed to evaluate each software package. The three packages evaluated are Photoscan, 123D Catch, and Visual SFM. Several other dimensions of building a 3D model became evident throughout testing. These included the camera used, which was further divided into post processing steps, as well as the location of photography. In order to compare the test results, tests have been conducted by using different cameras and in different locations.
The GoPro Hero 2 was the first camera used as it fit well within the current VR Doc workflow. The Canon 60D was added to the tests as the GoPro was producing poor results. A comparison would help direct efforts in determining sources of error. Initial testing was done in Room H135 to remain consistent with previous testing on change detection in panoramas. Two other locations were added to overcome low texture and contrast in Room H135.

With the original goal of evaluating the software in mind, the following discussion is organized by location with the other dimensions discussed within each section.

5.2 Room H135

Low texture walls combined with repeating patterns found in the desks and chairs presented significant challenges in this location. Seventy nine images were taken with the GoPro camera in Room H135 and loaded in Photoscan. Using a medium alignment setting and pair selection disabled, 20 images were aligned and included in the point cloud. Photoscan was unable to move further in the processing due to the low number of key points. The point cloud did not resemble any specific section of the room. Using the Canon 60D, 99 photographs were taken and loaded in Photoscan. Using a medium alignment setting, a model was able to be produced with 81 images although significant distortions were present. Fifty seven of the 79 images from the GoPro camera could not be matched in 123D. The images which were matched produced a distorted and hole filled model indicating the matches were poor. Slight improvements were noted using images from the 60D although key point matching is still poor with only 32 of the 102 images matched. 123D Catch shows great difficulty matching key points of interior photographs.

The point cloud generated by Visual SFM with the GoPro images was broken into 3 models. Without sufficient key points to match images Visual SFM will create sub models with the matched images. Thirty nine images were match with the sub models containing 18, 12 and 9 images. All of the sub models included components of the same objects and excluded the same portions of the room. Excluded portions contained little texture and were highly repetitive. Using the images from the 60D Visual SFM produced 4 separate models which included similar components to those in the GoPro model. The geometry of the models appears to be correct in both the GoPro and 60D models. The 60D model has notably more points than the GoPro model, 124,413 vs. 28,899 respectively. The different 3D models created for Room H135 are shown in Figure 2.

5.3 Room H229B

Room H229B (office) is much smaller than Room H135 (classroom), but contains more texture and randomness. The number of photos taken with the GoPro was increased to 102 in an attempt to capture occlusions generated by the furniture. The arrangement of the furniture and size of the room made photography difficult, therefore only two walls were captured for reconstructed. Photoscan was expected to produce better results than those obtained in Room H135 due to the added texture. One hundred images were aligned in the point cloud but Photoscan was unable to continue with the model due to a lack of key points. A significant improvement was noted with the 63 images taken using the Canon 60D. All 63 images aligned and produced a clean textured model with minimal holes or distortions.

123D Catch produced a slightly better model with the GoPro images from Room H229B than ROOM H135. While there were very few holes, the geometry was visibly incorrect as noted by the angle between walls. The texture was also distorted indicating poor key point matching. The improvement over ROOM H135 demonstrates the necessity of texture. The added texture was also noted in the images taken with the Canon 60D which produced a significantly better model than Room H135. The textured model did contain holes but geometry was visibly correct.

Multiple models were again created with the GoPro images in Visual SFM indicating a disconnect between key points. One main model contained the majority of the images and the geometry was visually correct. A significant improvement was noted with the images from the 60D. Visual SFM created a single model with a dense point cloud consisting of 365,970 points compared to 24,976 points in the main GoPro model. Comparing the results between Room H229B and Room H135 across all software reveals
some weaknesses in the GoPro camera. Inspecting the images reveals a considerable amount of noise in the GoPro images, similar to that seen when using high ISO. This increases the difficulty in identifying and matching key points and therefore building the model. The different 3D models created for Room H229B are shown in Figure 3.

Figure 2: Room H135; (a) Photoscan GoPro, (b) Photoscan Canon 60D, (c) 123d Catch GoPro, (d) 123d Catch Canon 60D, (e) Visual SFM GoPro, (f) Visual SFM Canon 60D

5.4 Head Hall Exterior

Reconstructing the exterior of Head Hall was done in attempt to overcome challenges encountered during the interior tests. This location provides a large open space and ample light. The increase in light reduced the amount of noise visible in the GoPro images. Interior GoPro images were taken with an ISO of 400 and exterior images with an ISO 100. All of the 70 photographs taken with the GoPro were aligned in Photoscan. This performance is attributed to the decrease in image noise resulting in more points being identified and detected. This was the first GoPro model which would successfully build in Photoscan signifying the importance of sharp, low noise images. The textured model contained moderate distortions and low detail compared to the model generated with photographs from the 60D. The GoPro model contains 12,636 points while the 60D model contains 149,031. While the reduced noise improved the GoPro model, there are still significantly less points being identified.

The importance of texture is demonstrated well in 123D catch using the GoPro images. Only one of the 70 GoPro images was not matched which is a major improvement compared to previous results. The model does contain a large amount of holes but the geometry is generally correct. 123D Catch has a limit of 70 images per project and crashes when trying to upload the 143 images taken with the 60D. It is
speculated that these images would produce a better result than the GoPro. Another trial with fewer images is required. Testing with Visual SFM failed using both the GoPro and 60D images. Both sets of images are similar to those used successfully in the past. Failures occur during sparse reconstruction which performs well on other data sets. Further investigation is required to determine the cause of failure. The different 3D models created for Head Hall Exterior are shown in Figure 4.

Figure 3: Room H229B; (a) Photoscan GoPro GoPro, (b) Photoscan Canon 60D, (c) 123D Catch GoPro, (d) 123D Catch Canon 60D, (e) Visual SFM GoPro, (f) Visual SFM Canon 60D

5.5 Walk-through Model

A new location was chosen to implement the walk-through to overcome the challenges encountered during testing. The location consisted of a wide hallway approximately 15 feet wide and 45 feet long and contained ample textured objects. The hallway had minimal clutter and low traffic. Connected at one end is a narrow hallway and small room. The goal of the walk-through was to connect the main hallway to narrow hallway and small room. The Canon 60D was used due to its performance during testing.

Photography for each of the three components was performed separately and three models built independently to narrow any errors to specific locations. Once the models were successfully generated, the components were compiled into a single model and processed as a single element. The final textured walk-through was exported as a standalone executable file. The largest errors are located in the small room. This is attributed to the low texture, making key point identification and matching difficult. This difficulty was compounded by the use of a high ISO due to low light. The room is also cluttered making photography challenging.
The effort required to produce a virtual walk-through depends largely on the photography. The ideal scenario is to physically walk-through the construction site with a set of calibrated cameras that are able to capture the required information in a single pass. The path of photography would consist of the perimeter of rooms and around objects. Performing the walk-through at the end of a shift would eliminate the problem of moving objects and capture the most recent work completed. The effort required to photograph the site thus depends only on the time required to walk all perimeters. With post processing programmed to run sequentially through each step, the user would only be required to download the images and start the program.

Figure 4: Head Hall Exterior; a) Photoscan GoPro, b) Photoscan Canon 60D, c) 123D Catch GoPro

The effort required to build the hallway virtual walk-through was mostly photography based. A single Canon 60D camera was used with a Sigma 20 mm lens. The field of view was further restricted as the 60D does not have a full frame sensor. Accounting for this, the lens provides a field of view comparable to a 32 mm lens. Many trials were performed to fine tune and reduce errors in the model but if photography were to be completed in a single session all three components could be captured in approximately 15 minutes. After capture is complete, the user is required to download the images to the computer and start post processing. With the appropriate settings determined, the user is only required to start each processing step. Each step varies from minutes to hours.

Figure 5: First Person Walkthrough

6 ALTERNATIVE WALK-THROUGH METHODS

Other methods of creating a virtual walk-through have been identified as a result of this research. GoPro cameras are of great interest due to their portability and functionality in multi-camera panoramic heads. These panoramic heads incorporate six to eight GoPro cameras arranged to capture a full spherical panorama. Unlike traditional panoramic photography, the user is not required to rotate the head and can therefore capture a spherical panorama in the time it takes to capture a single image. This type of system could be programmed to capture panoramas at a specified rate as a user walks through the site. The end result would be similar to Google Earth Street View with the ability to choose your location on site. The
system could be expanded to capture spherical video instead of photographs, providing complete coverage of the site. These methods would require software development as there are no off the shelf solutions.

7 CONCLUSION

Construction sites contain vast amounts of information. Photographs capture this in great detail while allowing the user to absorb as much information as they need. The photographic recorded provided by VR Doc panoramas captures great detail yet excludes portions of the site which may become of interest. The use of a 3D model to create a virtual walk-through enables a comprehensive record and delivers the information in an intuitive manner. With further refinements, the virtual walk-through could become a key component to construction personnel. Future efforts would be well spent investigating photography workflows and automating post processing. Improvements in these areas would reduce the workload involved and make integrating the technology into live construction sites simpler. Methods of cleaning up the model are also an avenue worth exploring.

This paper investigates different image-based modeling methods to improve VR Doc applications. Pilot studies have been conducted to test different hardware (GoPro camera and Canon 60D) and software (Agisoft PhotoScan, Photomodeler, Autodesk 123D Catch, Visual SFM, and Unity 3D) available for creating a 3D walk-through model. The results show that although GoPro is a portable, light, and handy camera for the construction sites, it has significant distortions due to the wide angle lens. Although corrections are applied in Photoscan, better results were found if distortions were corrected in DxO before attempting to build the model. The built-in corrections were sufficient when using the Canon 60D with a Sigma 20 mm lens. Moreover, results show that the Unity walk-through software with its web delivery option fits well with the current delivery of VR Doc and could be easily integrated into the workflow. However, the current walk-through model contains distortions which would need to be refined in future studies before implementation in the construction industry.

References

MAINTAINING VERTICAL GARDENS USING QUADROTOR AERIAL INSPECTION

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\textsuperscript{2} Technical University Dresden, Germany
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Abstract: The upkeep of the building requires continuous monitoring to maintain the safety aspects as well as aesthetic elements of the building including facades, marble constructions and gardens. With the decrease of the amount of green areas, human race will face climatic catastrophes, which will affect the quality, type and life longitude of the Earth habitants. To tackle this issue, vertical gardens were designed to fit in the overwhelming world of concrete and to adapt in order to do photosynthesis. The growth of the plants is supported by spraying insecticide periodically. In this paper, we offer to use an unmanned aerial vehicle, to recognize the targeted green areas using HSV algorithm, track the generated trajectory and perform the spraying process all along the recognized area. We believe this will automate the maintenance of the gardens, improve the effectiveness of the treatment and assist to the ecologic factor, by applying the necessary amount of chemicals on the targeted place only.

1 INRODUCTION

Recently unmanned aerial vehicles are used to perform several civil tasks. Particularly, in construction fields, the idea of aerial robot is directly related to photogrammetry, site scanning and buildings status. In this regard, many literatures supported the cost efficiency, safety and quality control for such technological implementation (Bulgakov A. et al. 2014; Emelianov S. et al. 2014; Rango, et al. 2009. Chao, H et al. Shang et al. 2010)

Similarly, aerial robots can be used to scan vertical gardens and improve the irrigation system by controlling the quantity of water supplied to a certain site. This can be of great importance when talking about large agricultural areas, mega-polis with limited greenery and quantifying forest fire impact.

The technology being used to sense is based on satellite inspection. The limitation of such technology consists of the low resolution and the update ratio of the images provided. On the other hand, UAVs are more cost effective, can reach difficult scanning corners and provide more accurate visual information, as they can be equipped with high definition cameras. In this paper, we offer to use a vertical take off and landing aerial robot to perform visual inspection for vertical gardens.
2 RELATED WORKS

UAV’s successful results in improving military tasks have pushed the developers of such technology to try it in the civil market. The verdict: we got a miniature class of rotorcraft assisting in fire fighting, cinematography, television broadcasting and so on. The technology is being used to improve irrigation systems (Chao H, et al.), to address the climatic changes in the north and south poles (Lucieer A. et al. 2012), inspection of bridges and facades (Bulgakov A. et al. 2014; Emelianov S. et al. 2014).

As a sensing technology, band-reconfigurable fixed wing UAV were used more frequently. This is due to the optimized flight range, lifting capability and improvement in Micro (MEMS) and Nano electromechanical systems (NEMS). The sensors used are based on thermal infrared and machine vision. But these sensing technologies have limitations, especially the thermal infrared: the cost involved and the reliability of the acquired data especially in a humid atmosphere (Lucieer A. et al. 2012). The other limitation is the UAV itself: stability problem leads to false reading.

Having analyzed the pros and cons of aerial inspection, the optimization problem can be divided into two subtasks:

1. Coverage control problem consisting of path planning and control of the UAV;

2. Geo-reference problem consists of registration of each acquired pixel from the aerial images including temporal and spatial information (time and location).

Both of the subtasks can be addressed in either of two ways: global path planning consisting of trajectory planning before the flight and local planning that generates the trajectory during flight.

3 AIM OF THE PAPER

The aim of the paper is to address the aforementioned subtasks in order to inspect vertical gardens in the cities using quadrotors. As it is noticeable in most of the megapolises in the world, where green areas are lacking. The uncontrollable population growth is destroying the remaining of “mother nature”. Engineers and social workers have invented the concept of green wall or vertical gardens. The idea, as shown in figure 1, consists of planting wall climbing trees and plants on vertical walls. Due to the ergonomics involved the idea is widely spread.

![Figure 1: Vertical garden concept](image)

The role of the quadrotor is to acquire visual information such as images and pictures and spray the insecticide on the target area.

3.1 Coverage Control Problem

This subtask is divided into two points: path planning and control. Since, for the geo-reference problem, we will be using GPS data to acquire the temporal and spatial information, we will limit ourselves with the control part of it. As it is known, a quadrotor is a take off and landing rotorcraft, having six degrees of
freedom. But this miniature aircraft can perform only four flight regimes: roll, pitch, yaw and hover. This mechanical limitation makes the quadrotor nonlinear system. The dynamics of the quadrotor can be described as follows:

\[ x' = (\sin \psi \sin \phi + \cos \psi \sin \theta \cos \phi) \frac{u_1}{m}; \]

\[ y' = (-\cos \psi \sin \phi + \sin \psi \sin \theta \cos \phi) \frac{u_1}{m}; \]

\[ z' = -g + (\cos \theta \cos \phi) \frac{u_1}{m}; \]

\[ \dot{p} = \frac{i_{yx} - i_{zz}}{i_{xx}} q r - \frac{i_{rp}}{i_{xx}} q \dot{\Omega} + \frac{u_2}{i_{xx}}; \]

\[ \dot{q} = \frac{i_{zz} - i_{xx}}{i_{yy}} p r - \frac{i_{qp}}{i_{xx}} p \dot{\Omega} + \frac{u_3}{i_{yy}}; \]

\[ \dot{r} = \frac{i_{xx} - i_{yy}}{i_{zz}} pq + \frac{u_4}{i_{zz}}. \]

Where,  \( x, y, z \) are the projection of the linear acceleration of the quadrotor in the Earth fixed axis,  \( \dot{p}, \dot{q}, \dot{r} \) are projection rotational acceleration of the quadrotor in the body fixed axis,  \( g \) – the gravitational acceleration,  \( i_{rp} \),  \( i_{qp} \),  \( i_{qr} \) – the torque generated from the rotors,  \( m \) – the mass of the quadrotor,  \( i_{xx}, i_{yy}, i_{zz} \) are the projection of the Inertia of the quadrotor,  \( \dot{\Omega} \) – is the rotational speed of the propellers,  \( \phi, \theta, \psi \) are the roll, pitch and yaw angle consequently,  \( U_1, U_2, U_3 \) and  \( U_4 \) are the aforementioned flight regimes.

### 3.2 Fuzzy Logic Position Controllers

As it is important to know the value of the error, it is similarly critical to understand how it is changing over time. The error and its derivative in time are one of the possibilities to configure a Fuzzy logic controller. It is an artificial intelligence approach that computes mathematical operations based on degree of truth rather than the conventional True-False Boolean logic. The Fuzzy logic allows having more adaptable controller specially when dealing with nonlinearities (i.e. nonlinear aerodynamic model of the quadrotor as described in equations 1-6) and uncertainties (i.e. permanent changes in the flight circumstances, wind, temperature, obstacles positions etc.).

Although in many cases, heuristic algorithms were ruled out, due to the time consumption, we saw a need to include this algorithm in our survey to cover most of the techniques used. We would like to clarify that the term heuristic is used to describe the estimation ability in artificial intelligence. Moreover, the linguistic power of the fuzzy logic may be extremely useful while navigating in totally unknown areas. The trick in such controller is how to set up the linguistic rules for input and output.

We fine tuned the rules by using the resulting graph (figure 2) for the function  \( de(t) = f(e(t)) \), where  \( e(t) \) is the deviation in position of the quadrotor with reference to the desired trajectory and  \( de(t) \) is the variation of the deviation.

![Figure 2: Resulting Graph \( de(t) = f(e(t)) \)](image-url)
Using the graph in figure 2, we assign the following labels for the numeric values: Negative big (NB) = -1, Negative Small (NS) = -0.5, Zero (Z) = 0, Positive Small (PS) = 0.5 and Positive Big (PB) = 1. As a result, we obtain the linguistic rules listed in table (1). A linguistic rule defines the output of the fuzzy controller based on discrete logic (i.e. if $e(t) = \text{NB}$ and $d(e(t)) = \text{PB}$, then the output is $Z$). The graphical representation of the linguistic rules is illustrated in figure 3.

<table>
<thead>
<tr>
<th>de</th>
<th>NB</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
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<tbody>
<tr>
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Figure 3: Graphical Representation of the linguistic rules

The inputs of the fuzzy controller $de(t)$ and $e(t)$ are represented using triangular membership functions as shown in figure 4a and 4b. The output of the fuzzy control is also 5 triangular membership functions (figure 4c).

Figure 4a: membership function for input “e(t)”
The results of controlling the quadrotor using fuzzy logic regulators are shown in figure 5a and b for position and rotation control consequently.

Figure 5a: Quadrotor position control with reference to GPS waypoints. Horizontal axis – time [s], vertical axis- position [m]
The results shown in figure 5a and 5b give a fair idea about the reliability of the fuzzy controller. For instance, figure 5a illustrates the fact of stabilizing the linear movement of the quadrotor (described in equations 1-3, X (red curve), Y (blue curve), Z (green curve)) without overshooting. This allows the quadrotor to move along Earth-axis OXYZ smoothly. The other advantage of avoiding overshooting is contributing to better energy-efficient control systems (i.e. overshooting in altitude control means flying higher and consuming more power).

Taking into consideration the nonlinearity of the aerodynamic model of the quadrotor, linear movement cannot be achieved unless stabilizing Euler angles (roll (red curve), pitch (blue curve) and yaw angles (green curve)) as shown is figure 5b. Control signals are generated in order to increase or decrease Euler angles (equation 4-6) with reference to linear position control task (equations 1-3).

### 3.3 Geo-reference Identification Problem

Identification of the vertical garden can be done using the green pattern. Many machine vision algorithms are dedicated to recognize colors. We will be using the HSV algorithm due to its mathematical model, which is more reliable than the other methods. The HSV consists of giving a certain color 3 coordinates: Hue, saturation and value as shown in picture 4. HSV is used is many literatures in order to detect static and dynamic agents/objects based on histogram criteria, such as recognition of traffic lights (Yixin Chen et Al. 2013), gesture identification (Mokhtar M. Mohsen et al. 2010), image and structure retrieval (Durgesh N. et al. 2013) and face detection (Naresh Kumar R. et al. 2014, Sayfeddine D. 2013).
From figure 6, we can see clearly that the green color is varying between 60 and 180 degrees. Hence, the role of the algorithm is to identify the green patches on the wall and apply the insecticide on the recognized area. This can be done by dividing the frame of the camera mounted on the quadrotor into 9 identical cells. Hereafter the registered pixel coordinates will be modified to metric using the following equations:

\[ d(x) = H_k = H \cdot \tan(\psi + \alpha); \]
\[ d(y) = H_y = H \cdot \tan(\theta + \beta); \]
\[ x_n = \frac{X}{11} \cdot \cos\left(\arctan\left(\frac{H_y}{H_k}\right)\right); \]
\[ y_n = \frac{Y}{11} \cdot \sin\left(\arctan\left(\frac{H_y}{H_k}\right)\right); \]
\[ \rho_x = \sqrt{x_n^2 + y_n^2} \cdot \cos\left(\arctan\left(\frac{H_y}{H_k}\right)\right); \]
\[ \rho_y = \sqrt{x_n^2 + y_n^2} \cdot \sin\left(\arctan\left(\frac{H_y}{H_k}\right)\right). \]

Where, \(d(x)\) and \(d(y)\) — the projection of the altitude on the pixel coordinates, \(H\) — is the flying altitude, \(x_n\) and \(y_n\) are the horizontal and vertical pixel coordinates of the recognized area, \(\Pi_x\) and \(\Pi_y\) are the scale factors, \(\rho_x\) and \(\rho_y\) are the rotation of the quadrotor in the pixel axis, \(\alpha\) and \(\beta\) are the rotation of the diaphragm of the camera from the body axis.

After identification of the desired pixels based on color criteria, Cartesian subtraction is computed to identify the distance between the center of the fixed camera and the centroid of the detected colored surface. The subtraction result represents the distance that the quadrotor has to fly in pixels. The following approach is known as visual odometry. Depending on the position of the centroid, metric control task is generated for flight altitude stabilization (equation 7 and 8), linear movement (equations 9 and 10) and rotational movement (equation 11 and 12).

Using the concept of reactive control and based on the results obtained in equations (8,9 and 11,12), control signals are generated to initialize one of the four available flight regimes described in equations (3-6).

4 REAL-TIME RESULTS

HSV and visual odometry algorithms were tested in real-time in order to trace the possibility of their implementation on high-rise structures covered with vertical gardens. As figure 7 shows, the identification process was successful and the generation of the pixel coordinates was obtained.

Figure 7 can be interpreted as follows; the green surface is detected by algorithm HSV (i.e. position Middle-Middle in the 9-cells frame). The green pixels are generated (i.e. \(x_n = 69, y_n = 72\)). The Cartesian subtraction is obtained and metric control task is formed. The graph is figure 7 shows how the quadrotor changes its position (\(X\) (green curve), \(Y\) (purple curve)) with the changes of the pixel coordinates \(x_n\) (blue curve) and \(y_n\) (red curve).

A comparison between real time two dimensional flight results (figure 7) and simulation results (figures 5a/5b) shows that the deviation in sensors readings is as follows: roll reading (0.045°/s); yaw reading (0.125°/s); pitch reading (0.15°/s). The reasons of such deviations can be caused by the Euler angles MEMS gyroscopes, asymmetric structure of the quadrotor, influence of shifted center of gravity on the control systems, and propellers non-uniformity. The obtained deviation values lay in the tolerance interval and allowed Metrologic norms (deviation of real-time results ±5% from the simulation results).
5 CONCLUSIONS AND FUTURE WORK

The paper focused on how to use the quadrotor to maintain vertical gardens on high-rise structures. The adopted concept was to divide the autonomous flight problem into control of the quadrotor over an identified area using HSV algorithm. The control was performed using fuzzy logic position regulators based on reactive control concept interconnecting the rotation speed of the propellers with the positioning of the quadrotor. No overshooting was registered in the simulation results. Regarding the identification of the green area, HSV algorithm was used. The pixel coordinates were modified to metric in order to create flight mission. The identification and control algorithms were tested in real time using a commercial quadrotor (AR DRONE) linked to a stationary computer using datagram protocol UDP through a Wi-Fi connection.

Although the results were outstanding and the computational power was enough to drive the quadrotor to the end of the experience, we have noticed the influence of the light nature and temperature on identifying the green color. Having just the color as tracking criteria, the stationary computer could run into local minimum problem (between green and blue). This issue was addressed earlier as extrapolation of motion function. A solution was suggested based on nonlinear neural network model with exogenous input (NARX). The results can be accessed in the following literatures (Sayfeddine D. 2014, Sayfeddine D. et al. 2014).

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Chao, H. and al. Band reconfigurable multi-UAV based cooperative remote sensing for real time water management and disturbed irrigation control. 9 pages.


ADAPTIVE CONTROL OF BULLDOZER’S WORKFLOWS

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Abstract: The most important task for bulldozer’s traction mode control is to use its traction capacity in full by means of its end-effectors control. To keep traction mode at maximum or at a given resistance value applied to end-effectors automatically is difficult due to a great number of stochastic factors affecting the bulldozer. Bulldozer is taken as a mechatronic system [1, 2]. The study presents analytic dependences for the sub-processes where analytic modeling based on bulldozer’s parameters correlation knowledge is applicable. Models of the sub-processes are included into the general structure of bulldozer’s workflow simulation model. Simulation technique is demonstrated through model development of the bulldozer as a universal machine operating in modes of soil movement and subgrade surfacing. In developing the models mathematical apparatus of the theory of random processes, transfer functions, table interpolation, numerical solution of algebraic equations and ordinary differential equations in the Cauchy form was used. A dynamic model of the drawing prism formation was developed describing the dependence of the volume of prism on the variable digging depth and variable bulldozer speed. A general structure of the model of bulldozer’s workflows [3] due to the working process control objectives was developed.

1 INTRODUCTION

Bulldozers equipped with modern navigation and information systems are mobile mechatronic objects, and they can be integrated into general process of intellectual construction. The integration will provide optimal efficiency of the construction cycle and will ensure lean production process.

On the basis of bulldozer’s workflow dynamics modeling and analyses described in a variety of works, we have concluded that the models to describe kinematics and dynamics of its working equipment, hydraulic and transmission features tend to be analytical formulas derived from well-known laws of physics and from information on bulldozer’s structure and mechanisms. If some parameters of the workflow are unknown or constantly changing, the models are either statistical tables or empiric dependences summarizing experimental data. The models depict interaction of end-effectors, engines and environment as well as statistic features of bulldozer’s complex units.

Application of regulators based on classical control theory is difficult due to the frequent changes in workflow conditions. Thus, it is necessary to develop adapted control systems to eliminate the difficulties described. The system includes both the bulldozer’s dynamics modeling and bulldozer’s workflow control method to take into consideration the complex non-linear dependencies between workflow parameters and incomplete information on its working conditions changes.
Having reviewed adaptive and intellectual control methods [4, 5], we propose to create an adaptive control system for technological processes to increase efficiency of bulldozer’s control in comparison with traditional control methods.

2 MOBILE MECHATRONIC OBJECT - MATHEMATICAL DESCRIPTION TO PERFORM EXCAVATION WORKS ON THE BASIS OF A DOZER

When researching a dozer’s working process usually a number of design schemes are considered – straight line, thread milling, wedge and exponential cutting. Meanwhile, a dozer moves along the surface that is formed by its blade. Therefore, when driving onto any surface roughness resulting from the dozer blade control or the change in its position due to any reason, causes position changes of the machine frame and along with the cutting edge that is any face deviation from a straight line in some extent is copied by the dozer.

Observations [1] show that quite often while designing a face its roughness is progressing, reaching a size at which the control over the workflow is lost. In this case, the operator has to align the face deliberately, trying to ensure its “tranquil” profile that allows doing excavation works smoothly, without frequent control system switching and reducing the dozer’s operating speed that causes a slowdown and shows inferiorities of the blade control system. Obviously, if the control system operates in the antiphase towards deviations of the tractor frame with sufficient accuracy, the initial face roughness will not evolve and will be gradually cut. One of the most likely causes of the opposite phenomenon observed in practice, is the disparity between the velocity of the dozer \( V_p \) and actual conveying speed of the working body \( V_{ot} \) required in certain areas \( S_i \) of the digging operating cycle, where \( i \) - is the number of the speed change \( V_{ot} \). Speed ratio depends on the dozer’s geometrical dimensions (Figure 1) and its control system.

![Dozer’s geometrical dimensions](image)

Mathematical model of the dozer’s movement on a straight line tracking (frame alignment) is built using the Lagrange equations of the 2nd kind, under the assumption that the contribution to the dynamics of the drive gears and a track is small, compared with the contribution of the remaining parts of the dozer.

\[
\begin{align*}
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}} \right) - \frac{\partial T}{\partial x} &= Q_x \\
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\varphi}} \right) - \frac{\partial T}{\partial \varphi} &= Q_\varphi
\end{align*}
\]

where kinetic energy:
\[ T = \frac{1}{2} m_1 \dot{x}^2 + \frac{1}{2} m_2 (\dot{x}^2 + (l_2 c_2 \dot{\varphi})^2 + 2x l_2 c_2 \dot{\varphi} \sin(\varphi)) + \frac{1}{2} J c_2 \dot{\varphi}^2 + \frac{1}{2} \sigma h x (\dot{x}^2 + (l_2 \dot{\varphi})^2 + 2x l_2 \dot{\varphi} \sin(\varphi)) + \frac{1}{2} \sigma h x i_{c_2}^2 \dot{\varphi}^2 \]

Generalized forces acting on a dozer:

\[ Q_x = -\sigma h g l_2 \sin \varphi + F_t - F_{\text{comp}}; \]

\[ Q_\varphi = -(m_2 l_2 + \sigma x h) g l_2 \cos \varphi + M; \]

\( m_1 \) – tractor mass; \( m_2 \) – blade frame mass; \( \sigma \) – soil surface density; \( h \) – depth of the soil cutting; \( l_2 c_2 \) – center of the blade mass; \( i_{c_2} \) – gyration radius of the dumping soil.

\[ m_1 \ddot{x} + m_2 \ddot{x} + m_2 l_2 c_2 \ddot{\varphi} \sin \varphi + m_2 l_2 c_2 \dot{\varphi}^2 \cos \varphi + \sigma h \dot{x}^2 + \sigma h x h \dot{\varphi} \sin \varphi + \sigma h x l_2 \dot{\varphi} \sin \varphi +
\sigma h x l_2 \dot{\varphi}^2 \cos \varphi \right) - \frac{1}{2} \sigma h \dot{x}^2 - \frac{1}{2} \sigma h x i_{c_2}^2 \dot{\varphi}^2 \right) \right) = -\sigma h g l_2 \sin \varphi + F_t - F_{\text{comp}}; \]

\[ m_2 l_2 c_2 \ddot{\varphi} + m_2 x l_2 c_2 \cos \varphi \dot{\varphi} + l_2 \dot{\varphi} + \sigma h x l_2 \dot{\varphi} + \sigma h x l_2 \sin \varphi + \sigma h x l_2 \cos \varphi + \sigma h x l_2 \dot{\varphi} + \sigma h x i_{c_2} \dot{\varphi} - m_2 x l_2 c_2 \cos \varphi - \sigma h x l_2 \cos \varphi = -(m_2 c_2 + \sigma x h) g l_2 \cos \varphi - (m_2 c_2 + \sigma x h) g l_2 \cos \varphi + M; \]

The system (1) solution allows getting the differential equations (4) and (5) that describe the dozer’s movement on a straight line track, and determining control actions through the parameters of the machine in areas \( S_i \) of the digging operating cycle as the coefficients \( a_i \) in the dependence \( V_{ot} = a_i V_p \). Such a dependence is typical for dozers with a single-motor drive with a hard pump hydraulic drive connection to the motor shaft.

\[ S_1 \]

\[ +V_{ot} \]

\[ S_2 \]

\[ \text{Figure 2: The movement of the tractor frame the beginning of digging.} \]

At the beginning of digging (Figure 2), the frame of the tractor makes a strictly forward movement over a distance of \( S_1 + S_2 \) without hesitation relatively its mass center. The blade cutting edge in the area \( S_1 \) dives into the soil to a depth equal to a predetermined cutting thickness \( h \). Thus, the control action \( a_1 \) may be determined by the formula:
\[ a_1 = \frac{30i_{tr} m_2}{m_h F_{zp} C_0 n} \]

where \( i_{tr}, i_{pr} \) - tractor transmission and hydraulic pump ratios;
\( n \) - number of hydraulic cylinders;
\( m \) - fluid mass in the hydraulic cylinders;

In the area \( S_2 \) the movement is made with \( a_2 = 0 \) until the mass center of the tractor won’t move to the buttonhole edge.

On further movement the dozer "dives" in the drawn buttonhole (Figure 3), so in the area \( S_3 \) it is necessary to lift the blade at a rate of \( V_{ot} \), determined by the coefficient \( a_3 \):

\[ a_3 = \tan \beta \left[ e^{a_{1} V_{o_{t}}} \left( 1 + \frac{a_{C_1}}{C_1 + V_{o_{t}}} \right) - 1 \right] ; \]

The area \( S_3 \) ends after the dozer’s back gear hits the edge of the face and reverse alignment of tractor frame starts. Length of the alignment area is \( S_4 \approx S_1 \). Obviously, during this period it is necessary to start dropping the blade. The \( a_4 \) determines the rate of dropping the blade in the given area:

\[ a_4 = \frac{c_{3} S_1}{(c_4 + S_3 + V_{o_{t}})^2} ; \]

To implement control actions \( a_i = f(S_i, t, h) \) the dozer must be equipped with a vertical blade control system.

3  NEURAL NETWORK MODEL OF BULLDOZER WORKFLOW

The Autoregressive model structure with external inputs (Figure 4) is a dynamic two-layer recurrent neural network. It is found from the autocorrelation signal functions that the autocorrelation coefficient is greater than 0.8 in the time interval 0.1 sec. for speed \( v(t) \) of 0.5 sec. for digging depth \( h(t) \) and 0.2 sec for the resistance force \( P(t) \). Length of delay lines TDL taking into account the sampling frequency of 10 Hz are up to 1, 5 and 2 accordingly (Figure 4).
Vector for adaptive model adjustable parameters comprising weights and displacements of neural network,

\[ X = [b^1; b^2; IW^{1,1}; IW^{1,2}; LW^{1,2}; LW^{2,1}] \]

Criterion for neural network model optimal tuning, i.e. current learning error at a given moment of time we take as follows:

\[ F(X) = e(t) = P(t) - a^2(t) \to 0 \]

The network learning task is the task of multiple non-linear optimization

\[ X = \arg \min_X F \]

The author propose the bulldozer workflow neural network model adaptive learning algorithm based on the recurrent least square method (exponential forgetfulness method) and on the algorithm of Forward Perturbation or dynamic back propagation.

In the process of learning the neural network accumulates information on workflow dynamics, new tendencies of process development prevail on the earlier ones at that. Degree of importance for the previously learned information is considered with forgetfulness parameter \( \lambda \). Network optimal learning criterion gradient comprises frequent derived learning errors based on neural network model adjusted parameters:

\[ \nabla F = \frac{\partial F}{\partial X} = \left[ \frac{\partial F}{\partial b^1}, \frac{\partial F}{\partial b^2}, \frac{\partial F}{\partial IW^{1,1}}, \frac{\partial F}{\partial IW^{1,2}}, \frac{\partial F}{\partial LW^{1,2}}, \frac{\partial F}{\partial LW^{2,1}} \right] = -\nabla a^2 = -\frac{\partial a^2}{\partial X} = \left[ \frac{\partial a^2}{\partial b^1}, \frac{\partial a^2}{\partial b^2}, \frac{\partial a^2}{\partial IW^{1,1}}, \frac{\partial a^2}{\partial IW^{1,2}}, \frac{\partial a^2}{\partial LW^{1,2}}, \frac{\partial a^2}{\partial LW^{2,1}} \right] \]

Software algorithm of adaptive learning for neural network model of bulldozer workflow has been designed and implemented. The weight vector and bias network \( X(t) \) are adjusted in accordance with the recursive expressions at each time step:
\[ X(t) = X(t-\Delta t) - P(t-\Delta t) \times \nabla F(t) \times \epsilon(t), \]

Covariance matrix of the vector \( X(t) \) of neural network parameters used in the algorithm:

\[
P(t) = P(t-\Delta t) - \frac{P(t-\Delta t) \times \nabla F(t)}{\lambda}.
\]

4 ADAPTIVE CONTROL OF BULLDOZER’S WORKFLOWS

Applying a hybrid neural network consisting of a combination of traditional neural networks and neural networks of higher order (Figure 5.). Thus, the neural network has the ability to switch between linear connections and connections of high order that can be described by the following dependencies.

Linear coupling:

\[ y_i = \sum(w_{ij}x_i + b_j); \]

High order coupling:

\[ y_i = f \left( \prod x_i^{\beta_{ij}} \times 1^{\beta_{jj}} \right); \]

Activation function:

\[ f(x) = \frac{1}{1+e^{-ax}}; \]

where \( w_{ij} \) – coupling weight coefficients; \( y_i \) – output neuron signal; \( x_i \) – input neuron signal;

![Hybrid Neural Network Structure](image)

This implies that each layer depending on the operating mode, may change the type of connection between neurons. For example, for a neural network consisting of 3 layers, the following options are possible (linear - L, higher order - HO): L-L; L-HO; HO-L and HO-HO.

To optimize the created neural network is possible with the help of the genetic algorithm adaptation (Figure 6).
It is a method of random search with elements of adaptation, which is based on principles similar to the Darwin’s evolution process of biological organisms. In this case, three types of operations are performed: crossing, mutation, selection. The fitness degree (how the population corresponds to the given task) is defined through the fitness function that can also include penalty functions for violation of additional restrictions on variable variables. There are various forms of crossing [5]. They make a selection of the fittest specimen, which constitute a parental pair and the crisscrossing of the chromosomal chains takes place, i.e. the descendant line code inherits fragments of codes of parental chromosomes. The mutation operator produces a local change in the line code of chromosomes with a given probability, which is one of the configurable parameters of the genetic algorithm [5, 6].

The selection operator allows creating a new population from a set of specimen, generated and modified descendants of specimen after mutation. The genetic algorithm is used to adjust the membership functions that are defined within the accuracy of a few changeable parameters, such as triangular, trapezoidal, radial functions. When simultaneously configuring several membership functions, the parameters of each of them are coded by their own segment of the chromosome, so that during the process of crossing the code sharing occurs only between chromosome segments of the same type. To configure a rule base to a specific chromosome fragment, some variant of the rule base is corresponded and in accordance with the accepted coding the choice of the genetic operators’ type is performed. Thus, the architecture of the management and control system can be represented as follows (Figure 7).

To conduct researches on the basis of fuzzy modeling, quite versatile software have been developed [7] that greatly simplify the creation of new control systems using neural networks and fuzzy models. The use of different aspects of evolutionary modeling as a new direction of computing technology allows applying principles of learning for the management and control system and adaptation of the described hybrid neural network allows getting the following results.

![Diagram](attachment:image.png)

*Figure 6: Hybrid neural network optimization algorithm*
5 CONCLUSIONS AND RESULTS

Automatic control function of blade positions precisely adjusts the cutting edge. Depending on the content of correction signals, the regulating dual hydraulic valve automatically lifts or drops the cutting edge of the blade, constantly keeps it in position that ensures the accuracy of work and ensures an optimum level of productivity.

Identification technique of the dozer’s working processes and models obtained on its base, are intended to be used in the development of adaptive systems of automatic control of the dozer’s working process.

Methods of development of adaptive systems of control of the dozer’s working process, is based on neural network technology. For the formation of control actions on a dozer, and of the electrical switch signals of the hydraulic directional valves of the lifting and dropping hydraulic cylinders of the working body, in particular, the structure and functioning algorithms of the adaptive neural network controller have been designed.

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PHOTOBIOLOGICAL TREATMENT PLANTS INTEGRATED WITH BUILDING’S ARCHITECTURAL SHELL

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Abstract: The article deals with issues of the use of photoreactors with growing algae as an element of urban construction. Using microalgae photobioreactors can solve multiple tasks: getting a third-generation biofuels, carbon dioxide recycling, wastewater disinfection, oxygen regeneration, and water purification from nutrients. The paper considers a wastewater purification plant where the major element is such a photoreactor. As examples of such a kind of facilities, we could mention as follows: BIQ House, Hamburg International Building Exhibition; Urban Algae Canopy Module by ecologic Studio; photoreactors at the incineration plant, Alcéade Nantes, France; etc. Unlike the existing projects, we study all the system as a whole. Considered treatment facility includes an algae photobioreactor, a bacterium mineralizer and a desilter as well as a control system that regulates concentration of biogens, oxygen, and carbon dioxide by governing flow between devices. The article investigates the opportunity of incorporation of the photobiological treatment facilities into a building’s architectural shell. Structurally, we propose to make the main technological nodes from the translucent membrane of Ethylene Tetrafluoroethylene (ETFE). Photoreactors with algae are placed on the building facade. That location significantly reduces the required area and provides optimal natural lighting. It also allows using solar radiation for heating and adaptive lighting. The construction form is optimized with using a genetic algorithm. The engineering solution which is given in this article can be used for already existing treatment plants as well as for urban structure directly.

1 INTRODUCTION

The article deals with issues of the use of photoreactors with growing algae as an element of urban construction. Using photoreactors with algae in construction can solve multiple tasks: getting a third-generation biofuels, wastewater disinfection, oxygen regeneration, and water purification from nutrients. One more property that is important is that a photoreactor perfectly works as a natural filter absorbing flue gases and greenhouse gas. All these unique features of algae attract the attention of biologists, construction engineers, and architects. Examples of architecture projects with photoreactors, which have been presented at the exhibitions recently include: BIQ House, Hamburg International Building Exhibition [The Building Exhibition. Smart Material Houses, 2013]; Urban Algae Canopy Module by ecologic Studio [EcoLogicStudio, 2014]; the projet “SymBio2 photoreactors at the incineration plant [Des capteurs solaires biologiques élaborés au laboratoire GEnie des Procédés, 2014]; the project “ENERGY.2010.3.4-1: Bio-fuels from algae” [Co-financed by the EU Commission within the FP 7 programme, 2010].

In our previous publications [Buzalo, Bock, and Bulgakov, 2014], [Buzalo, Ermachenko, Bock, and et al., 2014] the concept of the local photobiological wastewater treatment plant was described. Unlike the
existing projects, we study all the system as a whole. Considered treatment facility includes an algae photobioreactor, a bacterium mineralizer and a desilter as well as a control system that regulates concentration of biogens, oxygen, and carbon dioxide by governing flow between devices. The example of a possible organisation of a technological scheme is shown in Figure 1.

Figure 1: Technological scheme of purification system, where (1) is the photobioreactor, (2) is the desilter, (3) is the methane tank, (4) is the boiler plant

The basic elements of the system are units with microalgae. The cultivation of microalgae under artificial illumination conditions is very energy-intensive. We focus on the use of natural light. The article investigates the opportunity of incorporation of the photobiological treatment facilities into a building’s architectural shell when, to save the useful area, the main elements, photobioreactors, are placed on a special carcass covering separately located facilities or directly on the facade of a residential building. In the context of our work we consider photobiological treatment facilities located within the city. Therefore, it is necessary to take into account shadows of surrounding buildings. The goal is to optimize the illuminance of a carcass with photobiological units to provide the best conditions for algae growth. That can be reached due to the variation of an architectural shell shape.

One if the disputable issues is the construction cost of a facade with algae photoreactors. For a long time this technology have been held back because of the price of one square meter of photobioreactors made of glass and steel exceeds the cost of solar panels. However, the use of modern membrane structures from Ethylene Tetrafluoroethylene (ETFE) can significantly reduce the cost of construction. This is the way, that we propose for a structural solution of main technological nodes.

2 OPTIMIZATION OF ARCHITECTURAL SHELL SHAPE

2.1 Statement of Problem

Algae cultivated in the water purification system of a treatment plant are considered as a source of biofuel. In addition to providing the necessary level of water purification, the second important goal of the system is to produce the maximum algae biomass.

Factors affecting the rate of growth of microalgae:

- The amount of available solar radiation;
- The amount of nutrients coming from organic waste;
- Availability of sources of carbon dioxide;
- Thermal characteristics of the medium.
In this article, we consider the influence of insolation on the algae growth. The optimization problem is to maximize the function of total amount of algae biomass cultivated for a year divided by the surface area of the shell:

\[ \text{max } F(\Omega), \]

where \( \Omega \) is the shape of an architectural shell.

The geometric shape of an architectural shell foundation is fixed. There are also constraints for the maximum and minimum height of the structure.

The maximizing functional in [1] is as follows:

\[ F(\Omega) = \frac{1}{d\Omega} \int_{\Omega} \mu \cdot \exp \left( -\frac{(I(x,y,z,\Omega,t) - c)^2}{2 \cdot \sigma^2} \right) d\Omega \, dt, \]

where \( \mu \) is the dissolution rate of oxygen; \( I(x,y,z,\Omega,t) \) is the level of illumination of a photobioreactor: the function of coordinates \( (x,y,z) \in \Omega \), time \( t \), and shape of an architectural shell \( \Omega \); \( c \) is the optimal insolation; \( \sigma \) is the tolerance interval. The period of integration is one year.

Despite the fact that the obvious goal is producing the maximum amount of biomass, normalization of the objective function by the surface area of the shell is necessary in order not to ‘overblow’ the shape extremely. We would also like to emphasize that the design corresponding to the maximum brightness of a surface is not the solution. Microalgae can use only 5% of solar radiation for photosynthesis and the majority of solar energy is spent to heating. The solution of the optimization problem is also necessary to avoid critical overheating, which is deadly to living organisms.

2.2 Optimization Algorithm

The algorithm takes into account the shadow cast by the surrounding buildings. That make it possible to integrate photobiological treatment plants in the urban environment efficiently.

For solution the shape optimization problem, the genetic algorithm of the plug-in Heliotrope of the software Rhino / Grasshopper is used [Grasshopper. Algorithmic Modeling for Rhino, 2015]. The program has a set of geometric tools for the insolation analysis. It includes the calculation of parametric components of solar vectors for a certain date, time and place.

The calculation algorithm:

1. Parametric description of the architectural shell in the software environment Rhino / Grasshopper;
2. Time discretization and discretization of the curved surface of an architectural shell by a finite number of planar polygons;
3. Calculation of average components of solar vectors for every time step and polygon with the plug-in Heliotrope by geographical coordinates, time, and date;
4. Projection of the shadow from surrounding buildings on polygons uniformly for every time step;
5. Setting proportions of direct and scattered light and calculation of the amount of solar radiation on polygons for time steps;
6. Calculation of average growth of microalgae biomass for every time step on each polygon;
7. Using a genetic algorithm for the search of architectural shell parameters corresponding the maximum of the objective function [2] that is being calculated numerically for each iteration in accordance with steps 1-6.

2.3 Model Problem

As an initial approximation for the optimization algorithm, we consider the architecture shell of treatment facilities of the surface area of 16119 m². Free area between the buildings is 150 m × 150 m. Height varies from 9 to 28 m.

The algorithm takes into account the shadows cast by the surrounding buildings. The computational domain is shown in the Figure 2. Green color corresponds to the minimum value of insolation, red color - the maximum value.

![Figure 2: Views of the architectural shell before the optimization](image)

Design is located at coordinates 51°02' N 13°44' E (coordinates of Dresden, Germany). Changing the position of the sun at its zenith is shown in the Figure 3.

![Figure 3: Changing the position of the sun at its zenith over the computational domain during the year](image)

Figure 4 presents the architectural shell before and after optimization. Views of the shell are shown with different angles. Calculation parameters: the proportion of scattered light is 40%, the density of the solar radiation is 1000 W/m², $\mu = 10$ g/m²h, $c = 650$ W/m², $\sigma = 95$ W/m².
The results of the optimization:

- Before optimization:
  - The surface area of $\Omega$ is $s(\Omega) = 16119.2 \text{ m}^2$;
  - The average daily specific growth of biomass per unit area $f = \frac{1}{365} F(\Omega) = 51.6 \frac{\text{g}}{\text{m}^2\text{day}}$;

- After optimization:
  - $s(\Omega) = 11061.2 \text{ m}^2$;
  - $f = 95 \frac{\text{g}}{\text{m}^2\text{day}}$.

3 PHOTOBIOLOGICAL MODULAR BUILDING BLOCKS MADE OF THE TRANSLUCENT MEMBRANE OF ETFE

Structurally, we propose to make the main technological nodes from the architectural translucent membrane of ETFE. The architectural membrane can sustain the temperature from $-80^\circ\text{C}$ until $155^\circ\text{C}$. The capsules are transparent, have heat-reflective properties, and inert to acid and alkaline mediums. They do not lose their chemical features during their term of service (approximately 25 years). Membrane are self-cleaned by the action of water flow due to the adhesive properties and a very smooth surface. This property is particularly valuable, taken into account biofouling of bioreactors. Figure 5 and 6 show an architectural shell of the installation for photoreactors with algae and photoreactor units.
The modular building blocks of the membrane translucent with integrated photobioreactor can be located into an architectural shell as an insulating walling. Sanitary zone around the facilities can be greatly reduced due to the recovery of carbon dioxide, shell hermeticity, and transparency of material. The design of an architectural shell generated by genetic optimization algorithm blends harmoniously with the natural landscape and has aesthetically pleasing appearance.

4 CONCLUSION

This paper discusses the problem of shape optimization of an architectural shell with photobioreactors. The parametric approach to the design of engineering structures is the most suitable for the creation of urban objects in accordance with the principles of biosphere compatibility. For example, to maximize the use of natural lighting. In this paper, the algorithm of integration of an architectural shell of photobiological treatment facilities in dense urban areas was considered. The algorithm takes into account shading from neighboring buildings and provides the maximization of the specific growth of microalgae biomass. In the future work, we plan to improve the proposed optimization algorithm in order to take into account the effect of the scattered and reflected light, as well as the spectral composition of the radiation, which influences on the efficiency of photosynthesis.

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EVALUATION OF ORGANISATIONAL CONTEXT AND REQUIREMENTS FOR LEVERAGING BUILDING INFORMATION MODELS TO SUPPORT HANDOVER AND OPERATIONS & MAINTENANCE

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Abstract: The handover of building information upon completion of a project is a critical and challenging step for owners. It is at this stage that the owner gets all the relevant information about the facility to support operations and maintenance (O&M) over its lifecycle. However, experience has shown that this step is often given little attention and that the information that is obtained is often erroneous, incomplete or unstructured. The increasing use of Building Information Modeling by architects, engineers and contractors and the resulting models that are created during the design and construction phases are now starting to be handed over to the owner as part of the as-built facility information. While BIM has the potential to consistently represent systems and equipment with the required information to support O&M, traditional design and construction models need to be significantly reworked to make them useful for O&M tasks. In order to achieve a digital BIM-based handover process we need to understand how a model-based process aligns with a given organizational structure. This paper presents the findings from a retrospective study of a large public owner and the handover process for a high performance institutional building. On this project, we analyzed the owner’s technical guidelines, interviewed numerous O&M personnel, analyzed the software and systems used and the associated information flows, and analyzed the building handover artifacts. In particular, this paper focuses on the analysis of the handover BIM for mechanical systems and its compliance with the owner’s technical guidelines and user requirements with the intent of characterizing the model structure and content required to support the owner’s O&M activities. This analysis identifies the extensive processing required to configure design and construction BIM’s to satisfy owner’s O&M needs. For example, geometric and non-geometric content needs to be added, the models need to be re-structured to define space-equipment-system definitions and relationships, and equipment names and system definitions need to be aligned with the technology infrastructure within the organisation. The findings suggest that in order to have a consistent and useful BIM for O&M at handover, the model structure and content should comply with the owner/user requirements and they need to be in alignment with the organisational and technological processes and infrastructures of the owner organisation.

1 INTRODUCTION

The handover of asset information upon completion of a project is a critical step for owners. It is at this stage that the owner gets all the relevant information about the facility which is essential for O&M personnel to operate and maintain equipment and systems in buildings efficiently and effectively, to extend the service life of equipment, to optimize maintenance activities, to achieve energy efficiency and
to minimize labour time and downtime. We found that the current handover and operations phases suffer from numerous challenges including poor information fidelity, poor interoperability and poor maintenance. Poor information fidelity leads to issues during the operations phase there are related with not having consistent, up-to-date, and reliable data. According to East and Nisbet (2010), 30% of the content of document-based O&M manuals contains some type of errors. Gallaher et al. (2004) concluded that inefficient interoperability cost the construction industry more than $15.8 billion in 2002. Two thirds of this cost was borne by the owner and operators. According to a survey done by the Netherlands Organisation for Applied Scientific Research, %85 of complaints on comfort and high energy consumption are caused by handover and maintenance problems. Many have looked into the promises of BIM for the handover and specific uses in O&M. BIM promises can be summarised as; reducing redundant data collection and data re-entry and improve decision making (NRC, 2012), enabling better information exchange between project phases (Wu and Issa, 2012), supporting O&M functions (Fallon and Palmer 2007, Foster 2011), and improving access to information during operations (Francisco Forns-Samso D. 2010). BIM promises new approaches to the handover and organisational problems related with O&M by enabling data integration, structured information exchange, automated population of databases, facilities management information management, support organisational processes, support decision making through visualisation, evaluation of the models for compliance with the organisational requirements.

The use of Building Information Modeling (BIM) by architects, engineers and contractors is increasing and the resulting models that are created during the design and construction phases are now being provided to owners as part of the handover sequence of as-built facility information. BIM is becoming a delivery requirement for an increasing number of owner operator institutional organisations for its potential to address many of the challenges related to project delivery and handover, and to support O&M of the facility throughout its lifecycle. However the use of information models in handover and O&M is relatively new and numerous issues and challenges remain. The reality is that implementing BIM in large owner organizations is a complex challenge. Each organisation is a complex structure of departments, processes, cultures, networks of systems and databases that are used to support processes and people from different backgrounds and with different information needs.

This paper describes the results of a long-term case study of a large owner-operator institutional organisation that demonstrates the many challenges owner organizations face when considering the adoption of a new technology like BIM. We investigated the organization to better understand how BIM might impact or disrupt this large owner organization, focusing on the structure, processes, culture, work force, supporting IT systems and networks. We also analyzed numerous design models to better understand how the models being delivered were aligned with the organizational needs. This paper will summarize the challenges of aligning a given building information model with the organisational and technological processes and infrastructures of the owner organisation.

2 RELATED RESEARCH

The proposed research analyses the organisational context of BIM through the lens of functional alignment as defined by Henderson and Venkatraman (1993). Internal functional integration between business and information technology is used to understand the characterisation of organisational alignment. The functional alignment definition is extended around handover and delivery of projects. We propose integration of artifacts and requirements into the functional alignment to be able to understand the alignment in the organisational context. The owner organisations need to adapt to changing market where information management and integration are becoming increasingly important, and BIM implementation is being seen as an enabler to reach this goal. In the absence of clear strategy and cultural differences required to compete in both current market and also in a market that is changing according to the developing technologies organisations may fail to harvest benefits (Tushman and O’Reilly, 1996). This implies that organisations should develop clear strategies and consider adjustments to their cultures to be able to harvest benefits from BIM adoption. This requires an understanding of how to manage the change in the strategy and culture according that is required by BIM implementation.

In organisations, people require different sets of O&M information to perform their tasks. However, currently information required by different users is not formalised. Without such formalisation of
requirements, it gets challenging to agree on the content and structure of an handover BIM. Liu et al. (1994), Clayton e al. (1998) and Becerik-Gerber et. al. (2012) listed the information needed for operations and maintenance as shown in Table 1. A model intended to be used for O&M ideally should represent all required data in an accurately computable way.

Table 1: Information needed for O&M from the literature

<table>
<thead>
<tr>
<th>Liu et.al. (1994)</th>
<th>Information related to O&amp;M</th>
<th>O&amp;M manuals, Equipment model/type, Equipment manufacturer, Equipment capacity, Warranty information, Condition of equipment/facility, Equipment location, Utility information, Maintenance records, Date installed, Responsible division/person, Cost of maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayton e al. (1998)</td>
<td>Key content for maintenance and operations planning</td>
<td>Equipment identification, Cut off locations, Distribution capacity, Design rationale</td>
</tr>
<tr>
<td></td>
<td>Key content for major renovations and construction</td>
<td>Wall locations, Door locations, Furniture layout, Light fixtures, Finishes, Mechanical systems, Electrical systems</td>
</tr>
<tr>
<td>Becerik-Gerber et. al. (2012)</td>
<td>ID and Name</td>
<td>Data Structure of non-geometric data requirements:</td>
</tr>
<tr>
<td></td>
<td>Service Zone</td>
<td>- Site, Building, Floor, Room, Zone</td>
</tr>
<tr>
<td></td>
<td>Group and Type</td>
<td>- Based on Industry Standards (Uniformat, Masterformat, or Omniclass), or Organization- Specific Categories</td>
</tr>
<tr>
<td></td>
<td>Manufacturer/Vendor Data</td>
<td>- Manufacturer, Model, Serial Number, Acquisition Date, Vendor, Warranty Expiration Date, Warranty Usage</td>
</tr>
<tr>
<td></td>
<td>Specifications and Attributes</td>
<td>- Specifications such as Type, Unit, Value, Lower and Upper Limits, and Description and Attributes such as Weight, Power, Energy Consumption, Spare Parts</td>
</tr>
<tr>
<td></td>
<td>Operation &amp; Maintenance Data</td>
<td>- Activity Status, Maintenance Status (e.g., Maintained, Not Maintained, Abandoned, Removed, Replaced), Maintenance History, Space Occupancy Data</td>
</tr>
</tbody>
</table>

Wani and Gandhi (1999) proposed a procedure based method developed for evaluation of maintainability index of mechanical systems. The study identified features which characterise or ease in maintenance of a system and named them as the “maintainability attributes” (Table 2). These attributes and their correlations are used to evaluate index. Wani and Ganhi identify maintainability as the design attribute of system which facilitates the performance of various maintenance activities. The particular maintenance activities are listed as inspection, repair, replacement and diagnosis (Wani and Gandhi, 1999). However the handover and O&M specific information and modeling requirements are still yet to be identified.
Table 2: Maintainability attributes for mechanical systems and maintainability design factors

<table>
<thead>
<tr>
<th>Maintainability Attributes (Wani and Gandhi, 1999)</th>
<th>Maintainability Design Factors (not all listed) (Dhillon, 2006)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Standardization</td>
</tr>
<tr>
<td></td>
<td>Modular design</td>
</tr>
<tr>
<td></td>
<td>Interchangeability</td>
</tr>
<tr>
<td></td>
<td>Ease of removal and replacement</td>
</tr>
<tr>
<td></td>
<td>Servicing equipment</td>
</tr>
<tr>
<td></td>
<td>Work environment</td>
</tr>
<tr>
<td></td>
<td>Required number of personnel</td>
</tr>
<tr>
<td>Personnel</td>
<td>Adjustments and calibrations</td>
</tr>
<tr>
<td></td>
<td>Weight</td>
</tr>
<tr>
<td></td>
<td>Installation</td>
</tr>
<tr>
<td>Logistic Support</td>
<td>Training requirements</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility</td>
<td></td>
</tr>
<tr>
<td>Disassembly/assembly</td>
<td></td>
</tr>
<tr>
<td>Standardization</td>
<td></td>
</tr>
<tr>
<td>Simplicity</td>
<td></td>
</tr>
<tr>
<td>Identification</td>
<td></td>
</tr>
<tr>
<td>Diagnosability</td>
<td></td>
</tr>
<tr>
<td>Modularization</td>
<td></td>
</tr>
<tr>
<td>Personnel including ergonomics</td>
<td></td>
</tr>
<tr>
<td>System environment</td>
<td></td>
</tr>
<tr>
<td>Tools and test equipment</td>
<td></td>
</tr>
<tr>
<td>Documentation</td>
<td></td>
</tr>
</tbody>
</table>

3 METHODOLOGY

The research is based upon a long term analysis of an owner-operator organisation and its handover and O&M processes, requirements and artifacts. The organization studied was the University of British Columbia (UBC) as the owner organisation, and the specific building studied was the Center for Interactive research for Sustainability (CIRS). Different approaches were used for data collection during this research which are summarised in Figure 1.

Figure 1: Different methods used in the research to analyse organisation, requirements and model.

We conducted interviews with the Building Operations department personnel in UBC were used to understand information requirements, available tools and processes, areas of improvement and areas
that would benefit from BIM implementation. A number of processes within UBC Building Operations were mapped to better understand people involved, information required, tools used, effort involved to complete these processes. The processes that were mapped so far are; service call management and leading steps in the field by O&M personnel, gathering data from the field for asset database for existing buildings, and getting the received records documents ready for the users. Mapping the process of gathering equipment and system data from the field helped understanding the complexity of the information collection and data entry during the operations phase. Process mapping also helped identifying the bottlenecks and inefficiencies, and also helped evaluating potential areas for BIM adoption to eliminate bottlenecks or improve the overall performance. Walkthrough of the CIRS building with the maintenance personnel was used understand the requirements of O&M personnel to perform maintenance efficiently, compared to the handed over building characteristics that hindered the performance. Walkthrough information was also used to evaluate the maintainability of CIRS mechanical systems and equipment. Shadowing of maintenance personnel was used to understand how a work request is received, what steps are taken afterwards, what kind of information is required to do the job, types of building mechanical room or equipment design characteristics that affect the performance of maintenance activities, problems with the current maintenance practices and information that is available to the O&M personnel.

Handover artifacts, owner’s Technical Guidelines and interview findings were analysed to identify requirements. The handover documents were investigated specifically to understand the characteristics of the information set for metrics like usability, reliability, consistency, accessibility. Combined with the interviews, this approach enabled evaluation of the fit between user requirements and handover artifacts and available technology that was used to manage, store, and access this information. The investigation of the Technical Guidelines documents helped understand requirements of the owner which led to a better understanding of the gap between what was required and what was delivered at the end of the construction. This also helped understanding the reasons behind the gap like owner accepting whatever delivered as part of the handover, owner not having the tools or resources to evaluate handover information for metrics like accuracy and reusability. The technology structure within the organisation was mapped to better understand the silos of organisational information, complexity of the network of tools and databases used for managing information.

The design model analysis was used to evaluate the model’s fit for handover and O&M use. Model analysis was performed on the CIRS project’s final version of the model that was developed during design. The project’s handover documents were investigated to understand the characteristics of the information set for metrics like usability, reliability, consistency, accessibility. Combined with the interviews, this approach enabled evaluation of the fit between user requirements and handover artifacts and available technology that was used to manage, store, and access this information. In order to understand the complexity of the model content analysis process and the output quality, different methods of model content evaluation were used, including Revit schedules, COBie outputs (using Revit COBie Toolkit), lifecycle information management tool (Ecodomus), Navisworks visualisations and Solibri Model Checker. The goal of the model analyses was to understand the model contents, contents’ fit with O&M requirements and required model structure to create and exchange information.

4 ANALYSIS OF BIM AND ORGANIZATIONAL ALIGNMENT

In the context of university campuses, there is an interest in integrated approaches for FM information management and leveraging BIM for handover and O&M. Implementation of BIM necessitates a need for developing a better understanding of the organisational context, characteristics and forces within an organisation that have an influence on the BIM adoption. BIM is a disruptive technology, which changes the way organisations are structured and the way they work.

It is important to understand where the information for O&M comes from, internally and externally to an organisation and how information flows down to users. All owners have unique requirements which affect how alignment can be assessed. Building information is handed to the owner after construction and this information flows within an organisation through complex networks of IT systems, databases, and departments and is finally accessed by the user (Figure 2).
Figure 2: Complex structure of organisation and technologies used to manage and support FM
Our analysis of the organisation indicated a number of issues in the current handover and O&M practices like fragmented organisational structure. Within the observed organisation two separate groups within the organisation are responsible for projects before and after the handover. One group is responsible for the project from start to handover, and their main goal is to deliver the building on time, on budget and with quality. The operators of the buildings take over the buildings at handover but have limited influence on the previous phases. Problematic commissioning practice, not having the input of the operations personnel’s during design and construction leads to issues during operations phase. There are no processes (and requirements) defined to gather required information from the project participants to populate FM databases for O&M. Maintenance history information has been kept in the personnel memory and person-to-person communication has been the method to transfer maintenance history information. The organisation has a complex IT structure that supports the performance of FM tasks performed by departments. Non-integrated FM information leads to duplication of effort to manage, create, maintain, and update information. It also leads to information inconsistencies between different databases, and inefficiencies in tracking and monitoring maintenance activities. There is currently no process for automated population of FM databases with required information for the new buildings.

The analysis of the CIRS building and the projects handover artifacts resulted in a number of compliance issues related with the quality, reusability, accuracy, timeliness, accessibility of the handover information. O&M personnel require information (Table 3) to be in different levels of detail, in a reusable format, and information visualisation depending on the O&M function. The interview data shows that while the head of mechanical maintenance project requires equipment information like performance data, manufacturer, and inventory information, a millwright is interested in system layouts within a building or equipment accessibility, information such as what equipment do, which system it belongs to or which areas it serves.

Table 3: Information required by different personnel to perform O&M functions (from conducted interviews)

<table>
<thead>
<tr>
<th>System Attributes</th>
<th>Component Attributes</th>
<th>Maintenance Information</th>
<th>Records Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance Personnel</td>
<td>System visualization System performance (commissioning information)</td>
<td>Component performance, Replacement part, Vendor information, Serial number, Location, Cost to replace/ maintain etc.</td>
<td>Electrical panel location, Shut off valve location, Start-up/ shut down information (sequence of operation), Maintenance history</td>
</tr>
<tr>
<td>BMS</td>
<td>Accurate system visualization System performance (commissioning information)</td>
<td>Location, Performance,</td>
<td>Commissioning, and records information</td>
</tr>
<tr>
<td>Asset Mgmt</td>
<td>System (availability) Equipment lists, System it belongs to Cost information (to replace and/or to maintain)</td>
<td>Maintenance history</td>
<td></td>
</tr>
</tbody>
</table>

Technical Guidelines contain owner design requirements for systems that the building design should comply with, however there are issues related to compliance of handed over artifacts and the building to the equipment design criteria such as installation requirements, equipment accessibility and clearance requirements for accessibility (Table 4).
<table>
<thead>
<tr>
<th>Owner/User Requirements</th>
<th>Delivered to Owner</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Guidelines-Plumbing-General Requirements:</td>
<td>The CIRS mechanical room is one of the most cramped and problematic mechanical rooms on the campus.</td>
<td>Pumps are installed on the ceiling and buried under a maze of pipes making it difficult to access for maintenance.</td>
</tr>
<tr>
<td>Confirm that all plumbing equipment requiring frequent maintenance is readily accessible.</td>
<td></td>
<td>Crews will need to remove other components, use equipment (like ladders and lifts) to remove the pumps that are installed at the ceiling height.</td>
</tr>
<tr>
<td>Do not locate at ceiling height, in walls, requiring scaffolds, ladders, removal of other equipment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owner requires the timely delivery of the handover information.</td>
<td>It is important for the building operators to have available information about the building to perform O&amp;M functions.</td>
<td>However handover set may not have all the required information at the time of handover.</td>
</tr>
<tr>
<td>Owner requires the delivery of handover set at the end of the construction, however quality and reusability of the deliverables is depended on the project participants.</td>
<td>There are information inconsistencies within the handed over information set.</td>
<td>Much of the handover information is not searchable, scanned images that limit usability.</td>
</tr>
</tbody>
</table>

Model analysis was done using the perspectives of content and structure to understand the gap between design and construction BIMs and a BIM for FM, and to identify issues with current design and construction BIMs. The goal of the model analyses was to understand the fit of the model contents with O&M requirements and the required model structure to create and exchange information. Analysis of the CIRS design model resulted in identification of missing geometry, missing information related with component and systems, LOD issues and modeling problems. We indicated model content and structure related issues that have to be addressed in order to bring these models to a required FM BIM level (Table 5). Content problems consist of completeness and availability of geometric and non-geometric information within a model. The model content needs to comply with the requirements of the owner and users for specific BIM uses, and the structure is supposed to enable exchange of the right model information in a format and structure that is meaningful to the owner. Analyses also indicate that each method required model manipulation to get required information output. Besides the missing content and structure, required model manipulation necessitates a level of expertise in using the modeling software that most owners lack. Analyses indicated that the models were lacking structure that was required for exchange of O&M information, organisation of model components in a way that is aligned with users’ requirements and models were also lacking both geometric and non-geometric information. The examples are intended to illustrate the gap between a handover BIM and design/construction BIMs.
Table 5: Examples of identified content and structure problems with the design BIM

<table>
<thead>
<tr>
<th>Problem Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracked information about the mechanical equipment is not available in the design</td>
</tr>
<tr>
<td>model.</td>
</tr>
<tr>
<td>Analysis of the model content by using a life-cycle information management tool</td>
</tr>
<tr>
<td>indicated that most of the information required by the owner for the handover was</td>
</tr>
<tr>
<td>not available in the model.</td>
</tr>
<tr>
<td>Modeling errors like missing system components; (1) model component representing the</td>
</tr>
<tr>
<td>air intake is not represented as one complete piece, (2) duct is not attached to</td>
</tr>
<tr>
<td>the AHU.</td>
</tr>
<tr>
<td>(3) LOD is not at a level to represent required AHU components tracked by the owner.</td>
</tr>
<tr>
<td>Single components are defined as systems in the model. “Mechanical Exhaust Air 3”</td>
</tr>
<tr>
<td>is a single exhaust grill that is defined as a system.</td>
</tr>
<tr>
<td>Space information is not assigned to all mechanical equipment.</td>
</tr>
<tr>
<td>System and equipment nomenclature do not indicate anything significant to the</td>
</tr>
<tr>
<td>model reviewer.</td>
</tr>
<tr>
<td>Information tracked by the owner on AHU components is not available in the model.</td>
</tr>
<tr>
<td>AHU is modeled as a shell and does not represent any of the AHU components inside</td>
</tr>
<tr>
<td>the unit.</td>
</tr>
<tr>
<td>Component naming used in the model is not aligned with the nomenclature used in</td>
</tr>
<tr>
<td>owner’s asset database.</td>
</tr>
<tr>
<td>Modeling errors like openings left in the walls lead to miscomputation of room</td>
</tr>
<tr>
<td>areas, and room boundaries. This leads to errors when assigning equipment to spaces.</td>
</tr>
<tr>
<td>Modeling errors like duplications of created spaces or overlapping spaces impact the</td>
</tr>
<tr>
<td>quality and usability of the model output.</td>
</tr>
</tbody>
</table>
Problems like overlapping space defining model components lead to issues when assigning equipment to spaces. Solving this issue gets complicated if the building design has hard to define spaces like spaces that extend multiple floors or mezzanines.

5 CONCLUSION
The handover of BIM for operations and maintenance is a complex challenge for owners. Our detailed analysis of an organisation and a specific design model indicates the extensive processing required to configure the design BIM to satisfy O&M requirements. Within the model geometric and non-geometric content needs to be added and the models need to be re-structured to enable transfer of model information in an accurate and reusable way. Spaces and room boundaries in the model should be accurate, space-equipment-system relationships need to be defined. Equipment names and system definitions need to be aligned with the organisational technology infrastructure to enable information exchange. There are also organisational issues of alignment and compliance that need to be addressed. In order to support the transition to BIM, organizations need to reshape the way they manage their facility information both before and after the building handover. There is also a need to reshape the way owner organizations function so that they are better aligned with a model-based workflow.

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CHARACTERIZING BOTTLENECKS IN BUILDING DESIGN COORDINATION MEETINGS

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Abstract: We conducted an ethnographic study of design coordination meetings to better understand the challenges faced by project teams as they coordinate designs in multi-disciplinary meeting environments. This ethnographic study involved observation and analysis of twenty-seven design coordination meetings from the design development phase of a high performance institutional research building. Design coordination and conflict detection are two of the most common and highly valued uses of Building Information Modeling (BIM). However, in our observations of these meetings, we found that BIM tools were extremely under-utilized. This research identified and characterized the bottlenecks encountered during these in-person design coordination meetings. We observed meeting bottlenecks when meeting activities were performed inefficiently, when the meeting process was slowed down, when meeting workflow was interrupted, or when decision-making was hindered. We identified and characterized meeting bottlenecks in a framework that illustrates the nature of each bottleneck and the frequency of its occurrence. According to our observations, we identified five types of bottlenecks that hindered the efficiency of design coordination meetings: people, meeting environment, drawings, interaction/access and information. We anticipate that these findings will help to inform the development of better meeting processes, the design of new interaction, visualization, and integration technologies that better support the meeting processes of design teams.

1. INTRODUCTION

During the design phases of a project, design teams meet regularly to control and monitor the design process, to share design information, and to coordinate the various disciplines’ designs. The system designs are iteratively updated to accommodate each discipline’s requirements. Successful management of this design process is critical to the efficient delivery of cost-effective and quality projects (Chua et al. 2003). Coordination among stakeholders is critical to ensure that a design meets the functional, aesthetic, and economic requirements of the owner. Timely delivery of a coordinated design and a less problematic and on time construction process also depends on the effectiveness of the coordination meetings. However, Liston et al. (2007) found that teams spent only 20% percent of time on “coordination” activities. The remainder of the meeting time was spent for “direct discussion of design” (50%), “taking stock”, “digression and other” project activities. Although digital technology has become integral to the design process, design coordination is often still accomplished using paper printouts of 2D schematic diagrams and other related project information. However, there are limitations of paper for coordination. Design coordination is challenging and needs to be understood so it can be better managed.
This paper presents the results of a long-term ethnographic field study that investigated the challenges faced by project teams as they coordinate designs in multi-disciplinary meeting environments. This study involved observation and analysis of twenty-seven design coordination meetings from the design development phase of a high performance institutional research building over 16 months. We identified and characterized meeting bottlenecks in a framework that illustrates the nature of the bottleneck and the frequency of its occurrence. We observed meeting bottlenecks when meeting activities were performed inefficiently, when the meeting process was slowed down, when meeting workflow was interrupted, or when decision-making was hindered. According to our observations, we identified five types of bottlenecks that hindered the efficiency of design coordination meetings: people, meeting environment, drawings, interaction/access, and information.

2. LITERATURE REVIEW

This section summarizes relevant literature on group work, coordination meeting challenges, and group decision making. Group decision making is a complex process in construction given the fragmented nature of the construction industry, the barriers set up by traditional contractual relationships, and the conflicted roles and responsibilities of project teams (Issa et al., 2006). In Grønbæk et al. (1993), the bottlenecks in daily work and collaboration were divided into three subsections: bottlenecks related with sharing materials, coordination and communication. Liston et al. (2001) looked at challenges in visualization, sharing, exchange and interaction with the electronic information in multi-disciplinary project team meetings. Their main focus was on interactive information workspaces. When compared to this study; rather than documenting overall meeting bottlenecks, the paper proposed an approach for dealing with a number of specific bottlenecks. Tory et al. (2008) described meeting bottlenecks related to navigating digital information, individual information lookup, and accessibility of information. However, this work was focused on low level interactions with artifacts rather than high level meeting processes. These different efforts provided important points of departure in terms of understanding the different types of bottlenecks that we were observing in building design coordination meetings.

An important consideration in design coordination is that project teams must contend with numerous and diverse types of information. The participants use a variety of visual representations of project data in different formats (paper and digital documents, physical models, sketches etc.), to convey information within the group. Participants share, view, coordinate, and manage design information during coordination meetings. Several research efforts focused on activities performed by meeting participants in workspaces. In their study of small group design meetings, Olson et al. (1992) categorized meeting activities as issue, alternative, criterion, project management, meeting management, summary, clarification, digression, goal, walkthrough and other activities. In a subsequent study, Liston et al. (2001) built on this categorization of meeting activities and classified meeting activities as descriptive, explanatory, evaluative, and predictive.

Luck (2007) investigated artifact use in design and described how artifacts are used to mediate understanding in design conversations between people with different levels of understanding of design schemes. Luck concluded “it was only through the use of these artefacts and conversation about these artefacts that the users’ understanding of the design became explicit”. Meeting discussions mostly evolve around different forms of information artifacts. Participants interact with information in numerous ways, including pointing, mark-up, changing (Liston et al. 2007), and perform physical interactions, such as gestures, annotation, and navigation (Tory et al. 2008). Tory et al. (2008) described how a building design team used design artifacts during design coordination meetings as part of an effort to identify effective input methods for a digital system. They presented possible directions for future Computer Supported Collaborative Work (CSCW) technologies based on observations, like simplifying and enhancing navigation, design mechanism for digital bookmarking, enriching pointing techniques, augment pen functionality and supporting information access by both groups and individuals. Researchers have also recognized that group dynamics play an important role in collaborative work and may have a significant impact on meeting performance (e.g., Nunamaker et al. (1991) and Garcia et al. (2004).

This research builds on previous efforts mentioned in this section by developing a taxonomy of bottlenecks that captures the social, contextual and technical aspects of design coordination.
3. METHODOLOGY

This research is based on a sixteen month field study of design development and coordination meetings for the Centre for Interactive Research and Sustainability (CIRS) project (Figure 1). CIRS is a 58,000 square foot research facility that aspires to be the most innovative and high performance building in North America. The CIRS design coordination meetings were held weekly in the architects’ office and typically included structural, electrical and mechanical consultants, the owner’s representative, and construction manager’s representatives.

Figure 1: Left; 3D renderings of the Centre for Interactive research on Sustainability (courtesy of Busby Perkins + Will), Right; typical setting of the meeting environment.

We conducted an ethnographic field study involving the observation of design coordination meetings, and analyzed our results using a grounded theory (Phelps et al., 2010) approach. The work practices of project teams were observed in the field and qualitative observational data about meeting processes was systematically collected in the form of observer notes, video footage and a few targeted interviews with participants. Instead of observing many meetings from different phases of projects, observations on pre-construction design coordination meetings were chosen. Over a sixteen month period, twenty-seven consultants’ coordination meetings were attended in the architects’ office. Each meeting took between one and two hours. During the observational study, researchers looked for inefficient meeting practices: situations where the meeting workflow was interrupted or situations where the observers thought that the meeting tasks could have been performed more easily or more efficiently. Team members’ interactions with information artifacts were observed in order to better understand the use of these artifacts during meetings and their role in contributing to or mitigating bottlenecks. The interactions between meeting participants and their effect on the overall meeting process were considered. Detailed notes were collected during each meeting, including the names of attendees, discussion topics, bottlenecks observed, and observations related to the decision making process. A document was prepared for each meeting using observer notes, notes on available artifacts, artifact use, observations about execution of meeting tasks, and interactions between meeting participants as much detail as possible. The meeting agenda and meeting minutes (if available) were added to this information set. Instances of observed live interactions were noted with actual time and descriptive notes by the observer and later a snapshot of the corresponding recorded video frame was added in order to reflect the context during the meeting. Additional instances were observed from viewing of the videos. This way, informative and descriptive vignettes were created from each meeting. The vignettes included textual information and provide contextual clues for the reader about the specific bottleneck. Formal and informal interviews were conducted with the meeting participants in order to crosscheck our intuition about the causes of the observed bottlenecks. The analysis and coding of project meetings were performed according to conventions of grounded theory as defined in Phelps et al. (2010). Open coding, axial coding and selective coding were used sequentially to develop the proposed taxonomy of meeting bottlenecks. An open coding process was performed on the data set created from the meeting documents. This process resulted in a list of observed bottlenecks. Among the list of all observed bottlenecks single events were eliminated. During axial coding, similar bottlenecks were grouped, resulting in a set of bottleneck categories. After the selective coding, the taxonomy of design coordination bottlenecks was structured.
4. CASE STUDY RESULTS

The proposed taxonomy of design coordination bottlenecks in building design coordination meetings that we developed using the findings from the CIRS case study is represented in Table 1. The case study is representative of typical projects in the industry.

<table>
<thead>
<tr>
<th>People</th>
<th>Meeting Environment</th>
<th>Drawings</th>
<th>Interaction / Access</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group Composition</td>
<td>Access to Design Information</td>
<td>Content</td>
<td>Visibility</td>
<td>Exchange</td>
</tr>
<tr>
<td>Group Dynamics</td>
<td>Meeting Management</td>
<td>Symbols</td>
<td>Annotation</td>
<td>Interdependencies</td>
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<td>Availability</td>
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<td>Visualisation</td>
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Figure 2 shows the breakdown of the 294 identified meeting bottleneck instances from data collected during the 27 co-located paper-based meetings. The largest number of bottlenecks observed in the analysis was of interaction/access group of bottlenecks, followed by information, drawing, people and meeting environment groups of bottlenecks. When we look at the distribution of the bottlenecks in more detail, we see that visibility bottlenecks are the most observed meeting bottlenecks followed by remote pointing, content and information exchange bottlenecks. Parts of the taxonomy will be explained in detail in the following sections.

Figure 2: Distribution of observed meeting bottlenecks according to meeting bottlenecks categorisation.

4.1 People

4.1.1 Group Composition: The composition of a design team may change multiple times as the team players sometimes change throughout the project phases (Liston et al. 2001). When a team member changes, the knowledge about the evolution of the design may not be completely transferred to the successor. This creates breakdowns in the information flow between team members, and leads to iterations of coordination tasks like descriptive, explanatory tasks. Throughout the CIRS design phases, team members like the project architect, mechanical consultant and owner’s representative changed positions with people from the same organizations. The example below shows a captured conversation between the project architect and the new mechanical consultant who replaced a consultant from the same engineering firm. The new member of the team is not aware of and was not briefed about a previous discussion by his predecessor.

Architect asks for an update about a part of the mechanical system that was discussed previously. Mechanical consultant apologizes for not having that information. Architect says “it’s okay, you joined the team later during the design process, and we discussed this before you joined the team”
4.1.2 Group Dynamics: Meeting participants are often from various professional backgrounds, with different levels of experience, characteristics, responsibilities and authority. Sometimes a participant’s approach to a coordination issue may be influenced by responsibility to his/her firm or a specific goal related to the individual’s position in the project. This section covers bottlenecks that occur because of the clash between individual goals of meeting participants and the lack of a collaborative agreement on the project goals. The example below shows that team members have different concerns and goals about design process and the use of Building Information Modeling (BIM) and how individuals prioritize project goals differently.

Architect mentions resynchronization of drawings for digital coordination. Owner's representative wants to know why they need the project models and expresses concerns about starting with Revit. Owner's representative: "Should we coordinate at own offices? It is going to be a big loss of time if everybody … What will we be looking at on the model during the meeting?" [Architect's concern is implementing a coordination process through model use. But the owner representative’s main concern is speeding up the overall process and not spending time on trying to figure out requirements of this new process.]

4.1.3 Availability: This section covers bottlenecks related to not having the right group of people available in coordination meetings to make informed decisions. Sometimes people with the required information or knowledge are simply not present in the meetings to provide the necessary input on a discussion topic. There were two common reasons for this bottleneck type: (1) a team member who is a part of the regular meeting group was not available in a meeting, and (2) a person with the required knowledge and authority on a discussed topic is not included in the meeting. Availability bottlenecks caused delays in decision making or delays in getting required information. In the example below, the Construction Manager’s (CM) representative is not present during the meeting to clarify a concern about the sequencing of construction. The discussion ends without a clear answer to the consultants’ concerns.

The building is going to be built in phases and the participants are not sure when the auditorium is planned to be built by the general contractor. Mechanical consultant has a concern that the ground source cooling system construction (proposed to be located underneath the auditorium space) would lengthen the construction time but architect doesn’t think so, because he believes that the auditorium will be built last.

4.2 Meeting Environment

4.2.1 Access to Design Information: This section covers bottlenecks involving access to the large amount of project information that the design teams use during design and coordination meetings. Teams may need to access this information during any meeting, at any moment. Most of the time, it is difficult to know in advance which information will be needed. The observed design team used an online design and data management software (Autodesk Buzzsaw), but the technology was not used during the coordination meetings.

Structural engineer is giving an update on glulam frame details. The consultant did not bring any detail drawings with him to the coordination meeting. The drawings are at the consultant’s office. Architect goes to the white board and sketches the detail on the board.

4.2.2 Meeting Management: This section covers bottlenecks related to handling of the meeting process, including the facilitator’s preferred meeting management style, emphasis on the agenda and minutes, inefficient use of meeting time as a result of digression from the main topics, and forming the agenda from issues that do not interest most people in the group. Garcia et al.’s (2004) study on how to manage meeting agendas indicates that often a substantial number of agenda items concern only a few people in the meeting group. We observed that meeting productivity was impaired in the absence of an experienced facilitator or a well prepared meeting agenda. During one of the observed meetings the senior project architect, who was the regular meeting facilitator, was not present in the meeting. During this meeting, the discussion often shifted from the main focus of coordination and participants spent more time on details that did not necessarily concern all participants.
4.3 Drawings

4.3.1 Content: This section covers bottlenecks related to the content of drawings used during design coordination. The content of a design drawing is limited based on its intended use and a consultant’s drawing focuses only on information about a particular system’s design. During evaluation of the design from different perspectives, participants end up using multiple drawings and/or artifacts in order to effectively communicate design information with others. When participants need to use multiple representations to compare data from multiple drawings, they need to go through sets of printed documents in order to find the relevant information, and reconcile information from multiple related documents, which requires time.

The architect uses the physical model and the artist’s rendering at the same time because rendering has the ability to represent the visual effect of the materials used on the façade. It is not possible to see these effects on the physical model. Meanwhile participants can observe more than one facade at once on the physical model and compare facade characteristics to one another. They then will refer to plan drawings to get an understanding of the space use.

4.3.2 Symbols: This section covers bottlenecks involving a failure to correctly understand or interpret representations on a consultant’s drawing. Design drawings represent the consultants’ design intent—they contain domain specific language and information. The representation of information on drawings may even differ from one design phase to another in the same domain. The following is an example for a bottleneck caused by the architect’s representation of windows on the elevation drawings.

At the end of the meeting CM asks for clarification about components represented on architectural elevations. CM to architect: “Could you let me know which ones are the windows and which are the panels in drawing A301?” [It is hard to identify the panels and windows from the drawings and the information is required for a more accurate cost analysis.]

4.3.3 Visualization: This section covers bottlenecks related to drawings’ incomplete ability to communicate design information; for example, not representing all component characteristics or system designs’ interaction with other systems or components. Visualization of design information on paper drawings (especially on 2D drawings) have shortcomings that hinder communication. For instance, within 2D plan drawings, it is not easy to understand systems or components that are above a certain height. In the example below the project architect requires additional information from the mechanical consultant because the 2D design drawings do not visually represent 3D characteristics of the mechanical system components. Visualization bottlenecks were also observed when the meeting participants were examining an issue about a vertical component that extended across multiple floors.

“So the equipment is tall?” Architect is evaluating different options about a mechanical room layout. He is asking the mechanical consultant about the physical characteristics of mechanical system components. [3D characteristics of the equipment are not represented in the drawing. Participants have to mentally visualize the component in order to evaluate different layout options.]
4.4 Interaction/Access

While design teams perform meeting tasks they use information artifacts such as drawings, documents and physical models. In order to perform meeting tasks efficiently, design teams need to be able to easily access and interact with these artifacts. Interaction/access bottlenecks include remote pointing, annotation, navigation, visibility and manipulation bottlenecks related with the artifacts.

4.4.1 Remote Pointing: Observations in this study showed evidence that the lack of tools for remote pointing on digital and physical artifacts created interaction bottlenecks, which in return slowed down meeting processes and interrupted workflow. Participants did not take advantage of information artifacts that were available in the meeting room, just because they did not have instant access to the artifact or did not have the proper tools for remote interaction. Instead, they preferred longer verbal descriptions.

While the owner's representative is talking about an issue about the site and one of the neighbouring streets, he does not use the physical model which sits on a table in the room, simply because he does not have an efficient way to interact with the artifact; he would need to stand up to get closer to the model.

4.4.2 Annotation: During meetings, team members perform sketching, annotating, and note-taking activities on different information artifacts. Annotations are often used to clearly express an idea, propose a design change, and create meeting notes. Observations in this study showed that annotations, which are used often during meetings and can be very explanatory, are often not used efficiently. Annotation bottlenecks were observed when participants were making annotations on physical and digital artifacts (which cannot be kept as a record if required), communicating an idea using sketches, note-taking, viewing and manipulating annotations of other people, keeping a record of these annotations, etc. The following example shows a need for personal annotations (in this case sketches) to be easily accessible and viewable instantly by other group members in order to solve problems faster:

While discussion continues on the drawing board, the architect is sketching a detail on his notepad, which will be used in a minute to help solve the discussed issue. If he could have used a common display to show his sketch remotely on this surface, he could have helped others solve the issue faster, and other participants would be able to view the explanatory sketch much easier on the display rather than trying to see the sketch on a notepad.

4.4.3 Navigation: Navigation bottlenecks were observed when participants were searching for the most relevant data amongst different forms of information sets. During the meetings, consultants had to go through stick sets of drawings in order to find relevant drawings. The example below explains an instance where the architect navigates in a stick set. The architect had to move back and forth in the stick set during a discussion about mechanical system layout. In this case the actual navigation time takes virtually as long as the discussion itself. Often the participants preferred to bring smaller scale drawings so that it would be easier to navigate through pages and the drawings would take less space in the meeting environment. But this caused visibility problems when looking at detailed information on drawings.
The architect is going through different plan drawings to point out areas on floor plans while discussing space requirements for the supply and return for the cistern. He spends time finding the first related drawing page in the drawing set. Then he flips back and forth between the different plan drawings as he talks about the mechanical system routing.

4.4.4 Visibility: This section includes viewing problems (group viewing, individual viewing etc.) that were observed while the participants were working with paper drawings and documents, digital representations of information and physical models. During observed meetings, there were often times when team members had problems viewing artifacts. Visibility of information artifacts was noted as a bottleneck during this study since it was one of the most common observations. However, the effect of this problem was not usually noticeable from the workflow perspective. People were often observed having difficulty on viewing artifacts but most of the time they seemed comfortable with it.

Meeting participants often passed around drawings during discussions to have a better look at relevant information. Participants talk about the design as they view the drawing. However, not all participants have access to the drawing during the discussions. It is hard for the participants to view and interact with the artifact collaboratively at the same time.

4.4.5 Manipulation: Traditional 2D drawings do not allow many interactions that project teams need to perform during a meeting such as zooming in on a part of the drawing and getting quick measurements. Lack of such interactions can affect the efficiency of the team and hinder the effectiveness of information flow between participants. In the following example design team was using a small scale paper drawing. The plumbing consultant needed to zoom in on the problem area to be able to take an accurate measurement.

Plumbing consultant says, “I have to measure this distance. I have to blow this up,” as he is trying to answer architect’s question about the spacing of the sprinkler heads. [The architect’s question remains unanswered since the required manipulation (zoom in and measure) cannot be done on paper drawings.]

4.5 Information

4.5.1 Exchange: A great amount of information is exchanged between consultants throughout a project. Design progresses fast, especially in the early design phases. The nature of design process makes seamless information exchange an important factor for a project to be successful. We observed numerous bottlenecks resulting from delays in information exchange between consultants. There was often a time lag between a design change and notification of other consultants about the change, which led to inefficiencies in the design process and created bottlenecks in information flow. In the following example, it turns out that CM’s budget calculations, which were discussed earlier in the meeting, were from an older version of the design drawings.
The design team is discussing the auditorium design. CM's representative: “the drawing that I am working with right now doesn’t have that detail.” [It turns out that the CM, who is working on the project's cost estimate (a very important aspect about the progress of the project), has not been working with the latest version of the design drawings. The CM was not informed about recent design changes.]

4.5.2 Interdependencies: Interdependency between the consultants’ design information were noted as one cause of inefficiency in decision making. Design decisions and discussions are multidimensional and interrelated with the decisions made by other consultants. Although discussion of interrelated items is considered as a natural part of problem solving, the observed issues were more about (a) not being able to move forward (or make a decision) because of complexity or the absence of information required, (b) moving away from a discussion topic that is in the meeting agenda, to a number of different topics that requires detail information or considers only specific members of the design coordination team. During the coordination meetings, consultants have to evaluate scenarios together to come up with a solution that works well with everyone’s design criteria. That is why discussion of a topic sometimes triggers other discussions.

The owner’s representative explains a storage area requirement in the building. Topic of accessibility to the storage area comes up and the team evaluates the possibility of moving washrooms to the storage area. The solution also depends on other system designs. Dropping the washrooms might trigger problems with the plumbing. Washrooms can be below the utilities level from the street, but in this case pumps and extra mechanical equipment may be required. The discussion takes too long and the issue remains unresolved. Team decides that they need mechanical consultant’s approval or ideas about moving the washroom to the storage level and they move on to the next issue.

4.5.3 Availability: When information was not available during a meeting, the design team could not make informed decisions, issues remained unresolved, questions remained unanswered, and the design team moved on to the next topic on the meeting agenda without a final decision. We observed three main reasons for this bottleneck: (a) the required information was created, but was not available in the meeting, (b) more information was required to make a decision or (c) needed information was not created yet. In the following example, the discussion was about the size calculation of the emergency generator fuel tank. The team realizes that the required information was simply not available to make a final decision.

Q: “How long does it (the generator) have to run?”
Q: “Is it thirty minutes (until everybody is out) or does it have to run longer?”
Q: “Where does ‘the generator has to be able to run for 12 hours’ come from?”
[After discussing the same issue for about fifteen minutes the team understands that available information is not enough to make a decision on the subject. Additional information is required from consultants before making a final decision.]

4.5.4 Analysis: Project teams evaluate different design options throughout the evolution of a project, in an effort to find the best fit to achieve the project goals. We observed a lack of technological support during the evaluation of different design ideas or solutions. The analysis required by the team includes evaluating the effect of a proposed design option according to compliance with other parts of the design, cost, schedule, construction sequencing or code requirements. The following is an observation where a participant would like to know what the incremental cost of a design change would be.

Partnering consultant asks “what if” questions about the cost: “what if ...... then what would be the incremented cost?” [There may not be a quick answer to these types of questions since further analyses and calculations have to be done before answering them.]
5. CONCLUSION

This paper described the results of a 16-month ethnographic field study that involved observation and analysis of twenty-seven design coordination meetings during the design development phase of a high performance institutional research building. We identified and characterized meeting bottlenecks in a framework that illustrates the nature of each bottleneck and the frequency of its occurrence. The taxonomy of design coordination meeting bottlenecks provides a more holistic characterization of meeting bottlenecks than what has previously been represented in the literature. This research studied the existing work practice of project teams in design coordination meetings. Our observations point out the need for improved information sharing amongst team members, new tools to help design team to be able to more easily and quickly understand and analyze design issues and options, and make informed decisions. During a meeting information artifacts should be accessible by all participants. Project teams need to be able to view information both publicly and in private to better understand and evaluate discussion topics. When an artefact is being used by a participant, other participants should still be able to view or be able to interact with the same, or the digital representation of the same artifact. Personal interaction with the artifact should not hinder other participants’ interaction with the same information. Our hope is that by better understanding the meeting process and the bottlenecks observed, we can design technologies that provide better support for the unique needs of building design teams. In particular, technologies that enable better interaction with information artifacts, seamless exchange of data in meeting settings, and advanced visualization technologies for better communication and decision-making.

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DATA COLLECTION FRAMEWORK FOR CONSTRUCTION SAFETY RESEARCH

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Abstract: Engaging workers from construction companies of various sizes and ensuring their participation in construction safety research is often very difficult. Voluntary participation is typically limited by industry-specific recruitment challenges such as the transient nature of the workforce, industry perception of safety research, schedule limitations, and economic constraints. This paper uses the lessons learned and best practices from several years of data collection experience to present a data collection framework for research within the construction industry. The framework includes organizational support, research instruments, data collection processes, and measures of data collection efficiency. The framework was developed following an intensive six-month data collection period, resulting in 370 completed surveys. A 95\% survey completion rate following survey site visits was observed, however the overall recruitment time per survey was 3.8 hours. It is clear that data collection itself is often one of the most challenging and time consuming activities related to construction safety research. Clear communication protocols, strict confidentiality measures, and effective incentive strategies are discussed. Methods of engagement are also provided: often a hybrid of a top-down and bottom-up approach is required ensuring participation and worker/company buy-in. The data collection framework in this paper provides a point of departure for researchers to improve their data collection processes and in turn, work toward improving safety performance more efficiently in the construction industry.

1 INTRODUCTION

The construction industry is a dynamic and evolving environment where the employees can experience disproportionately high injury and fatality rates (Hallowell and Gambatese 2009). Although significant improvements in safety performance continue to be made in Ontario following the development of the Occupational Health and Safety Act in 1978, construction worker safety has become forefront in recent years (Government of Ontario 2002). Therefore, ongoing and consistent safety research to improve practices and worker-hazard interactions is required (Hallowell and Gambatese 2009). Moreover, recruiting workers to participate in voluntary safety research and data collection is necessary to understand the ever-changing, remote, and transient nature of the industry (Kidd et al. 2004).

Construction safety problems are ubiquitous and are rarely unique to a specific trade, employer, region, province, or country (Hinze 2008). Thus there is an opportunity to solve safety problems on a global level by addressing many facets including managerial components, behavioural aspects, technological advancements, and cultural characteristics (Hinze 2008). Construction projects are defined by various
unique factors including frequent crew changes, exposure to adverse weather conditions, and ever changing topology, topography, and general work conditions. This makes construction site safety more difficult to measure and research (Rozenfeld et al. 2010), requiring a universally effective data collection program and approach.

The effort, time, and resources required to recruit and retain participants for construction safety research is often far greater than anticipated at the project outset. The top two reported reasons for nonparticipation in safety research projects is the time required to complete the survey process and participants’ and supervisors’ perception of the safety record of their company or site (Kidd et al. 2004). Lessons learned from the recruitment stage of safety studies are useful when engaging participants in future safety research initiatives. Lessons learned include understanding the stability of the construction companies, ensuring sufficient time is provided to recruit participants, oversampling to meet data set targets, approaching both owners and workers during the initial recruitment stages, and understanding the burden perceived by the participants and providing tailored incentives to overcome this burden (Kidd et al. 2004).

Time demands, economic constraints, worker turnover, industry perceptions, and various worksite conditions often limit worker participation in data collection and research. A gap in the research exists in that a systematic and pragmatic data collection framework has not been proposed to overcome participation issues related to construction safety research. Methods to overcome recruitment challenges in small construction companies have been suggested however a comprehensive and universally applicable data collection framework has not been put forward (Kidd et al. 2004).

1.1 Objective and Scope

This paper outlines a practical and efficient framework to identify and recruit participants in construction safety data collection initiatives. This will involve selecting potential construction sites, engaging and gathering initial site contacts, connecting with site and company representatives, coordinating and scheduling site visits, and managing onsite survey distribution and collection.

Lessons learned and best practices from the researchers’ construction safety improvement initiative are presented in a case study format to capture data collection challenges and successful mitigation techniques. The case studies were obtained while researching construction safety to better understand the behavioural and cultural aspects of the industry, nature of the work, attitudes, and demographics. The data presented in this paper was gathered by surveying workers from construction sites across Ontario. The need for a data collection framework was identified by reviewing the rate of buy-in from the engaged site/employer contacts (site participation rate), the ratio of actual participation verses expected participation, the overall recruitment effort (time), and the onsite feedback obtained during survey distribution and collection.

2 THE FRAMEWORK

This framework was developed after several years of data collection experience that took place from 2004 to 2006 (McCabe et al. 2008), and in 2014. In particular, data on the safety climate of construction workers in Ontario were collected through self-administered surveys. The process of engaging site management to allow access to the sites helped the team hone their practices in an effort to maximize the yield. Embedded in the framework are our best practices. The assumptions of this framework are:

- Access to individual workers is desired versus having one person represent the site
- Data collection is completed in person as opposed to on-line surveys
- The sample should be representative of a broad target population. This is different from working with one or two employers to collect data on their sites.

Figure 1 shows a data collection framework with four main parts: organizational support, research instrument, data collection processes, and measures of data collection efficiency.
2.1 Organizational Support

In most cases, the two major parties in this endeavour will be the research team and the construction team.

The construction team includes head office management, site management and supervisors, and workers. To gain access to the site and therefore the workers, permission was required from those ultimately responsible for the site – head office management. As noted in the third part of the framework, the path that the request may take depends on the way in which they are approached. However, it is noted that a lack of enthusiasm at any level can end the conversation quickly. Finding the right champion, therefore, is important.

The research team at University of Toronto comprised the principal investigators (PI), two graduate research assistants (RA) and three undergraduate research interns (RI), who assisted with site identification and data collection. The RAs coordinated their responsibilities to eliminate duplicated effort and missed opportunities. As such, RA1 worked directly with the three RIs to implement introductory site visits and data collection. RA2 was responsible for follow up communications with the employers (corporate and site managers) and for scheduling survey collection visits. Having RA2 also invest some time in the onsite data collection efforts allowed for an enhanced understanding of the on-site needs and dynamics, while also allowing for relationship building at the site level. This proved useful during the implementation of top down engagement strategies. Communication protocols such as updating experience diaries and site contact lists daily were established to facilitate quick and complete information sharing between the two teams.

It was essential that the team have safety training before gaining access to any site. They all had their own personal protective equipment (boots, hardhat, and vests) and completed training for WHMIS, Ministry of Labour’s Worker Health and Safety Awareness, and Fall Awareness. They also carried a letter of introduction from the PI, and a letter from the university outlining its insurance coverage for registered students undertaking research off-campus. This did not preclude individual sites requiring the team to undergo site-specific training.
2.2 Research Instrument

Preparation of the research instrument, finalizing approvals, and establishing protocols are next. The survey should be prepared carefully to ensure that the questions being asked will result in targeted responses to the research questions. One way in which this can be achieved is by using validated safety climate scales. These scales are available in the psychology literature for a large number of topics, as shown in Table 1. Each scale is described by several questions. Although these scales have already been validated, they should be re-validated when applied to new industries. Principal component analysis (PCA) in conjunction with other statistical methods (e.g. collinear test) was used to achieve this. Consequently, the questions that were either not correlated with any others or were highly correlated with others were removed. Cronbach’s alpha reliability test was also run. As shown in Table 2, seven out of 13 alpha values are between 0.7 and 0.9, which suggests good internal consistency. Three alpha values are between 0.6 and 0.7, which is acceptable. For the remaining 3 scales (Conscientiousness, Leadership, and Role overload), the alpha values are below but around 0.6, which is acceptable but weak. These three scales should be reviewed and adjusted in subsequent research.

The participants’ demographics and incidents are also measured in this survey, and their relationship with safety climate is analyzed.

<table>
<thead>
<tr>
<th>Scales</th>
<th>Explanation</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conscientiousness</td>
<td>A group of personality traits, referring collectively to one’s competence, responsibility, and self-image in general. It is believed conscientiousness influences safety behavior.</td>
<td>(Goldberg 1992)</td>
</tr>
<tr>
<td>Fatalism</td>
<td>One’s views of the importance and controllability of safety.</td>
<td>(Williamson et al. 1997)</td>
</tr>
<tr>
<td>Safety consciousness</td>
<td>One’s awareness of safety issues.</td>
<td></td>
</tr>
<tr>
<td>Leadership</td>
<td>One’s satisfaction with leadership’s ability to provide influence, motivation, intellectual stimulation, and individual consideration.</td>
<td>(Barling et al. 2002)</td>
</tr>
<tr>
<td>Role overload</td>
<td>One’s perceptions about whether there is more work than can be accomplished in the time frame available in one’s job.</td>
<td></td>
</tr>
<tr>
<td>Work pressure</td>
<td>One’s perceptions of whether there is excessive pressure to complete work faster, thereby reducing the amount of time available to plan and carry out work.</td>
<td>(Glendon and Litherland 2001)</td>
</tr>
<tr>
<td>Job safety perception</td>
<td>One’s perceptions of how safe their job is.</td>
<td></td>
</tr>
<tr>
<td>Co-worker safety</td>
<td>One’s perceptions about whether their co-workers have good safety behaviors.</td>
<td></td>
</tr>
<tr>
<td>perception</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervisor safety</td>
<td>One’s perceptions about their supervisor’s safety practices.</td>
<td>(Hayes et al. 1998)</td>
</tr>
<tr>
<td>perception</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management safety</td>
<td>One’ perceptions about whether the company’s managers have good safety attitudes and provide a safe work environment.</td>
<td></td>
</tr>
<tr>
<td>perception</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety program and</td>
<td>One’s perceptions about the effectiveness of safety programs and policies in place.</td>
<td></td>
</tr>
<tr>
<td>policies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>perception</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interpersonal conflict</td>
<td>The level to which I get along with others at work.</td>
<td>(Spector and Jex 1998)</td>
</tr>
<tr>
<td>at work</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Job involvement</td>
<td>One’s beliefs regarding the importance of the role work plays in their life.</td>
<td>(Kanungo 1982)</td>
</tr>
</tbody>
</table>

Table 1: Safety climate scales
Table 2: Scale reliability test

<table>
<thead>
<tr>
<th>Scales</th>
<th>No. of questions</th>
<th>No. of valid cases</th>
<th>Alpha Value</th>
<th>Acceptability level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conscientiousness</td>
<td>10</td>
<td>215</td>
<td>0.55</td>
<td>Acceptable but weak</td>
</tr>
<tr>
<td>Fatalism</td>
<td>4</td>
<td>246</td>
<td>0.64</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Safety consciousness</td>
<td>5</td>
<td>258</td>
<td>0.74</td>
<td>Good</td>
</tr>
<tr>
<td>Leadership</td>
<td>12</td>
<td>246</td>
<td>0.55</td>
<td>Acceptable but weak</td>
</tr>
<tr>
<td>Role overload</td>
<td>2</td>
<td>259</td>
<td>0.57</td>
<td>Acceptable but weak</td>
</tr>
<tr>
<td>Work pressure</td>
<td>2</td>
<td>263</td>
<td>0.75</td>
<td>Good</td>
</tr>
<tr>
<td>Job safety perception</td>
<td>4</td>
<td>258</td>
<td>0.60</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Co-worker safety perception</td>
<td>2</td>
<td>261</td>
<td>0.75</td>
<td>Good</td>
</tr>
<tr>
<td>Supervisor safety perception</td>
<td>4</td>
<td>253</td>
<td>0.63</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Management safety perception</td>
<td>3</td>
<td>262</td>
<td>0.83</td>
<td>Good</td>
</tr>
<tr>
<td>Safety program &amp; policies perception</td>
<td>7</td>
<td>244</td>
<td>0.89</td>
<td>Good</td>
</tr>
<tr>
<td>Interpersonal conflict at work</td>
<td>3</td>
<td>244</td>
<td>0.70</td>
<td>Good</td>
</tr>
<tr>
<td>Job involvement</td>
<td>6</td>
<td>243</td>
<td>0.90</td>
<td>Good</td>
</tr>
</tbody>
</table>

The PIs must decide if the participants are to be assured confidentially with respect to their responses, and how that will be achieved. In our case, the surveys were confidential, and several strategies were used to ensure that confidentiality. First, participants completed the survey on their own under the oversight of the research team and not their bosses. Once completed, the surveys were put through a slot of a locked box, which was taken away by the researchers at the end of the data collection visit. Participants did not put their names on the surveys, and we even brought pencils with us to ensure that individuals could not be identified by the colour of the ink they used. In the office, the surveys were entered into the database.

Even if confidentiality is ensured, participants must sign a Consent Form before completing the survey. It contains important pieces of information, written in language that is appropriate for the participant population. This form is required by the research ethics review panel and includes:

- Contact information for the researchers and for the Office of Research Ethics should they have any questions.
- The purpose of the research, its sponsor, and the time commitment expected from them as participants.
- Conditions for participation, and it must explicitly state if it is voluntary, and how they can withdraw from the research should they wish to.
- Risks and benefits to participants due to their taking part in the research.
- Explaining who will have access to the data, how it will be used, and how it will be published.
- Procedures for maintaining confidentiality, both of hard and electronic data.

PIs and the RAs are strongly encouraged to complete research ethics training to better understand some of the issues that relate to their specific research.

To improve the uptake and acknowledge the contribution of the participants, an incentive strategy may be employed. That strategy should acknowledge each level of participation, and it doesn’t have to be expensive. In is our case, when participants completed their survey and put it in the box, they were given a sports drink and a hardhat sticker that was made specifically for this project (see Figure 2). It is interesting to note that many workers chose to have the stickers but refused the drink. Site managers were also given a certificate of participation.
We had the survey translated into various languages (English, Italian, Spanish, and Portuguese) to facilitate the participation of those who were less comfortable in written English. Without regard to the language, it was observed we often needed to explain what some questions meant. This reinforced the benefits of going to the sites to collect data.

2.3 Data Collection

This discussion examines the process of implementing the research instrument, from first contact to completion of the data collection. Engagement of the industry is the first challenge; top-down or bottom-up methods can be employed.

Top-down means that the team first contacts the head office management, in this case the person responsible for safety, to introduce the project. If the person is enthusiastic about the project, then they will engage their site managers and schedule data collection visits. This method involves three steps: RA2 contacts the corporate management and if permission is given, schedules site visit(s), and RA1 collects data.

The bottom-up method involves engaging the site managers first, who then work to gain corporate permission. It has four steps: initial contact at the site by RA1, follow-up by RA2 and communication with the site and/or the corporate management until approval is given, schedule site visit(s) by RA2, and collect data by RA1.

In either case, the first contacts must be introduced to the project with sufficient detail to allow them to make informed decisions whether to move forward or not. Details may include:

- The objectives of the research
- Who on site is being targeted (e.g. everyone, only specific trades)
- The process being used to collect data (e.g. interviews, surveys, observation)
- The time commitment that would be needed by the participants and when that time would be needed (the start of the day is best in most cases).
- A small sample of the survey
- The overall benefits of participating
- Safety training of the research team
- Documentation summarizing the information

The challenge with the top-down method is identifying the companies and then identifying the right person to contact. The challenge with the bottom-up method is finding construction sites. In the ideal case, engaging a site manager resulted in many more sites from that contractor if the corporate manager was equally engaged. We used a combination of top-down and bottom-up methods. The research team often went to site before the workers started work, e.g., 6 to 7AM, so that the normal work was not overly disrupted.
Factors that can negatively affect the willingness of management (corporate or site) to participate include being behind schedule, poor communications with the company representatives, and negative attitudes of the supervisors toward safety research. Factors that reduced the number of surveys collected on a particular day included poor weather, a high proportion of workers with limited English, generally poor morale on-site, lack of acceptance from the site supervisors, poor introductory explanations about the survey by the research team, and the research team arriving late at the site.

One example that demonstrates these factors was when using the bottom-up method; a construction worker was approached at the site gate to ask where the site office was. He was very helpful and began to direct the team to the site office. However, as soon as safety was mentioned, his helpfulness vanished and he started making excuses about why he could no longer take the team to the site office. This was not an isolated case, and the team soon learned to avoid discussing the specific topic of the research in the first few minutes of first contact.

2.4 Data Collection Efficiency and Effectiveness

Data collection efficiency relates to how well the team is turning effort into surveys. It may be gauged using the measures outlined in Equations 1 to 6.

\[
\begin{align*}
[1] \quad & R_1 = \frac{N_1}{N} \\
[2] \quad & R_2 = \frac{M}{N_1} \\
[3] \quad & R_3 = \frac{\sum (a_i/b_i)}{N_1} \\
[4] \quad & R_4 = \frac{T}{M} \\
[5] \quad & R_5 = \% \text{ within bounds} \\
[6] \quad & R_6 = \text{no. surveys 90\% completed} / M
\end{align*}
\]

Where:
- \( R_1 \) is the site participation rate
- \( R_2 \) is the average number of surveys collected per site
- \( R_3 \) is the ratio of actual to expected number of surveys
- \( R_4 \) is the recruitment time per survey achieved
- \( R_5 \) is the sample representativeness
- \( R_6 \) is the survey completeness
- \( a_i \) is the actual number of surveys collected for site \( i \), \( i=1: N_1 \)
- \( b_i \) is the expected number of surveys for site \( i \), \( i=1: N_1 \)
- \( M \) is number of surveys collected
- \( N_1 \) is the number of sites that participated in the research
- \( N \) is the total number of sites that were visited without regard to whether they participated
- \( T \) is the total recruitment time

The calculation of \( T \) can be challenging. In our case, recruitment and data collection was conducted intensely from June to August 2014, and sporadically from September to November 2014, as shown in Table 3. This is a surprisingly high number.

Table 4 shows the performance of our research efforts thus far. 370 surveys were collected after initial contact with 68 sites. Eighteen of the 68 sites participated in the project. Among these 18 sites, 8 were contacted using the top-down approach and 10 sites were obtained using the bottom-up approach. The overall participation rate (\( R_1 \)) is 26.4% and the average number of surveys per site (\( R_2 \)) is 21. It is difficult to know the success rate of the top-down approach because the discussions about which sites will participate are typically internal to the corporation.
The overall ratio of actual surveys to expected surveys (R3) is 0.76 with values ranging from 0.25 to 1.5 on individual sites (Figure 3). Thirteen of 18 sites over-promised the number of surveys on their sites, with 3 of them resulting in less than 40% of the surveys anticipated. Two sites provided the exact number of surveys expected and 3 provided more than promised.

Table 3: Recruitment time

<table>
<thead>
<tr>
<th>Category</th>
<th>Number of people</th>
<th>hrs/mo. each</th>
<th>no. of months</th>
<th>Total hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact/ schedule</td>
<td>1</td>
<td>136</td>
<td>3</td>
<td>408</td>
</tr>
<tr>
<td>Site visits Jun-Aug</td>
<td>4</td>
<td>80</td>
<td>3</td>
<td>920</td>
</tr>
<tr>
<td>Site visits Sept-Nov</td>
<td>3</td>
<td>10</td>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>T = 1418</td>
</tr>
</tbody>
</table>

Table 4: Our Effectiveness

<table>
<thead>
<tr>
<th>Measures</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M Number of surveys collected</td>
<td>370</td>
</tr>
<tr>
<td>N Number of sites contacted</td>
<td>68</td>
</tr>
<tr>
<td>N1 Number of sites participated in the research</td>
<td>18</td>
</tr>
<tr>
<td>T Total contact/schedule time (hours)</td>
<td>1418</td>
</tr>
<tr>
<td>R1 Site participation rate</td>
<td>26.4%</td>
</tr>
<tr>
<td>R2 Average number of surveys per site</td>
<td>21</td>
</tr>
<tr>
<td>R3 Actual-to-expected surveys</td>
<td>76%</td>
</tr>
<tr>
<td>R4 Recruitment time per survey (hours)</td>
<td>3.8</td>
</tr>
<tr>
<td>R5 Sample representativeness</td>
<td>56%</td>
</tr>
<tr>
<td>R6 Survey completeness</td>
<td>94.9%</td>
</tr>
</tbody>
</table>

Figure 3: R3 distribution

Representativeness is to verify that the sample being collected is not biased or skewed, and is representative of the target population. It can be determined by comparing the collected data with publicly
available workforce data (Koehoorn et al. 2013). This should be checked part way through the data collection period so that adjustments can be made to correct any unintentional biases or gaps in the data.

In our case, the data were compared to Statistics Canada Ontario workforce data on age, gender, and company size. The age distribution is reasonably similar, as shown in Table 5. A higher male percentage was found in our sample. The employer size distribution is skewed to larger companies, however, and will be addressed immediately.

Table 5: Intermediate Verification of Sample

<table>
<thead>
<tr>
<th>Category</th>
<th>Verification Data</th>
<th>Our sample (n=370)</th>
<th>Within Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age Distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 to 24 years</td>
<td>16.7%(^1)</td>
<td>9%</td>
<td>✓</td>
</tr>
<tr>
<td>25 to 54 years</td>
<td>69.6%(^1)</td>
<td>77.2%</td>
<td>✓</td>
</tr>
<tr>
<td>55 years &amp; over</td>
<td>13.7%(^1)</td>
<td>13.8%</td>
<td>✓</td>
</tr>
<tr>
<td>Gender Distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>88%(^1)</td>
<td>98%</td>
<td>✓</td>
</tr>
<tr>
<td>Female</td>
<td>12%(^1)</td>
<td>2%</td>
<td>✓</td>
</tr>
<tr>
<td>Employer Size Distribution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro (1-4 employees)</td>
<td>16.7%(^2)</td>
<td>3.1%</td>
<td>×</td>
</tr>
<tr>
<td>Small (5-99 employees)</td>
<td>57.1%(^2)</td>
<td>30.6%</td>
<td>×</td>
</tr>
<tr>
<td>Medium (100-499 employees)</td>
<td>13.6%(^2)</td>
<td>25.8%</td>
<td>×</td>
</tr>
<tr>
<td>Large (500+ employees)</td>
<td>12.8%(^2)</td>
<td>40.5%</td>
<td>×</td>
</tr>
</tbody>
</table>

\(^1\) (StatsCan 2014b)
\(^2\) (StatsCan 2014a)

Completeness reflects how much of the survey has been completed by the participants, as shown in Table 6. In our case, 95% of the 370 surveys have a high degree of completeness. We believe that this high rate is due to having the research team on site to immediately respond to any questions about the survey.

Table 6: Completeness of the surveys

<table>
<thead>
<tr>
<th>Completeness</th>
<th>Number of Surveys</th>
<th>Percent of Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2</td>
<td>0.5%</td>
</tr>
<tr>
<td>10%</td>
<td>3</td>
<td>0.8%</td>
</tr>
<tr>
<td>40%</td>
<td>2</td>
<td>0.5%</td>
</tr>
<tr>
<td>60%</td>
<td>5</td>
<td>1.4%</td>
</tr>
<tr>
<td>75%</td>
<td>7</td>
<td>1.9%</td>
</tr>
<tr>
<td>&gt;90%</td>
<td>351</td>
<td>94.9%</td>
</tr>
</tbody>
</table>

3 Conclusion

There are many challenges when collecting reliable data for safety research. In addition to the data collection process itself, safety tends to be a sensitive topic associated with liability. This paper describes a framework for facilitating that process and includes many lessons learned and best practices. The
framework consists of four main parts: the organizational structure, the survey instrument, data collection, and effectiveness measures.

The survey instrument portion examined the process involved in developing a survey, including research ethics review, confidentiality issues, and participation incentives. Data collection itself is one of the most challenging activities, and some of our lessons learned are included. With respect to effectiveness, our sample shows a high completeness and representativeness of age but not for employer distribution. Recruitment time per survey is a surprisingly high 3.8 hours.

Acknowledgements

We are indebted to all of the managers, safety coordinators, and workers who participated in this study. Special thanks go to those who took extra time to share their experiences and insight. We gratefully acknowledge the funding support of Ontario’s Ministry of Labour Research Opportunities Program.

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Statistics Canada. 2014b. Table 282-0071, Labour force survey estimates (LFS), wages of employees by type of work, North American Industry Classification System (NAICS), sex and age group, unadjusted for seasonality, monthly (data in thousands).  
ANALYSING PARTIES’ BEHAVIORS ON MEDIATING BUILDING MANAGEMENT CASES

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Abstract: Although mediation is a topical research topic in construction management studies, building management dispute mediation is rarely reported in academic community. This study was conducted in the light of marked increase in the number of building management dispute settled by mediation. Within the context that the parties’ behaviours during the course of the mediation would influence the outcome, the focus of the study is to examine the behaviours adopted by mediators and disputants. Data was collected with specially designed questionnaire and Relative Importance Index (RII) was used to rank the significance of the behaviours. The findings reveal that disputants often adopt aggressive approach to push their counterparts in defending their case as well as pressing for concessions. Mediators moreover, prefer establishing a trusting relationship with the disputants. In this regard, mediators seldom criticise and challenge disputants’ point of view and argument. Instead, they would attempt to establish a harmonious environment by engendering heartfelt feeling and rational understanding. Mediators would refrain from responding inappropriately to the pressing behaviours of disputants. The research findings also suggest further research in building management disputes mediation would further provide insight to the public at large in understanding how building management disputes can be settled more effectively through mediation.

1 INTRODUCTION

Hong Kong is a small place and possibly the most densely populated city in the world. Most of the Hong Kong people live in multi-storey buildings having a large number of units. The common areas of their buildings (hereafter building management) are managed collectively by the property owners. These building management tasks include, inter alia, the daily maintenance and cleaning of facilities. In addition, larger scale maintenance activities like external wall renovation are regularly conducted. However, these tasks are not straightforward in view of complicated ownership involved. Having consensus view on tender and schedule etc. is always difficult if not impossible. Collecting the necessary funds is the most daunting task. As such, lack of maintenance and indifference to common areas become the key issues of building management. Having said that, it is clear that inadequate maintenance can present risk to the public at large.

An Owners’ Corporation (OC) is usually formed to represent the interests of the owners. OC is a body corporate set up under the Building Management Ordinance (BMO) by the owners and registered with the Land Register to exercise and perform the rights, privileges and duties of the owners…. (ICAC 2010). OC can also appoint a Management Committee to oversee the building manager or property management
company responsible for building management functions. Maintaining common areas of the buildings and the improvement of facilities are normally managed by the property management company. Other regular services such as security and cleaning may further be outsourced to other specialist companies. The web of contractual relationship so established adds to the complexity in effecting the building management functions.

Despite the fact that the operation of OC can facilitate the incorporation of property owners to carry out building management functions, disputes remain common in the operation. The practice of outsourcing exaggerates the incidences of building management dispute where quality of the service providers are at stake (Chan 2009, HAD 2011). These disputes can be very complicated in terms of the relationship among the parties. For example, difficult cases often involve substantial element of human issues where the building management company, property owners and tenants are having conflicts and differences. Typical examples include the liability of the maintenance of the common areas/facilities, the payment of management fee and the building maintenance fee shared by the property owners. For the period of 2008 to 2011, the Hong Kong Judiciary has reported 1,361 building management dispute cases. Among others, 18.7% are related to maintenance funds, 6.2% involved water leakage and 15.3% are having illegal structures. It can be observed that building management issues often create disturbance to the residents one way or the other. The parties concerned may not know each other and if tenants are involved, convoluted communication is inevitable. As a result, it is not easy to identify the real causes and who should be responsible. Disputes in this connection among the owners, management companies and occupants are therefore quite common.

1.1 Mediation – A Way to Resolve Building Management Disputes

The increasing number of the building management dispute in recent years is raising concerns. The Hong Kong Judiciary is keen to streamline the settlement of these disputes through mediation so that courts' time can be saved. Mediation is considered as an effective way to resolve building management disputes. It is a sensible and economical way to handle these disputes where maintaining harmony with the community is desirable. For example, the Land Tribunal of Hong Kong introduced a pilot scheme to encourage disputing parties of building management disputes to resolve their differences by mediation. A Building Management Mediation Co-ordinator’s Office (BMMCO) was set up in January 2008 to facilitate the disputing parties in seeking mediation. Mediation is more likely to derive mutually acceptable settlement agreements that should well fit disputants who are living closely to each other. Thus, it is the preferred way of settling building management disputes than adversarial litigation (Bateson 1997; Fenn et al. 1998). The success of mediation depends on the joint efforts of mediator and disputants. Experienced mediators should be able to provide active assistance in managing time and building a harmonious atmosphere to make communication easier. With these, the chance of reaching settlement is improved. Likewise, disputants should be sincere and refrain from holding a confrontational attitude. Otherwise, reaching mutually beneficial mediation outcome is quite distant. On these notes, it is important to understand the behaviours of both mediators and disputants that would enhance the success of mediating building management disputes. Upon a literature review in this topic, it is observed that reported research studies in mediating building management disputes are very few. This study aims to fill the knowledge gap in this area in studying the behaviours of mediators and disputants. The findings should raise the awareness of the importance in promoting a climate of harmony, effective communication and encouraging cooperative behaviors in building management dispute mediation. The study is reported in the following sections: i) a comprehensive review on the behaviors of parties involved in mediating building management disputes; ii) the research methodology and data collection procedure; and iii) results and discussions.

1.2 Mediating Building Management Disputes – A Behavioral Study

As there is a lack of research on mediation for building management disputes, studies on mediation in construction, business and psychology provided valuable references to develop a framework for the study (Yiu 2006; Karim and Pegnetter 1983; Carnevale et al. 1989; Douglas 1962; Stevens 1963; Pruitt 1981; Eiseman 1977; Young 1972). Accordingly, behaviors of disputants and mediators can broadly be categorised into three groups: (1) emotion-related; (2) process-related; and (3) outcome-related. Emotion-
related behaviour is inherent in all human interaction. It is one of the key influencers in negotiation and would eventually affect the mediation process. Process-related and outcome-related behaviours are much more direct as far as the mediation process is concerned. The behaviours of disputants and mediators are listed in Tables 1 and 2 respectively.

Table 1: List of Behaviours of Disputants

<table>
<thead>
<tr>
<th>Behaviours of Disputants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emotion-related</strong></td>
</tr>
<tr>
<td>D_EB1 Being hostile toward the other parties</td>
</tr>
<tr>
<td>D_EB2 Being emotional in the mediation process</td>
</tr>
<tr>
<td>D_EB3 Tend to argue with other parties</td>
</tr>
<tr>
<td>D_EB4 Being optimistic in the mediation process</td>
</tr>
<tr>
<td><strong>Process-related</strong></td>
</tr>
<tr>
<td>D_PB1 Jointly solve the issue</td>
</tr>
<tr>
<td>D_PB2 Making concession</td>
</tr>
<tr>
<td>D_PB3 Actively communicating with other parties</td>
</tr>
<tr>
<td>D_PB4 Paying attention to others’ words and show respect</td>
</tr>
<tr>
<td>D_PB5 Defending himself for every argument raised</td>
</tr>
<tr>
<td>D_PB6 Suspecting the mediator</td>
</tr>
<tr>
<td>D_PB7 Providing false information in the mediation process</td>
</tr>
<tr>
<td><strong>Outcome-related</strong></td>
</tr>
<tr>
<td>D_OB1 Showing motivation towards the settlement</td>
</tr>
<tr>
<td>D_OB2 Showing concerns about future relationship with the other parties</td>
</tr>
<tr>
<td>D_OB3 Showing unrealistic expectation</td>
</tr>
<tr>
<td>D_OB4 Being motivated to solve the dispute</td>
</tr>
<tr>
<td><strong>Outcome-related</strong></td>
</tr>
<tr>
<td>M_PB9 Avoiding social conflict between disputants</td>
</tr>
<tr>
<td><strong>Outcome-related</strong></td>
</tr>
<tr>
<td>M_OB1 Suggesting solutions</td>
</tr>
<tr>
<td>M_OB2 Introducing consequences for not being settled</td>
</tr>
<tr>
<td>M_OB3 Developing plan for settlement</td>
</tr>
<tr>
<td>Behaviours of Mediators</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td><strong>Emotion-related</strong></td>
</tr>
<tr>
<td>M_EB1 Show empathy to disputants</td>
</tr>
<tr>
<td>M_EB2 Giving pressure to disputants</td>
</tr>
<tr>
<td>M_EB3 Building rapport in the mediation process</td>
</tr>
<tr>
<td>M_EB4 Gaining trust from disputants</td>
</tr>
<tr>
<td>M_EB5 Encouraging disputants to jointly solve the dispute</td>
</tr>
<tr>
<td>M_EB6 Giving face to disputants</td>
</tr>
<tr>
<td><strong>Process-related</strong></td>
</tr>
<tr>
<td>M_PB1 Showing professional knowledge</td>
</tr>
<tr>
<td>M_PB2 Criticising disputants’ argument</td>
</tr>
<tr>
<td>M_PB3 Challenging disputants’ point</td>
</tr>
<tr>
<td>M_PB4 Maintaining the order of mediation</td>
</tr>
<tr>
<td>M_PB5 Bring up unaware issue(s)</td>
</tr>
<tr>
<td>M_PB6 Effectively listening to disputants</td>
</tr>
<tr>
<td>M_PB7 Facilitating understanding of disputants</td>
</tr>
<tr>
<td>M_PB8 Promoting exchange of ideas</td>
</tr>
</tbody>
</table>

1.2.1 Behaviours of Disputants

Five typical disputant behaviours on mediation are highlighted as follow:

1. Disputants with optimistic mindset would enhance the desire of the other to cooperate (Sebok 1993). This type of disputant tends to identify areas of agreement with the other parties, acknowledge the other parties’ perceptions and express desire to see the others to get as much of what they want as possible from mediation (Sebok 1993). Furthermore, those disputants who show concerns about future relationship would influence the mediation outcomes (Mareschal 2003). It has also been suggested that disputants might consider future relationship with the counterpart when they choose among mediation, arbitration and litigation (Madden 2001).

2. Being motivated to solve the dispute and reach a settlement are behaviours concerning motivation derived throughout the mediation process. However, there is quite a significant difference between them. Being motivated to solve the dispute refers to behaviour that the disputants are willing to solve the dispute, preferably with a settlement that will satisfy both parties. But being motivated to reach a settlement refers to behaviour that disputants only put the settlement in the first priority, with other concerns left behind, such as the satisfaction of the other party on the settlement.

3. Demonstrating behaviour of joint problem solving and effective communication is highly related to mediation success. With these behaviours, disputants would attempt to put their best effort to exchange ideas and come up with a settlement. As suggested by Zubek (1992), these can be achieved by cooperating to seek a settlement that meets mutual needs. Alternatively, one party would make his/her own effort in seeking for possible solutions, and then work on a solution that would satisfy both parties’ interest. The latter has proven to be able to enhance the likelihood of mediation success (Zubek 1992). Similar effect would be given if effective communication, which increases the exchange of idea and information, exists in the course of mediation (Zariski 2010).

4. According to Sebok (1993), demonstrating behaviours of paying attention to others would imply that disputant has been listening attentively, indicating that the other party ‘has a good point’ when he
makes a point you believe has merit. This type of behaviour demonstrates a real participation in mediation, and would enhance the overall mediation process.


1.2.2 Behaviours of Mediators

Mediators play an important role to steer a successful outcome (Goldberg 2005, Goldberg 2007, Stulberg 1997). Similar to the classification of the disputant behaviours, three types of mediator behaviours, emotion-related, process-related and out-outcome related behaviours are applied. From the perspective of mediators, emotion-related behaviours refer to those that will influence the emotions of the disputants. This type of behaviour such as showing empathy, applying pressure, building rapport, gaining trust, encouraging jointly solving of the dispute, and giving “face” to disputants would lead to a change of emotions of the disputants. These are the demonstrations of concern and perspective taking (Zubek 1992). The mediator is concerned about the interest of either party, and through verbal or nonverbal actions, expressed this concern so that disputants’ interests in all aspects will be taken good care of (Zubek 1992). These behaviours will lead to both parties’ interests becoming aware in the mediation, so it is suggested that it will benefit the mediation process. Furthermore, demonstrating these behaviours would reduce tension between the disputants, and make the mediation progress easier from a psychological aspect. Similarly, the mediator can demonstrate process-related behaviours to affect the mediation process. These include showing professional knowledge, criticizing disputants’ arguments, challenging disputants’ points, maintaining the order of mediation, bringing up unaware issues, listening to disputants effectively, facilitating understanding of disputants, promoting exchange of ideas, and avoiding social conflict between disputants. The influence of mediator is always critical to the mediation process. Mediator is appointed because his background is relevant to the subject matter of the disputes, and he does possess a high reputation for his expert knowledge. Finally, a mediator quite often adopts outcome-related behaviours in the course of mediation in facilitating settlement formulation. These include suggesting solution, introducing the consequences of not being settled, and developing a plan for settlement.

2 METHODOLOGY

This section presents the steps performed to study the behaviours of mediators and disputants in the process of mediating building management disputes. These include questionnaire design and data collection procedures and data analysis procedures.

Questionnaire Design and Data Collection Procedures.

A questionnaire has been designed to identify the disputant and mediator behaviours in mediating building management disputes. As such, the target respondents of this questionnaire survey are the disputants or mediators of building management disputes. They were invited to participate in this questionnaire survey. If the respondent is the disputant (or mediator), he is required to evaluate his own behaviour, and evaluate the mediator’s (or disputant’s) behaviours as listed in Tables 1 and 2. A Likert scale of 1 (least occurred) to 7 (most occurred) was adopted.

Data Analysis Procedures

The 7-point Likert scale described previously were combined and converted into Relative Importance Indices (RIIs) for each identified behaviours, the use of RII can determine the relative rankings of different behaviours by comparing the individual relative importance indices for different behaviours (Shash 1993, Kometa, et al. 1994 and Chan et al. 2002). The individual numerical ratings were therefore transformed to RIIs by the following formula:
3 RESULTS AND DISCUSSIONS

A total of 53 respondents participated in this questionnaire survey. With the RII technique, the overall RIIs can be calculated for the adoptions of each behaviour (Figures 1 and 2 refers). Examining the indices, it is observed that the top-three disputants’ behaviours are ‘D-EB3: Tend to argue with other parties’, ‘D_PB5: Defending himself for every argument raised’ and ‘D_PB3: Actively communicating with other parties’. ‘Tend to argue’ can be considered as a contending behaviour. It is a strategy to push counterpart in the direction of one’s wishes (Carnevale 1992). This behaviour would usually bring an agreement at the end of negotiation. The party with forceful use of contentious behaviour will be favoured. However, this behaviour would discourage joint efforts from both parties. Being defensive is one of the key features when building management disputes are mediated, disputants often express their point of view to exclude liabilities (e.g. water leakage problems). Most of the disputants aim to take the high ground in order to take advantage in the settlement terms. In this study, it is found that the low-ranking disputants’ behaviour is ‘D_PB6: Suspecting the mediator’, implying that most disputants have confidence in their mediators. This may be due to the fact that the mediators are often jointly appointed by the disputant themselves. Trust can be hence maintained.

![Figure 1: Results of RII - Disputants’ behaviours](image)

Regarding mediators’ behaviours, the top-three mediators’ behaviours are ‘M-PB7: Facilitating understanding of disputants’, ‘M_PB6: Effectively listening to disputants’ and ‘M_PB8: Promoting exchange of ideas’. These behaviours are inter-related in the sense that effective listening promotes...
communication, exchange of ideas, and enhances understanding among disputants. Moreover, these behaviours would be deemed to be ‘paying attention to the others’ words (Sebok 1993). They are conveying that the disputant has been listening attentively, indicating that the other party “has a good point” when he makes a point you believe has merit. All these behaviours mean a real participation to the mediation, and both parties will have to make an effort to solve the dispute, preferably with a settlement satisfying both parties. These findings suggest that mediators are well connected with the disputants at the level of heartfelt feeling as well as rational understanding. Promoting the exchange of ideas is a positive mediator’s behaviour. This enables the disputants to understand the way of thinking of the other side, and facilitates the generation of new ideas based on what others had been suggested or raised. Zubek (1992) suggested that challenging disputant would encourage him to think about the issues, and stimulates him to look over the unaware issues in their arguments.

Unsurprisingly, the mediators' behaviours, ‘M_PB2: Criticising disputants’ argument’ and ‘M_PB3-Challenging disputants’ point’, are low-ranked in this study. Criticizing other’s idea is always not a smart tactic, as this will upset the disputants. Disputants will be dissatisfied when they were criticized (Zubek 1992). For example, asking embarrassing questions, a more subtle form of criticism, would be negatively related to goal achievement (Zubek 1992). Therefore, the behaviour of criticizing disputants’ argument would inhibit mediation success.

4 CONCLUDING REMARKS

Building management disputes have become one of the major sources of disputes in Hong Kong Building Sector. In this study, a questionnaire survey was conducted to investigate the behaviours of disputants and mediators in building management dispute mediations. Relative Importance Indices were used to rank the importance of behaviours identified from a literature review. It was found that disputants often adopt an aggressive approach to press for concession, while mediators would try to establish a trusting relationship with the disputants by showing heartfelt feeling and rational understanding. This can cultivate a harmonious environment that is conducive for richer information exchange. It is also found that disputants seldom challenge the mediators. Furthermore, this study reveals that mediators would refrain from criticising the argument raised by the disputants. Instead, they prefer to engender a harmonious
environment whereby he would not be pushed to respond inappropriately. Using an inappropriate strategy would invite pressing behaviours of disputants. The research findings of this study are of significant value to the public to understand how mediation works in settling building management disputes.

References


A MULTI-PERSPECTIVE ASSESSMENT METHOD FOR MEASURING LEADING INDICATORS IN CAPITAL PROJECT BENCHMARKING

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Abstract: This paper presents a new multi-perspective assessment method for measuring leading indicators deployed in the 10-10 Performance Assessment System that the Construction Industry Institute (CII) has recently launched. The CII 10-10 Performance Assessment System adopted a multi-perspective assessment approach for evaluating leading indicators that represent various management input measures throughout capital project delivery process. The leading indicators consist of 10 input measures, including four fundamental management functions such as planning, organizing, leading, and controlling as well as major management practices such as design efficiency, human resources, quality, sustainability, supply chain, and safety. This paper provides the theoretical background for the method through extensive review of existing benchmarking theories. Then it describes the development process for the assessment method. After this, it presents how the method was deployed to evaluate the system’s 10 leading indicators. Finally, this paper discusses how to practically utilize the input measure scores acquired from the method for performance improvement. The assessment method in the system will help project management teams to diagnose their project’s performances and thus allow them to set up proactive strategies for the subsequent phases of the project.

1 INTRODUCTION

Since 1996, Construction Industry Institute (CII) has initiated various industry specific performance assessment programs in order to reliably measure an organization’s performance against recognized leaders for the purpose of determining best practices that lead to better performance (CII 2015). As a big data repository of capital projects in the construction industry across the world, the CII Performance Assessment database has been used for benchmarking of capital projects collected from the CII member companies and various research efforts such as project planning (Gibson et al. 2006) and impact of technology use on project performance (Kang et al. 2013). The CII 10-10 Performance Assessment Program (the 10-10 Program), as the newest initiative, builds on this legacy by providing the industry with a benchmarked set of leading indicators for several project types and industry sectors (CII 2014a). All CII research studies and the existing CII Performance Assessment surveys were investigated in developing the questionnaires. Moreover, extensive industry experts’ inputs were also reflected on the 10-10 Program, which was acquired from a number of CII activities and events held from 2012 to 2014 such as CII’s Board of Advisors (BoA) meetings, CII Performance Assessment Community of Practice (PACOP) and CII Performance Assessment Workshop (PAW). The knowledge from industry expertise and previous academic researches thus forms the basis of the program.
There are three different sets of industry specific questionnaires in the 10-10 Program. Each set consists of five phase level questionnaires, which are front end planning (or programming), engineering (or design), procurement, construction, and startup (or commissioning). Thus, the 10-10 Program was designed to collect capital project data by project phase instead of at project closeout when previous performance assessment programs are typically conducted (CII 2014b). Notably, the 10-10 Program was developed to survey members of a project’s management team regarding their project's performance, team dynamics, and organizational relationships (Kang et al. 2014). Since 10-10 surveys by phase using simple statement-based questions, 10 leading indicators (i.e., input measures) are obtained throughout a project’s development, which can identify projects’ impending problems. On the other hand, 10 output measures (i.e., lagging indicators) is to provide certainty that the project is proceeding on target through various metrics related to cost, schedule, capacity, quantity, and safety. Together, these measures are the basis of the new program’s name of 10-10 (CII 2014b).

For the input measure section, the 10-10 Program adopted a multi-perspective assessment approach for evaluating leading indicators that represent various management efforts throughout capital project delivery process. The input measures consist of 10 leading indicators including four fundamental management functions such as planning, organizing, leading, and controlling as well as major management practices such as design efficiency, human resources, quality, sustainability, supply chain, and safety. Accordingly, questions in the input measure section are used to measure 10 scores representing 10 leading indicators so that they can be compared with the other similar projects. However, a structured process is required in order to obtain and benchmark the 10 input measures in an appropriate manner. This paper provides the theoretical background for the multi-perspective assessment method through extensive review of existing benchmarking theories. It then describes the development process for the assessment method.

2 RESEARCH BACKGROUND

One of critical issues in contemporary benchmarking is the lack of information supporting project decisions and influencing on project performance during project planning and execution (Kang et al. 2014). As project data is submitted to CII performance assessment database after completion of projects, the outcomes of benchmarking cannot directly benefit the projects being benchmarked. Rather, the results are typically used for their future projects. The fact motivated CII to develop a new program for gathering the information supporting project decisions and influencing on capital project performance through comprehensive review on references from academia and industry.

At the outset, CII benchmarking legacies were thoroughly reviewed including CII’s research publications (CII 1987, CII 1989, CII 1997, CII 2006a, CII 2006b, CII 2006c, CII 2008, CII 2010, CII 2010d, CII 2011b), implementation tools (CII 1995, CII 2003a, CII 2003b, CII 2011c), and survey instruments (CII 2011a, CII 2012a; CII 2012c). All existing survey questions created to capture the extent of implementation of CII best practices, which are defined as a process and method that leads to enhanced project performance when executed effectively, are thoroughly investigated (CII 2015).

Also, research results on performance assessment and benchmarking conducted in academia were reviewed (Kasunic 2008, Zhang 2005, Yu et al. 2005). In addition to that, survey instruments for the performance assessment developed by industrial practitioners were examined. Once the draft of the questionnaires were first generated from these multiple sources, questions were expanded, filtered, and combined later by industry practitioners’ expertise collected at several CII events and activities (Kang et al. 2014). Upon the completion of the questionnaires, the 10-10 Program intends to assess capital project performance by phase so that a capital project can identify if the project is properly positioned for success in that specific phase, as well as in subsequent phase (CII 2014a).

3 METHOD FOR MEASURING LEADING INDICATORS

Leading indicators are defined as the measurements of processes, activities, and conditions that define performance and can predict future results (CII 2012b). Moreover, leading indicators allow for proactive
management to impact project outcomes, revealed in a timely manner (CII 2006b). After thorough reviews on publications, tools, and survey instruments developed by CII, academia, and industry, the selected questions were organized and classified by leading indicators, which can be utilized during project planning and execution. Each leading indicator has linkage with potential CII resources for improvement of project performance (CII 2013). For example, when the organizing score of a project is low, this situation can be improved by looking at its linkage to applicable best practices and resources. This linkage will soon help the project identify which implementation resources should be considered for improvement (CII 2013). Among 10 leading indicators, planning, organizing, leading, and controlling have long been recognized as core management functions in a business organization (Tsoukas 1994). The other leading indicators have been accepted by the literature review and industry experts’ feedbacks (Kang et al. 2014). The first focus of this research was to define each of the 10 input measures so that each of the questions in the input measure section were grouped into the leading indicators with regard to industry group and phase. Figure 1 illustrates 10 leading indicators designed to perform a multi-perspective assessment framework for capital project benchmarking by industry group and phase.

Figure 1. Multi-Perspective Assessment Framework in the 10-10 Program

The 10 leading indicators are defined as below:

- Planning is the work a manager performs to predetermine a course of action. The function of planning includes the activities such as forecasting, objective setting, program development, scheduling, budgeting, and policies and procedures development.
- Organizing is the work a manager performs to arrange and relate the work to be done so people can perform it most effectively. The function of organizing includes the activities such as development of organization structure, delegation of responsibility and authority, and establishment of relationships.
- Leading is the work a manager performs to cause people to take effective action. The activities involved in the function of leading include decision-making, communications, motivation, selection of people, and development of people.
- Controlling is the work a manager performs to assess and regulate work in progress and completed. Management controls are achieved through the activities such as establishment of performance standards, measurement of performance, evaluation of performance, and correction of performance.
- Design Efficiency measures if the project team is exhausting all techniques to optimize the design in its use of material quantities to provide maximum capacity at minimum cost.
- Human Resources examines if the project is staffed correctly, with a minimum amount of staff turnover and appropriate training, and measures if people are capable of achieving project goals.
• Quality measures if the project team is strictly conforming to project requirements. Analyzes if programs are pursued to assure the delivery of material goods as intended.
• Sustainability evaluates steps taken by the project team to reduce the environmental impact of the project during construction and operation.
• Supply Chain examines the strategies used by the project team to promote enhanced working relationships amongst all project stakeholders including those in the project supply chain.
• Safety measures the practices followed by the project team to eliminate any possibility of personal injury or property damage on the project.

In order to effectively measure these 10 leading indicators as the multi-perspective assessment for capital project benchmarking, the 10-10 Program was designed to obtain the input measures by asking various types of questions that include yes/no, single/multiple selections, numeric open-ended, and Likert response scale from ‘strongly agree’ to ‘strongly disagree’ as presented in Figure 2. Fifteen 10-10 questionnaires have different numbers and types of questions so that they can measure phase- and industry-specific project performances.

Figure 2: Example of Types of Questions in the CII 10-10 Input Measures

Significantly, most questions in the input measure section were structured to be subjective on purpose. This approach makes respondents to invest less effort in data entry than when asked for real values that need additional effort to search and gather information such as actual project cost, duration, or number of cases (CII 2013). Often, statement-based assessment is criticized because of the presence of inconsistency in responses due to respondents’ subjective perceptions. For this reason, the 10-10 Program was designed to assess input measures by various members of the project’s management team (Kang et al. 2014). When numerous responses from a single project are collected, inconsistencies expected to be effectively reduced (CII 2013). Moreover, the assessment by multiple responses for a project benefits to identify what extent project’s team members are aligned during a project planning and execution (Kang et al. 2014).

The 10-10 Program can evaluate the level of managerial efforts for a capital project committed to implementing attributes of each leading indicator through a single representative value and compare the project with similar projects. These leading indicators then can be used for industry practitioners to identify where opportunities for improvement exist in the subsequent phases or next projects. A detailed procedure for quantifying the 10 leading indicators was established. The procedure can be applied to all industry groups and project phases as shown in Figure 3. The calculation procedure consists of four major steps; 1) score calculation of individual input measure question, 2) weighted score calculation, 3) aggregation of the weighted individual input measure scores, and 4) normalization of the aggregated input measure scores.
Score calculation of individual questions is first conducted by referring to point values defined according to each respondent’s answer for the input measure questions. From there, weights are reflected on the score with consideration of different impact of the question on the relevant leading indicator(s). Weighted scores are then aggregated to produce a single value representing the leading indicator score. Considerable effort of the research was made for the weight determination and question classification within leading indicators that each question impacts substantially on. Finally, the weighted score is normalized to a total of 100. The developed method and calculation procedures were reviewed and confirmed based on industry experts collected at several CII activities and event in 2013 and 2014. Each of the steps presented in Figure 3 is explained in detail as follows.

3.1 Score Calculation

As the first effort for developing the procedure, point values are defined for each question with regard to the question types and selections of respondents. The point values allow obtaining certain numeric values for further assessment analyses. It should be noted that statements of all questions are designed to measure positive impact of the leading indicators, which means that tendency to choose ‘agree’ or ‘yes’ for statements indicates high degree of effort or better implementation of certain practices represented in each question. It is also noteworthy that maximum point values of each question are five for all questions in the input measure section. For yes/no type questions, yes is converted into 5 points while 0 points for no. Taking over 70% of the input measure questions, Likert-scale questions uses five-point scales and are converted into points as presented in Table 2. In order for negative effort to get penalty, strongly disagree, disagree, and neutral are converted into 0, 1, and 2 respectively, rather than using scale ranging from 1 to 3 that applied to five point scales in general.
Table 1: A Five-point Scales Used for the Likert-scale Question

<table>
<thead>
<tr>
<th>Scale</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Differing from single choice questions such as yes/no and Likert-scale, multiple selection questions requires diverse point scales as positive and negative statements are mix-provided for the selection. Accordingly, positive and negative statements in the multiple choice questions are coded as negative and positive scales respectively, considering relative influence of statements in a given question. Again, the 10-10 Program surveys multiple project team members from a project. To mitigate inconsistencies and take a representative single score for the project, average scores are used to measure the level of implementation described in each question. Accordingly, the sum of point values acquired from multiple responses of a single project is divided by the number of the participants to evaluate the average score. Missing data is ignored when calculating the score, which indicates that the score is produced by measuring a project's average score for the variable for which respondents in the project have provided answers (De Vaus 2001). However, in case that nobody answers to a question, the point value for the question is recorded as zero based on the assumption that the project did not perform practice or implementation asked by the question.

### 3.2 Weighting and Aggregation of Individual Score

Answers on certain questions might have more negative or positive impacts on one or more input measures than those on the other questions might have. Weights were thus considered to address relative difference in influence of questions on the input measures. Additionally, in order to generate and then benchmark single scores of each leading indicator, each input measure question needs to be grouped into relevant leading indicator(s). Determining weights and classifying questions into 10 leading indicators were conducted simultaneously. To facilitate the process, all questions and 10 leading indicators were listed on a single column and a row in a spreadsheet in a matrix table according to phase and industry group. From there, industry experts' inputs were collected at CII activities and events in 2013 and 2014. Each participant provided opinion regarding relationship between questions and 10 leading indicators with relative strength of each relationship. Based on these feedbacks from the industry experts, the weights and linkage between questions and leading indicators finally were determined. The weights are used to calculate weighted individual question score by multiplying the score and weight. Thereafter, the weighted scores are aggregated in order to produce a single value.

### 3.3 Normalized Scores and Report

While the total weighted score can be used for benchmarking, it is hard to understand the exact implementation level of input measure without normalization. This is because different number of questions and weights were used for generating total weighted score of each leading indicator. Hence, each leading indicator has different scale by phase and industry group. In order to adjust total weighted score measured by different scale to a common scale, score adjustment is conducted so that the total weighted scores are normalized to a total of 100. The normalized scores of leading indicators are obtained by dividing total weighted score by the weights used for calculation in the total weighted score.

As a final score of each leading indicator ranges from 0% to 100%, high scores close to 100% represents a better implementation of relevant leading indicator than those of low scores. For the benchmarking purpose, the distribution of leading indicator scores of similar projects is necessary and the final score will be indicated in the distribution. To remove the scores differing greatly from the majority of a set of the other projects' scores, values excluding extreme outlying scores are only considered in the charts. Since the program is based on project phase, comparisons are made at the industry group and phase level. When necessary, further comparison can be made by secondarily respondent and project type. The difference in processes and characteristics of project and respondent types suggests that appropriate grouping is crucial for performance comparison (Hwang et al. 2007). The distributions of 10 leading indicators are illustrated by quartile information within comparison group. The fourth quartile is composed
of the 25% of the projects with the high input measure scores and the first quartile is populated with the 25% with the low scores. Result of a project is marked with a black dot within the quartile it belongs to. Through the information, projects can easily identify leading indicators they need to improve.

3.4 Case Study

To present how the 10-10 input measure report can be interpreted, a sample report was generated based on responses having collected from one of chemical manufacturing projects. Five project team members of the project responded the engineering phase of industrial projects’ 10-10 questionnaire. Score distributions of leading indicators in Figure 4 are presented within those of the other chemical manufacturing projects among all projects participated the engineering phase of industrial questionnaires. Thus, sample size (n), min (minimum), max (maximum), 1Q, 2Q, and 3Q (quartile) in the report are calculated by the scores of the similar project in terms of industry sector, phase, and project type. As can be seen in Figure 4, six leading indicators are placed in the fourth quartile. However, design efficiency, human resources, sustainability, and supply chain are located in the first or third quartiles. In particular, it appears that design efficiency in the engineering phase was poorly implemented rather than the other projects and it should be improved for the subsequent phases such as construction or procurement phases. Also, the project team needs to take attention on human resources, sustainability, and supply chain which is still better not the best in comparison to the other similar projects. To improve the situation, the project is recommended to implement relevant CII best practices and tools in order to enhance project performance and importantly, linkages between 10-10 leading indicators and CII resources can help the project to easily find which implementation resources should be considered for improvement (CII 2013).

![Figure 4: The Input Measure Report of the Case Project](image)
Although extreme outlying scores were already removed, relatively larger variations of supply chain and sustainability scores are identified in Figure 4. This fact indicates that management levels of the two areas have large deviations among chemical manufacturing projects during engineering phase. It implies that management skills and practices concerning supply chain and sustainability have not been well established in the chemical manufacturing projects.

4 CONCLUSION AND PATH FORWARD

The CII 10-10 Program adopted a multi-perspective assessment approach for evaluating leading indicators that represent various management input measures throughout capital project delivery process. The purpose of the study described in this paper was to develop a new assessment method for 10 leading indicators deployed in the 10-10 Program for benchmarking. To achieve this goal, attempts to transfer respondent’s answer to numeric values were made and score awarding criteria were developed. The concepts of 10 leading indicators are then defined. From there, each individual question was classified into 10 leading indicator(s) and weights of questions were determined with regard to the question’s level of influence on related leading indicator(s). Using the determined values, the study presented how to produce a representative single score of a leading indicator and how to report the outcomes with the most similar projects submitted to the 10-10 Program database. When necessary, projects are grouped by respondent and respondent types for performance comparison through leading indicators because project and respondent types involve highly different processes and characteristics of projects.

The method was developed based on a wide range of literature review as well as industry experts’ knowledge acquired from the CII events. The finding of this research is meaningful leading indicators can be evaluated and should be of significant value for capital projects performance assessment. Since 10-10 surveys by phase using simple questions, 10 leading indicators can be gathered throughout a project execution that can help projects to identify impending problems. More importantly, as established 10 input measures are based on the CII’s knowledge areas utilized during project execution and thus benchmarking outcomes direct the projects to easily find CII resources for mitigation of issues which projects can refer to.

For the future studies on the topic, continuous modification of the method should be considered with more data analyses. As data accumulate, more detailed validation on the accuracy of established assessment method will be possible. Also, the 10-10 Program questionnaires will be updated whenever required to ensure that they reliably measure the right leading indicators of all types of capital projects. Additionally, the relationship between input measure scores and output measure metrics in the 10-10 Program needs to be thoroughly examined. The finding can provide projects with which leading indicator should be conducted well to achieve better specific outcomes. For example, supply chain measure might have significant impacts on schedule performance in the procurement phase. In this case, project driven by schedule should focus on better supply chain measures. Overall, the developed method is expected to help project management teams clearly understand how their projects’ leading indicators are measured and also enable them to diagnose their project’s performances. Finally, it is strongly believed that the outcomes will allow them to set up proactive strategies for the subsequent phases of the project.

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CULTURE AND ORGANIZATIONAL CULTURE IN THE CONSTRUCTION INDUSTRY: A LITERATURE REVIEW

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Abstract: The effectiveness and competitive advantage of an organization/project can be enhanced when its members possess an understanding, respect, acceptance, and capacity to manage cross-cultural differences. Ignoring or failing to manage such differences may lead to many problems in the project (e.g., project delays and productivity decrease). In fact, international/transnational projects involving participants from diverse political, legal, economic, and cultural backgrounds are on the rise. Hence, firms should be cross-culturally competent and capable of managing in contrasting cultural factors. However, a recent study conducted in 2013 by the Construction Industry Institute (CII) reported that one of the major concerns of construction professionals is a widespread lack of understanding of foreign cultures, ethnicities, and languages. The aim of this paper is to present a comprehensive review of the literature on cultural aspects in the construction industry so as to identify the knowledge gaps and to suggest recommendations for future research. To do so, the authors have identified and compared major studies on cultural factors. From the comparison, the authors have identified the categories that are considered the most central to understanding cultural differences; they are, “group attachment and relations,” “authority and status,” “uncertainty and rules,” “gender roles and assertiveness,” and “time and future orientation.” The authors also summarize the current research topics in culture in construction and recommend ideas for future research into culture as it pertains to a construction context.

1 INTRODUCTION

Globalization has led to construction companies performing more work around the globe. As the construction industry globalizes, it is becoming increasingly important to understand the impact of cultural and linguistic differences on performance (Comu, Unsal, and Taylor 2011). The emergence of more international/transnational projects has given rise to the involvement of participants from diverse political, legal, economic, and cultural backgrounds. Consequently, scholars are focusing on understanding the less tangible management aspects of construction projects, such as building trust and an organizational culture. Managing organizations and projects and handling dispute negotiation involves individuals and their beliefs, so cultural differences have a significant influence on management success (Hofstede 1983). This is in addition to the environment of the host country, which has an effect on the operation of the construction project. Thus, for contracting parties to function effectively, it is critical that they be aware of others’ expectations and priorities (Chan and Tse 2003).
Understanding, respecting, accepting, and managing cross cultural differences effectively in construction projects can enhance the organization/project’s effectiveness and provide a competitive advantage, while ignoring or failing to manage cultural differences may lead to many problems in the project, such as project delays and decreases in productivity (Kivrak, Ross, and Arslan 2008). Arising from a failure to properly manage cultural differences are such problems as expatriates’ culture shock, unfamiliar local work style, different negotiation style, different professional standards and construction codes, and codes of conduct and ethical standards (bribery and corruption), causing many ethical and moral dilemmas (Hall and Jaggar 1997). However, a recent study conducted by the Construction Industry Institute (CII) (2013) reported that one of the major concerns of construction professionals is the lack of understanding of foreign cultures, ethics, and languages. Thus, there is a need to study and better understand culture in construction.

The aim of this paper is: 1) to present a comprehensive literature review on cultural aspects in the construction industry, and 2) to identify the knowledge gaps and suggest recommendations for future research. After addressing its research methodology, this paper presents the findings from the literature review on culture on construction projects. The findings include 1) definitions of culture, 2) cultural factors, and 3) research on culture. Later, the paper summarizes, in the Conclusions and Recommendations section, what was learned from the analysis and recommendations for future research.

2 RESEARCH METHODOLOGY

This study was conducted through four steps: 1) obtaining and screening the literature, 2) identifying major studies on cultural factors and comparing them, 3) summarizing the current research topics in culture in construction, and 4) identifying the gaps of knowledge and proposing recommendations for future research. First, the literature was obtained from peer-reviewed publications (journal articles or conference proceedings) on culture and on organizational cultures in construction. The authors reviewed and analyzed over 60 peer-reviewed publications from major construction engineering and management journals, including the American Society of Civil Engineers (ASCE) Journal of Construction Engineering and Management, the Journal of Management in Engineering, Computing in Civil and Building Engineering, and the International Journal of Management in Engineering. The authors screened the literature unrelated to construction since the wide-ranging topic of culture is addressed in a variety of disciplines. This literature review, conducted between 2013 and 2014, covered studies published between 1983 and 2014. Although the review is not exhaustive, it provides a comprehensive basis for understanding culture and organizational culture in construction.

Second, to get a firm grasp on the two topics, the authors defined culture and organizational culture. Based on the aforementioned literature review, the authors identified, summarized, and compared four of the most remarkable and most commonly referenced studies that introduced cultural factors—Hofstede (1983), Trompenaars and Woolliams (1999), Schwartz (2004), and Brodbeck, Chhokar, and House (2007). From the comparison analysis, the authors identified the five categories most central to understanding cultural differences.

Third, the authors identified and summarized current research topics on culture in construction. Those are 1) cultural factors and differences, 2) organizational culture, 3) culture diversity and its impact, and 4) culture effect on contractual arrangements. This step was needed to identify the knowledge gaps and suggest recommendations for future research. Based on these findings, the authors provide recommendations for future research in the Conclusions and Recommendations section.

3 CULTURE

Many scholars consider culture to be one of the major issues affecting the management of international construction projects. The contextual environment of the host country greatly impacts the operation of the construction project. Thus, to be able to function effectively, it has become important for professionals involved in international projects with participants from different cultural backgrounds to comprehend others’ expectations and beliefs (Chan and Tse 2003; Hall and Jaggar 1997). However, this
comprehension seems to be somewhat limited in the construction industry (Hall and Jaggar 1997). Before the authors move into presenting the current research topics on culture in construction, it is important to start by introducing the definition and factors of culture as agreed upon by many scholars.

3.1 Defining Culture and Organization Culture

According to many scholars, one of the most complicated words in the English language is culture, as it touches on many topics and processes. Complex and divergent in its applications (Hall and Jaggar 1997), the word is defined differently, according to the research field where it is studied. Culture describes the social system that a group of people create in which they share common rules, norms, values, beliefs, perspectives, practices, and rituals (Chan and Tse 2003). In the construction industry, culture is about “the characteristics of the industry, approaches to construction, competence of people, and the goals, values and strategies of the organizations they work in” (Kivrak, Ross, and Arslan 2008).

The dictionary (Guralnik and Friend 1960) defines organization culture as “the integrated pattern of human behavior that includes thought, speech, action, and artifacts and depends on man's capacity for learning and transmitting knowledge to succeeding generations.” Three of the many definitions of organizational culture found in the literature are as follows: 1) “A pattern of basic assumptions invented, discovered or developed by a given group as it learns to cope with its problems of external adaptation and internal integration that has worked well enough to be considered valid and to be taught to new members as the correct way to perceive, think and feel in relation to these problems” (Schein 2010). 2) “An organization’s culture reflects assumptions about clients, employees’ mission, products activities and assumptions that have worked well in the past and which get translated into norms of behavior and expectations about what is legitimate, desirable ways of thinking and acting” (Laurent 1983). 3) “The values and beliefs that govern behavior in an organization” (Maloney and Federle 1991).

3.2 Cultural Factors

The literature review revealed a plethora of culture-type categorizations. For example, Wallach (1983) categorized culture organizations as bureaucratic, innovative, and supportive; Liu, Shuibo, and Meiyung (2006) categorized organizational culture in terms of risk-taking and power centralization. Culture type was also categorized in terms of factors or dimensions. These factors map the cultural differences in terms of values and practices embraced by the organization (Ankrah and Langford 2005; Liu, Shuibo, and Meiyung 2006). The defined factors (dimensions) form a continuum that allows a framework for analysis and management of cultural differences (Hall and Jaggar 1997).

3.2.1 Four Major Studies on Cultural Factors

Four of the most remarkable and most commonly referenced studies that introduce cultural factors (or “dimensions” as Hofstede and several other scholars often used this term) are Hofstede (1983), Trompenaars and Woolliams (1999), Schwartz (2004), and Brodbeck, Chhokar, and House (2007). First, Hofstede (1983), by studying the national cultures of 50 countries, introduced culture’s four independent factors: 1) individualism/collectivism, 2) power distance, 3) uncertainty avoidance, and 4) masculinity/femininity. Hofstede’s factors are considered the most extensively used in many management and organizational behavior studies. Smith (2006) referred to Hofstede’s factors as being a decades-long landmark for subsequent researchers.

Second, Trompenaars and Woolliams (1999) studied 40 countries to explore how every culture determines the solution to problems arising from relationships with other people, the passage of time, and from the environment. They identified how values differ between cultures, grouping them into seven factors—1) universalism-particularism, 2) individualism-communitarianism, 3) diffuse-specific, 4) affective-neutral, 5) achievement-ascription, 6) attitudes to the environment, and 7) attitudes to time (Trompenaars and Woolliams 1999). According to Trompenaars and Woolliams (1999), every culture distinguishes itself from others by the solutions it chooses to certain problems.
Third, based on data collected from many countries, Schwartz (2004) defined three bipolar cultural factors that represent alternative solutions to three main problems confronting all societies. The factors are 1) embeddedness versus autonomy, 2) hierarchy versus egalitarianism, and 3) mastery versus harmony.

Last, the Global Leadership and Organizational Behavior Effectiveness (GLOBE) Research Program conducted a study over 11 years on 1,000 organizations in 62 countries to investigate cultural factors that affect leadership and organizational practices (Brodbeck, Chhokar, and House 2007). These researchers grouped the 62 societies into 10 societal clusters. They established nine cultural factors that make it possible to capture the similarities and/or differences in norms, values, beliefs, and practices among different societies.

Other miscellaneous factors proposed by other researchers include: unemotionality, depersonization, subordination, conservatism, isolationism, and antipathy; holographic and ideographic; constructive, passive/defensive and aggressive/defensive; involvement, consistency, adaptability and mission; organizational values, task organization, organizational climate and employee attitudes; leadership, structure, innovation, job performance, planning, communication, environment, humanistic workplace, development of individual and socialization on entry; time, space, human relationships, human activities, and human nature (Ankrah and Langford 2005; Liu, Shuibo, and Meiyung 2006).

3.2.2 Comparison between the Four Studies on Cultural Factors

A comparison of the four studies summarized above shows that certain factors are central to understanding cultural differences (Table 1). These factors have been grouped here into seven categories based on similarity. Those are: 1) “group attachment and relations,” 2) “authority and status,” 3) “uncertainty and rules,” 4) “gender roles and assertiveness,” 5) “time and future orientation,” 6) “emotions,” and 7) “caring for others.” The comparison revealed that the first three categories were covered by all four studies, the fourth through sixth categories were covered by three studies, the fifth was covered by two studies, and the sixth and seventh were covered by one study each.
The first category “group attachment and relations,” dealing with group versus individual, was addressed by all four studies and enjoyed the greatest popularity in cross-cultural studies. Brodbeck, Chhokar, and House (2007) divided this category into two sub-factors—one concerned with the institution and the other with the in-group collectivism. The second category “authority and status accorded,” which deals with unequal distribution of power and how success is achieved, was also addressed by all four studies. Brodbeck, Chhokar, and House (2007) addressed “power distance” in one factor that deals with how power is equally distributed and addressed the “status accorded” in the “performance orientation” factor that deals with how performance and excellence are encouraged. Trompenaars and Woolliams (1999) addressed the willingness to accept power distances, which the authors partially reflected in this category, in the “achievement/ascription” factor.

All four studies discussed the third category “uncertainty and rules,” which deals with uncertainties and setting rules to regulate them. Hofstede (1983), Trompenaars and Woolliams (1999), and Brodbeck, Chhokar, and House (2007) all addressed uncertainty and the significance of rules, while Schwartz (2004) dealt with managing uncertainty only.

The fourth category “gender roles and assertiveness” was discussed by three studies—Hofstede (1983), Trompenaars and Woolliams (1999), and Brodbeck, Chhokar, and House (2007). The authors located Trompenaars and Woolliams’ (1999) “specific/diffuse” factor under the assertive category as it is related to masculinity and femininity where masculinity is more assertive and aggressive (facts) versus the more caring (relationship) femininity.

The fifth category of “time and future orientation” was discussed also by three studies—Hofstede (1983), Trompenaars and Woolliams (1999), and Brodbeck, Chhokar, and House (2007). However, their view of time seems somehow different. While Hofstede (1983) and Brodbeck, Chhokar, and House (2007) viewed the time aspect in terms of how people plan their future, look at their present and past, Trompenaars and Woolliams (1999) dealt with specific events and tasks relative to time. The last two
factors, covered by one study each, are 1) “emotions” - the affective/neutral by Trompenaars and Woolliams (1999) and 2) “caring for others” - the humane-orientation by Brodbeck, Chhokar, and House (2007).

From the comparison above, this paper identifies five categories most central to understanding cultural differences. These five deal with "group attachment and relations," “authority and status," “uncertainty and rules," "gender roles and assertiveness," and "time and future orientation."

### 3.3 Research in Culture in Construction

The current research topics on culture in construction are identified and summarized to identify the knowledge gaps and suggest recommendations for future research. Those topics are: 1) cultural factors and differences, 2) organizational culture, 3) culture diversity and its impact, and 4) culture effect on contractual arrangements. The corresponding researchers, presented in Table 2, are categorized by research topic.

**Table 2: Culture Research in Construction**

<table>
<thead>
<tr>
<th>Topics of Research</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural Factors and Differences</td>
<td>Horii, Levitt, and Jin (2005) and Riley and Clare-Brown (2001)</td>
</tr>
<tr>
<td>a. Culture Type and Factors</td>
<td></td>
</tr>
<tr>
<td>b. Cultural Differences in Different Geographical Locations</td>
<td>Ozorovskaja, Voordijk, and Wilderom (2007); Tsai and Chi (2009); and Naoum, Alyousif, and Atkinson (2014)</td>
</tr>
<tr>
<td>Organizational Culture</td>
<td>Maloney (1989); Maloney and Federle (1991); Ozorhon et al. (2008); Ankrah and Langford (2005); Ankrah, Proverbs, and Debrak (2009); Fong and Kwok (2009); and Brunetto, Xerri, and Nelson (2014)</td>
</tr>
<tr>
<td>Cultural diversity and its impact</td>
<td>Javernick-Will and Levitt (2009); Miller et al. (2000); Chan and Tse (2003); Rahman and Kumaraswamy (2004); Fong and Lung (2007); Kivrak, Ross, and Arslan (2008); Barkema et al. (1997); Mahalingam and Levitt (2007); Comu, Unsal, and Taylor (2011); and (2000)</td>
</tr>
<tr>
<td>Cultural Effect on Contractual Arrangements</td>
<td>Chan and Tse (2003); Gad, Shane, and Strong (2010); and Gad and Shane (2012)</td>
</tr>
</tbody>
</table>

#### 3.3.1 Cultural Factors and Differences

Several studies on different cultures were identified. Horii, Levitt, and Jin (2005) examined and characterized cultural differences into two factors: cultural values and cultural practices. The former refers to an individual’s preferences in decision making and the latter refers to the cultural norms for adopting specific coordination mechanisms to control organizations and tasks. Interestingly, other than studies on cultural factors, Riley and Clare-Brown (2001) investigated the culture found in construction companies by comparing it to that found in manufacturing companies. They held that, as the culture in construction significantly differed to that in manufacturing industries, substantial modifications were needed in adopting tools or practices from other sectors.

In addition to studies on types and factors of culture, several studies were identified that focused on cultural differences in different geographical locations. Ozorovskaja, Voordijk, and Wilderom (2007), by comparing Lithuanian and Dutch construction firms, identified significant differences in leadership and cultures. Tsai and Chi (2009) investigated the influences of Chinese cultural orientations and conflict management styles on construction dispute-resolving strategies using Hofstede’s cultural factors. Naoum, Alyousif, and Atkinson (2014) identified the impact of national culture on the management practices of construction projects in the United Arab Emirates.
3.3.2 Organizational Culture

Organizational culture constitutes one of the major topics in culture research. This study identifies numerous researchers who have conducted studies on organizational cultures. Maloney (1989) claimed that once an organizational culture has been established and strongly maintained, it greatly reduces uncertainty, leading to higher performance along with the organization’s members’ higher satisfaction level. To investigate organizational culture and to determine its relationship with other organizational variables, Maloney and Federle (1991) used a framework developed by Quinn (1988) that was applied to an examination of organizational culture in educational institutions conducted by Cameron (1982). Ozorhon et al. (2008) examined the effect of cultural similarity/difference relative to the national and organizational characteristics of partner companies on international joint ventures. They argued that the differences in organizational culture have a greater impact on international joint ventures' performance than differences in national and host country culture. They also highlighted the importance of culture in international joint ventures noting that the cultural distance between the partners has a significant impact on alliance performance.

Later, Ankrah and his colleagues conducted several studies on organizational cultural differences by comparing architects and contractors’ organizational cultures (Ankrah and Langford 2005) and by investigating factors influencing the culture of a construction project organization (Ankrah, Proverbs, and Debrah 2009). Similarly, Fong and Kwok (2009) characterized and evaluated the composition of organizational culture, the strategic approach for knowledge flow, and the success of knowledge management systems at different hierarchical levels of contracting organizations. They identified that what was favored at both project and organization levels in contracting firms were the clan culture, the culture of honest communication, respect for people, trust, and cohesive relationships. Most recently, Brunetto, Xerri, and Nelson (2014) identified the impact of perceived organizational support and leader-member exchange on organizational culture within asset management organizations and the positive impact of organization culture and employee engagement.

3.3.3 Culture Diversity and Its Impact

Individuals and organizations in a project have different values, beliefs, and norms (Hofstede 2001; Kogut and Singh 1988) and among project participants, this cultural diversity can impact knowledge transfer (Javernick-Will and Levitt 2009; Miller et al. 2000) relationships in a contract (Chan and Tse 2003; Rahman and Kumaraswamy 2004), and trust developments (Fong and Lung 2007). A number of studies have scrutinized cultural diversity and its impact on a project. For example, Kivrak, Ross, and Arslan (2008) studied the effect of cultural diversity on construction management practices to the success of a project by interviewing senior managers in the United Kingdom. However, a consensus has yet to be reached on whether cultural diversity impacts project performance positively or not. Barkema et al. (1997) claimed that cultural diversity decreases project performance and Mahalingam and Levitt (2007) argued that cultural diversity leads to increased transaction costs both in monetary and efficiency terms. Comu, Unsal, and Taylor (2011) also observed cultural diversity to have a negative impact on initial performance; however, projects with cultural and linguistic diversity achieved better adaptation performance on average. Miller et al. (2000) contended that, in the long term, the benefits of cultural diversity can be achieved due to greater creativity, better problem solving ability, and a more comprehensive approach to problem solving.

3.3.4 Culture Effect on Contractual Arrangements

Chan and Tse (2003) explored the characteristics of international construction activities and discussed cultural contexts to establish a groundwork on the impact of cultural issues on contractual arrangements, conflict on international construction activities, and the selection of dispute resolution mechanisms for international construction projects. They contended that international construction projects are more prone to disputes compared to domestic projects. They attribute the disputes to cultural clashes and inappropriate contract arrangements. Recently, Gad, Shane, and Strong (2010) reviewed different dispute resolution methods employed and suggested the effects of culture on the selection of dispute resolution methods in international construction contracts (Gad and Shane 2012).
4 CONCLUSIONS AND RECOMMENDATIONS

This analysis provides useful insights into the importance of the social science aspects in a "human-based" industry such as construction. The literature review has revealed an increasing trend in construction management research on culture in construction. The findings suggest that cultural aspects of construction deserve greater research attention as they can enhance the organization/project's effectiveness and provide a competitive advantage. Based on the literature review, this study has identified, and then compared, major studies on cultural factors. Four of the most remarkable and most commonly referenced studies that introduced cultural factors are: Hofstede (1983), Trompenaars and Woollams (1999), Schwartz (2004), and Brodbeck, Chhokar, and House (2007). From a comparison of these four, this study has identified five categories it considers the most central to understanding cultural differences. These five deal with "group attachment and relations," "authority and status," "uncertainty and rules," "gender roles and assertiveness," and "time and future orientation." This study has also summarized the current research topics on culture in construction. These are 1) cultural factors and differences, 2) organizational culture, 3) culture diversity and its impact, and 4) culture effect on contractual arrangements.

Accordingly, research gaps and ideas for future research into culture in construction area include the following:

- global study on the effects of culture on contracts negotiation and formation, selection of dispute resolution methods, and disputes occurrence
- best practices and critical success factors for dealing with cultural diversity in international projects
- cultural differences in construction projects in South America, East Asia, Africa, and Middle East

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DEVELOPMENT AND UTILIZATION OF THE PROJECT DEFINITION RATING INDEX FOR SMALL INDUSTRIAL PROJECTS

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Abstract: Front end planning is arguably the most impactful activity in the management of construction projects. Organizations expend substantial effort in planning large projects, intending to minimize risk and promote project success. Small projects—typically classified as such based on their lower costs—often have minimal planning completed prior to the start of design and construction. To date, little research has been performed regarding the planning and management of small construction projects, especially those in the industrial sector. In 2013, the Construction Industry Institute (CII) set out to develop a Project Definition Rating Index (a front end planning tool) specifically for small industrial projects. CII Research Team 314 identified forty-one specific elements as most pertinent in assessing a small industrial project. Sixty-five industry practitioners reviewed and prioritized these elements through a series of focus group “weighting workshops.” The tool has been used to assess 12 separate small industrial projects to date, with positive results. This paper summarizes how the PDRI-Small Industrial Projects was developed, how the tool differs from the previously-developed PDRI-Industrial Projects tool, and how it has been utilized to date to assess small industrial projects. Future research opportunities are proposed, including use of the PDRI-Small Industrial Projects research methodology to develop similar tools for the infrastructure and building construction sectors.

1 INTRODUCTION

Poor scope definition has been shown to be one of the major factors leading to poor project performance (Gibson et al 2006). Many construction experts believe that planning efforts conducted during the early stages of a project (e.g., preproject planning or front end planning) have a significantly greater effect on project success than those undertaken after a project has begun. Since 1991, the Construction Industry Institute (CII) has created a suite of tools to be used to define project scope and assess the level of planning readiness during front end planning. These Project Definition Rating Index (PDRI) tools offer a method to measure project scope definition for completeness at any point prior to the start of detailed design and construction. These tools identify and precisely describe each critical element in a scope definition package, and allow project teams to quickly identify project risk factors related to desired outcomes for cost, schedule, and operating performance.

Prior to 2013, separate PDRI tools were developed for industrial, building, and infrastructure project types (CII 1995, 1999, 2011). Though effective in the planning of large construction projects, the PDRI tools were not developed or validated on small projects. Small projects were deemed by CII to be a significant portion of completed work across the industrial sector, including projects in oil/gas production facilities and refineries, chemical plants, manufacturing facilities, and electrical generation facilities to name a few. CII tasked Research Team 314 with developing a PDRI tool specifically for small industrial projects in the
summer of 2013. This paper summarizes how the PDRI-Small Industrial Projects was developed, how the tool differs from the previously developed PDRI-Industrial projects, and how the tool has been utilized to date to assess small industrial projects.

2 DEVELOPMENT OF THE PDRI-SMALL INDUSTRIAL PROJECTS

PDRI tools consist of two main documents that are used to assess a project: a set of elements (with comprehensive descriptions) that detail specific items that should be addressed during the front end planning phase of a project, and a score sheet that provides a hierarchy to the importance of each element relative to the total set of elements. The thorough analysis of planning tasks recommended for industrial projects completed by CII Research Team 113 led to the development of the PDRI-Industrial Projects in 1995. The tool has successfully been used to assess the level of scope definition on thousands of industrial construction projects across the globe since its initial publication. Research Team 314 felt it prudent to use this document as the baseline for developing the PDRI-Small Industrial Projects.

Research Team 314 was initially broken down into three sub-teams, each separately focusing on one of the three PDRI sections (Basis of Decision, Basis of Design, Execution Approach) to develop the element descriptions for the small industrial projects tool. The element descriptions in each section were reviewed and scrutinized by the sub-teams for applicability to small projects over the course of 10 months and 4 separate team meetings. Brainstorming sessions during team meetings, web-based conference calls, and individual reviews were all methods utilized to complete this review. Non-pertinent elements and "items to-be considered" bullets were removed, re-written, or combined with other elements. New elements were developed as necessary. All elements were then thoroughly reviewed by the entire research team during three separate team meetings. The team agreed upon a final set of element descriptions after rigorous discussion and debate. Figure 1 provides an example of one PDRI element description, specifically Element E.3, Electric Single Line Diagrams. Each PDRI element description is provided in this manner, starting with a description of the element. Additional items to be considered while assessing the project at hand follow the description. Pertinent renovation and revamp and program considerations are also listed.

<table>
<thead>
<tr>
<th>E.3 Electric Single Line Diagrams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric single line diagrams document the components, devices, or parts of an electrical power distribution system. These diagrams portray the system layout from the public utility's incoming supply to the internal electrical power distribution system. Depending on the size of the electrical system, the single line diagrams may include several levels of distribution. Items to consider should include:</td>
</tr>
<tr>
<td>☐ Incoming utility with owner substation/distribution to high and medium voltage motors and substations</td>
</tr>
<tr>
<td>☐ Electrical load list</td>
</tr>
<tr>
<td>☐ Unit substations and switch gear</td>
</tr>
<tr>
<td>☐ Motor control centers with distribution to motors, lighting panels</td>
</tr>
<tr>
<td>☐ Other user defined</td>
</tr>
</tbody>
</table>

**Additional items to consider for Renovation & Revamp projects**

☐ Field verify existing single line diagrams to ensure they are correct and have been maintained to reflect the actual site conditions.

☐ Verify locations and availability of power for new or relocated equipment.

Figure 1: Sample PDRI-Small Industrial Projects Element Description

The 41 elements created by the Research Team were broken into three sections, and further broken down into eight categories (Note: the PDRI-Industrial Projects has 70 elements). This structure was used
to keep the same “look and feel” as the previously developed PDRIs. Table 1 provides a breakdown of the PDRI-Small Industrial Projects sections, categories, and elements.

<table>
<thead>
<tr>
<th>Table 1: PDRI-Small Industrial Projects SECTIONS, Categories, and Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION I. BASIS OF PROJECT DECISION</strong></td>
</tr>
<tr>
<td>A. Project Alignment</td>
</tr>
<tr>
<td>A.1 Project Objectives Statement</td>
</tr>
<tr>
<td>A.2 Project Strategy and Scope of Work</td>
</tr>
<tr>
<td>A.3 Project Philosophies</td>
</tr>
<tr>
<td>A.4 Location</td>
</tr>
<tr>
<td>B. Project Performance Requirements</td>
</tr>
<tr>
<td>B.1 Products</td>
</tr>
<tr>
<td>B.2 Capacities</td>
</tr>
<tr>
<td>B.3 Processes</td>
</tr>
<tr>
<td>B.4 Technology</td>
</tr>
<tr>
<td>B.5 Physical Site</td>
</tr>
<tr>
<td><strong>SECTION II. BASIS OF DESIGN</strong></td>
</tr>
<tr>
<td>C. Design Guidance</td>
</tr>
<tr>
<td>C.1 Lead/Discipline Scope of Work</td>
</tr>
<tr>
<td>C.2 Project Design Criteria</td>
</tr>
<tr>
<td>C.3 Project Site Assessment</td>
</tr>
<tr>
<td>C.4 Specifications</td>
</tr>
<tr>
<td>C.5 Construction Input</td>
</tr>
<tr>
<td>D. Process/Product Design Basis</td>
</tr>
<tr>
<td>D.1 Process Safety Management (PSM)</td>
</tr>
<tr>
<td>D.2 Process Flow Diagrams along with Heat and Material Balance</td>
</tr>
<tr>
<td>D.3 Piping and Instrumentation Diagrams (P&amp;ID’s)</td>
</tr>
<tr>
<td>D.4 Piping System Stress Analysis</td>
</tr>
<tr>
<td>D.5 Equipment Location Drawings</td>
</tr>
<tr>
<td>D.6 Critical Process/Product Items Lists</td>
</tr>
<tr>
<td><strong>SECTION III. EXECUTION APPROACH</strong></td>
</tr>
<tr>
<td>E. Electrical and Instrumentation Systems</td>
</tr>
<tr>
<td>E.1 Control Philosophy</td>
</tr>
<tr>
<td>E.2 Functional Descriptions and Control Narratives</td>
</tr>
<tr>
<td>E.3 Electrical Single Line Diagrams</td>
</tr>
<tr>
<td>E.4 Critical Electrical Items Lists</td>
</tr>
<tr>
<td>F. General Facility Requirements</td>
</tr>
<tr>
<td>F.1 Site Plan</td>
</tr>
<tr>
<td>F.2 Loading/Unloading/Storage Requirements</td>
</tr>
<tr>
<td>F.3 Transportation Requirements</td>
</tr>
<tr>
<td>F.4 Additional Project Requirements</td>
</tr>
<tr>
<td><strong>SECTION III. EXECUTION APPROACH</strong></td>
</tr>
<tr>
<td>G. Execution Requirements</td>
</tr>
<tr>
<td>G.1 Procurement Plan</td>
</tr>
<tr>
<td>G.2 Owner Approval Requirements</td>
</tr>
<tr>
<td>G.3 Distribution Matrix</td>
</tr>
<tr>
<td>G.4 Risk Management Plan</td>
</tr>
<tr>
<td>G.5 Shutdown/Turnaround Requirements</td>
</tr>
<tr>
<td>G.6 Precommissioning, Startup, &amp; Turnover Sequence Requirements</td>
</tr>
<tr>
<td>H. Engineering/Construction Plan and Approach</td>
</tr>
<tr>
<td>H.1 Engineering/Construction Methodology</td>
</tr>
<tr>
<td>H.2 Project Cost Estimate</td>
</tr>
<tr>
<td>H.3 Project Accounting and Cost Control</td>
</tr>
<tr>
<td>H.4 Project Schedule and Schedule Control</td>
</tr>
<tr>
<td>H.5 Project Change Control</td>
</tr>
<tr>
<td>H.6 Deliverables for Design and Construction</td>
</tr>
<tr>
<td>H.7 Deliverables for Project</td>
</tr>
</tbody>
</table>

A basic tenet of front end planning is that not all items to be assessed are equally critical to project success. Certain elements are higher in the hierarchical order than others with respect to their relative importance. An analysis was necessary to “weight” the elements accordingly. Focus groups were utilized to gain prioritization data from a subset of the total industrial construction stakeholder population. Focus groups are simply a group of subjects interviewed together, prompting a discussion (Babbie 2011). This method was successfully utilized by each of the previous PDRI research teams (Gibson and Whittington 2010). Five such focus groups, or “weighting workshops,” were convened to weight the PDRI elements. The weighting workshops were held in multiple locations in an effort to gain a variety of industry
perspectives related to typical small industrial projects. Workshop locations, dates, and number of participants are shown in Table 2.

Table 2: PDRI-Small Industrial Projects Weighting Workshops

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Number of Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baton Rouge, Louisiana</td>
<td>4/10/14</td>
<td>19</td>
</tr>
<tr>
<td>Houston, Texas</td>
<td>5/9/14</td>
<td>12</td>
</tr>
<tr>
<td>Greenville, South Carolina</td>
<td>6/4/14</td>
<td>12</td>
</tr>
<tr>
<td>Indianapolis, Indiana</td>
<td>7/21/14</td>
<td>12</td>
</tr>
<tr>
<td>Houston, Texas</td>
<td>7/30/14</td>
<td>10</td>
</tr>
</tbody>
</table>

Purposive sampling, also referred to as judgmental sampling, is a method in which individuals are selected to be part of the sample based on the researcher’s judgment as to which individuals would be the most useful or representative of the entire population (Babbie 2011). Industry experts with substantial experience in the management and/or design of small industrial projects were targeted to participate. Snowball sampling, or asking targeted individuals to suggest other individuals with similar expertise (Babbie 2011) was used to increase workshop attendance. Figure 2 provides some demographical background information about the workshop participants.

- 65 Workshop Participants
- 65 Weighted PDRI forms completed
- 1,299 Collective years of experience
- 20 years (on average) estimating/project management experience
- 64% of experience (on average) related to small projects
- 85% of experience (on average) related to industrial construction projects
- 29 Organizations represented

Figure 2: Workshop Participant Demographics

During the workshop sessions, participants were asked to assign a contingency amount (i.e., weight) to each of the PDRI elements, indicating the relative importance of each element as compared to the balance of elements in the PDRI. The weights provided by the participants were compiled and analyzed to develop the weighted PDRI score sheet. An excerpt of the weighted score sheet is provided in Figure 3. The workshop participants were also asked to provide feedback relating to any concerns they had regarding the element descriptions. Items brought up during workshop discussions were noted by the workshop facilitators. Each participant was also provided a “Suggestions for Improvement” sheet where additional thoughts could be recorded. The research team reviewed all comments collected during the workshops, and revised the element descriptions as appropriate. For more detail on the data analysis procedures utilized, please see CII (2015).
Figure 3: Weighted Score Sheet for Category A Project Alignment

Previously developed PDRI’s use a scale of 70 (i.e., sum of all Level 1 definitions) to 1000 (i.e., sum of all Level 5 definitions). A project with low definition would receive a higher score (i.e., closer to 1000) than a project with higher definition that would receive a lower score (i.e., closer to 70). Any elements deemed not applicable would lower the potential Level 1 and Level 5 scores on a pro-rata basis depending on the weighting of the element. Research Team 314 chose to use this same scale for the PDRI-Small Industrial Projects to keep constancy with the previously developed PDRI tools.

3 COMPARISON OF INDUSTRIAL PROJECT PDRI’S

3.1 Characterization of Small Industrial Projects

Industrial projects with substantial scope, complexity, schedule duration, and cost are typically considered “large”. Considerable effort is expended to ensure success on large projects, as they are viewed to be critical to an organization’s overall financial prosperity. “Small” projects - projects typically differentiated from large projects due to having lower costs – oftentimes have minimal emphasis placed on detailed front end planning. Small projects tend to be seen as having low risk, and thus not warranting a structured planning approach. Younger or inexperienced project managers and engineers are assigned small projects as training tools in preparation for work on larger future projects (CII 1991).

In reality, assuming that a small project inherently carries lower risk or is less critical to an organization is short-sighted. Based on an industry survey conducted by Research Team 314, seventy to ninety percent of all projects completed in the industrial sector (on a count basis) are considered small, making up a vast majority of completed work each year. While additional project cost or schedule overrun on one small project could possibly have a minimal impact on an organization, the cumulative effect of poorly planned small projects can have a major impact on an organization’s bottom line. The PDRI-Small Industrial Projects was developed to specifically address this important and prevalent project type.

Small projects should not be differentiated from large projects based on solely on static levels of project costs within an organization or the industry at large. Project complexity is the true differentiator between small and large projects. Complex is defined as “a group of obviously related units of which the degree and nature of the relationship is imperfectly known” (Merriam-Webster 2014). Complexity is the quality or state of being complex. Industrial construction projects can fall anywhere along the spectrum of complexity, from projects with little to no complexity (i.e., pure maintenance projects) to highly complex projects (i.e., mega-projects). The rigor of planning efforts expended on a project should match its level of complexity. The PDRI-Small Industrial Projects focuses on lower-complexity projects.

Table 3 below provides data from a study of ninety industrial projects with varying levels of complexity completed by Research Team 314. The averages of nine separate project attributes for typical small and
large industrial projects are given. Table 3 also provides direction in selecting the appropriate PDRI tool for use on an industrial project, but PDRI users are urged to not see the matrix as a strict guideline. For example, in some organizations projects with total installed cost of US$10 million may be very small, while in other organizations projects of this caliber may be considered very large. In choosing a suitable tool for a specific project, project teams assessing industrial projects are urged to consider these factors and choose the appropriate tool based on their organization’s internal project planning specifications.

Table 3: Industrial PDRI Selection Guide

<table>
<thead>
<tr>
<th>Project Complexity Indicator</th>
<th>PDRI - Small Industrial Projects</th>
<th>PDRI - Industrial Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Installed Cost</td>
<td>Less than $10 Million (US Dollars)</td>
<td>More than $10 Million (US Dollars)</td>
</tr>
<tr>
<td>Construction Duration</td>
<td>3 to 6 months</td>
<td>9 to 15 months</td>
</tr>
<tr>
<td>Level of Funding</td>
<td>Between regional and corporate</td>
<td>Between corporate and Board of Directors</td>
</tr>
<tr>
<td>Project Visibility</td>
<td>Moderate</td>
<td>Significant</td>
</tr>
<tr>
<td>Number of Core Team Members</td>
<td>7 to 9 individuals</td>
<td>10 and 15 individuals</td>
</tr>
<tr>
<td>Availability of Core Team Members</td>
<td>Part-time availability</td>
<td>Combination of part-time and full-time</td>
</tr>
<tr>
<td>Extent of Permitting</td>
<td>None to minimal permitting</td>
<td>Minimal to significant permitting</td>
</tr>
<tr>
<td>Types of Permits</td>
<td>None to local/state permits</td>
<td>Locals/state to national permits</td>
</tr>
<tr>
<td>Number of Trade Contractors</td>
<td>3.4 separate trade contractors</td>
<td>7.8 separate trade contractors</td>
</tr>
</tbody>
</table>

3.2 Process vs. Non-Process Industrial Projects

The PDRI - Small Industrial Projects was developed to assess both process and non-process related projects. Research Team 314 defines a “process” related project as any project in an industrial facility related to constructing or refurbishing the systems, equipment, utilities, piping, and/or controls that directly affect the production rate, efficiency, quantity, or quality of the product being produced. These projects typically have a stated Return on Investment (ROI) expectation directly related to improved production factors, and may affect how the product is marketed to consumers (e.g., higher quality than before, increase in quantities available). In most cases, documents pertaining to the ongoing operations of the facility (e.g., piping and instrumentation diagrams, process safety management plans) need to be created, or existing documents updated. A “non-process” related project is defined as any project in an industrial facility that is ancillary to production processes, but does not directly affect the quantity or quality of the product being produced. Examples of these types of projects include additions to or expansion of the infrastructure that supports a facility, facility updates necessary for environmental or safety compliance, replacement-in-kind of facility components (e.g., equipment, structural, piping) that do not directly affect the nature of the product being produced. If an ROI is required on these projects, it is typically attributed to improving the operating efficiencies of the facility that are not directly related to production, such as increased energy efficiency related to installing Variable Frequency Drives (VFD’s) on HVAC equipment, or installing solar panels to lessen the amount of power needed from a public utility provider. Documents pertaining to the ongoing operations of the facility (e.g., piping and instrumentation diagrams, process safety management plans) may or may not need to be created or updated.
Examples of small industrial projects can include:

**Process**
- Oil/gas Refining Facilities
  - Stack monitoring and flare line replacement
  - Replacement of desalter effluent cooler fin fans
  - Installation of gasoline cooler in pipeline
  - Addition of hydrogen plant within existing refinery
  - Replacement-in-kind of process piping
- Pulp/Paper Mills
  - Replacement of entangling section
  - Replacement of internal screens in digester vessel
  - Replacement of headbox section
  - Replacement of components associated with wood yard log chipping line
- Manufacturing Facilities
  - Installation of a new packaging line
  - Modifications to existing packaging line
  - Addition of a motor control center
- Breweries
  - Replacement of cooker coils
  - Upgrade coders on can line
- Chemical Plants
  - Installation of new technology nylon compounding extruder and pack-out
  - Replacement of injection molder

**Non-Process**
- Plant Upgrade/Retrofit
  - Replacement of existing elevators
  - Replacement of existing HVAC equipment
  - Repointing of existing masonry structures
  - Replacement or upgrades to existing power supply
  - Installation of raw material railcar offload station
  - Water conservation projects
  - Replacement of constant speed electric-feed-water pumps with variable frequency driven pumps
  - Addition of waste water clarifier to storm sewer system
  - Installation of new dust collection equipment and ducting
  - Installation of environmental monitoring or noise abatement equipment
  - Installation of new security cage and associated security system within an existing operating warehouse facility

### 3.3 Industrial PDRI Application Points

Previous PDRI research (CII 2008, 2008(b), 2010) has found that assessing a large project (from any of the construction sectors) is best performed four separate times during the front end planning process, as shown in Figure 4. This iterative “stage gate” approach allows project teams to assess how well planning activities have progressed prior to formally moving the project forward to the next phase.
The speed and concurrent phasing of small projects makes it more difficult to provide guidance on the best time to conduct a PDRI review. In many small projects, the entire project may be charged against a funding budget; hence the users will want to perform an assessment to “get on track”. In other situations, there may be a funding point after the initial decision to proceed with the development, and just prior to that funding decision may be the optimal time to use the tool. A small project may be phased such that Feasibility, Concept, Detailed Scope, and Design, Procurement and Construction are all overlapping. This may not be the optimum way to proceed with a project, but may reflect the reality of typical small industrial projects.

The PDRI-Small Industrial Projects was designed with the intent that it could be used multiple times throughout the FEP process, or as a one-time use tool. Project size, complexity and duration will help determine the optimum time (or times) that the PDRI tool should be used. To aide in the expanded use of this tool, Figure 5 illustrates suggested application points for the PDRI-Small Industrial Projects. By utilizing the tool multiple times, project teams can capture the benefits of an iterative review process in a timeframe consistent with a shorter project schedule. However, if used only once in the FEP process, the project team may find the tool comparably effective if deployed properly. Proper review-team development, effective capture, and follow up on action items, and open and honest discussion aimed at revealing project scope concerns best support using the tool only once. If a project is assessed only once, the earlier in the project life cycle this occurs the better.

4 PDRI-SMALL INDUSTRIAL PROJECTS USAGE TO DATE

The PDRI-Small Industrial Projects has been used on 12 projects during real-time planning exercises. Nine of the projects were process related, including a stand-alone manufacturing facility, additions to
existing manufacturing lines, structural replacement of an existing cooling tower support system, a natural gas pipeline meter station, replacement of a reverse-osmosis water treatment system, and a clean-room manufacturing suite. The three non-process related projects included a new stand-alone QC lab, a petroleum pipeline measurement skid, and a natural gas pipeline meter station. The average budgeted total installed cost was US $4.0 million, and the average construction schedule duration was 5 months. Each assessment was completed at the PDRI-Final application point detailed in Figure 5. The average time to complete the PDRI assessment was approximately 1.5 hours.

In general, the feedback from users was extremely positive. The tool performed very well in identifying critical risk issues during the front end planning process, and spurred important conversations about elements not yet considered by the project team. As one user stated, "Utilization of the PDRI-Small Industrial Projects tool not only provided for a structured process to assess the status of project scope definition and execution readiness, it also assisted the team in bringing newly assigned individuals on the project up to speed on the project scope and status, as well as gaining alignment within the team on the project plan." As another user stated, "My first reaction was – this is going to take a long time… I picked it up and realized it wasn’t complicated at all. I like (the tool) because it’s easy and straight forward."

5 CONCLUSION

Effective front end planning practices can substantially improve project performance if implemented consistently and correctly. The PDRI tools developed by CII are meant to assess how well a project team has planned for an upcoming project, providing guidance to specific elements that should be considered during front end planning to quickly identify project risk factors related to desired outcomes for project cost, schedule, and operating performance. The PDRI elements are weighted to highlight their relative importance to project success. This paper has summarized the development of the newest PDRI tool, which was developed specifically to address small industrial projects, a project type the makes up a substantial portion of industrial projects completed each year. The tool has been used on 12 projects to date, with extremely positive feedback regarding the tool’s effectiveness and ease of use.

Empirical evidence would suggest that small projects are just as prevalent in the building and infrastructure sectors as they are in the industrial sector. The methodology described in this paper along with the Research Report (CII 2015) developed by Research Team 314 could be used in future research to develop PDRI tools specifically for small infrastructure and building projects.

Acknowledgements

The authors would like to thank The Construction Industry Institute, Research Team 314 PDRI for Small Industrial Projects, and all the workshop and survey participants for their help and participation in completing this research. Any and all views expressed in this paper are those of the authors and do not necessarily reflect the views of the Construction Industry Institute.

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AUTOMATED DIMENSIONAL COMPLIANCE ASSESSMENT WITH INCOMPLETE POINT CLOUD

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Abstract: Dimensional compliance assessment of prefabricated assemblies is a critical part of mitigating rework on heavy industrial construction projects. As assemblies become more complex, manual direct contact metrology becomes ineffective at detecting fabrication error and so automated alternatives that offer objective, fast, and continuous data collection must be explored. Nahangi and Haas (2014) developed an automated method for assessing pipe spools through an algorithm that compares as-built laser scans to 3D design files. The tool is capable of automatic and continual monitoring of prefabricated assemblies throughout their lifecycle and enables timely detection and quantification of dimensional non-compliance. In the original publication, the tool was validated using ideal input data. In this paper, the tool is tested for robustness when processing incomplete point cloud input data. Non-ideal input data is a risk associated with unfavorable conditions in the fabrication environment such as random assembly occlusions causing blind spots in sensing setup, budgetary constraints limiting the purchase of sensing equipment/viewpoints, and random hardware or software failures resulting in corrupt data. The tool was found to reliably detect dimensional non-compliance so long as the non-compliance indicator (pipe spool feature distinguishing the non-compliant state from the design state) was not fully occluded. Accuracy of non-compliance quantification was predominantly high, however, loosely proportional to the input point cloud’s coverage of the assembly’s surface area.

1 INTRODUCTION AND BACKGROUND

1.1 Introduction

As the use of modularization and prefabrication becomes more prevalent within industrial construction, the scope of modularization will expand to include a greater diversity of systems and account for a larger portion of constructed facilities (Chandler 2013). As a result, the effective execution of prefabrication will play an increasingly central role in total cost and schedule management on construction projects.

Prefabrication errors and omissions are considered a significant source of rework (Dissanayake et al. 2003), and so have been the focus of many quality control tool development projects (Bosché 2010; Akinci et al. 2006; Kim et al. 2015). In order to achieve successful deployment in the field, these tools need to be subjected to additional rigorous testing for robustness when operating under non-ideal conditions. In this paper, a series of data inputs of varying quality representing an as-built experimental pipe spool are collected and used for analysis using the tool presented in (Nahangi and Haas 2014). The relationship between input data quality and the accuracy of output fabrication error detection and quantification are explored.
1.2 Rework

In the construction literature, rework is the wasteful effort involved in redoing work that has not yet yielded a product adequately conforming to contractual requirements (Love and Li 2000; Hwang et al. 2009). Rework directly and significantly contributes to cost and schedule overruns on construction projects (Love 2002; Hegazy, Said, and Kassab 2011). Specifically, research published by the Construction Industry Institute (CII) states that rework costs between 2 percent and 20 percent of a typical project’s contract amount (Construction Industry Institute (CII) Research Team 252 2011). Using data from 178 construction projects, (Hwang et al. 2009, 187-198) assessed the impact of rework from a contractor’s perspective and concluded that it most greatly influenced cost increases on heavy industrial projects. It has been argued that the cause of rework on such projects is attributable to poor construction techniques and poor construction management policies (O’Connor and Tucker 1986). On a mining expansion megaproject in Alberta, it was discovered that errors and omissions in prefabrication and poor workmanship of prefabricated materials was a significant source of rework (Dissanayake et al. 2003). Systematic quality assessment of construction components during their lifecycle is important to reduce rework on projects (Love and Li 2000) and particular attention must be given to processes within prefabrication facilities to ensure they are meeting project requirements and mitigating field rework. Any automated quality assessment tools used for this purpose would need to have the capability of identifying errors and omissions in a timely and accurate manner, while using the most up-to-date design files as many rework situations occur because field changes are not communicated to the fabricator effectively.

1.3 Laser Scanning and Fabrication Process Control

Designers and QC specialists typically utilize standardized dimensional tolerance guidelines such as the systems published by American Society of Mechanical Engineers (ASME) or the International Organization for Standardization (ISO). Currently, the predominant processes for monitoring the critical dimensions outlined in these standards involve manual assessment by certified QC personnel using direct contact measurement devices such as measuring tapes, calipers, custom gauges, squares, and straightedges. These processes can help fabricators evaluate whether basic assemblies are compliant with design specifications, but their effectiveness deteriorates as the assembly’s geometrical complexity increases because manual measurement is subjective, time-consuming, costly, and discontinuous. There is a need for automated and systematic dimensional compliance control tools that offer objective, fast, and continuous data collection for reliable quality control on heavy industrial construction projects.

Laser detection and ranging (LADAR) is an increasingly important technology from 3D computer vision used for metrology in the AEC industry (Patraucean et al. 2015). Laser scanners are used to collect spatial data about their surrounding in the form of a 3D point cloud. Compared to contact metrology, laser scanning collects data quickly (up to 976,00 data points per second) allowing for comprehensive coverage of large structures, and with millimeter accuracy (error ± 2mm) (FARO 2015). Considering these capabilities, the feasibility of laser scanning technology for dimensional quality control has been studied by several researchers. (Bosché 2010) proposed an automated method for recognizing 3D CAD model objects in laser scanned data for dimensional compliance control of construction assemblies. (Akinci et al. 2006) proposed a general formalism involving the comparison of as-built laser scans with design CAD models for quality control. (Kim et al. 2015) proposed a holistic approach for dimensional and surface quality assessment of precast concrete elements based on comparing BIM and 3D laser scans.

1.4 Automated Dimensional Compliance Checking in Pipe Spool Fabrication

The increasing complexity of off-site fabricated modules necessitates the implementation of automated dimensional compliance feedback tools capable of comprehensive and reliable measurement. (Nahangi and Haas 2014) presented an automated compliance control method for construction modules that reliably detects the presence of dimensional non-compliance and has consistently quantified the deviations with less than 10% error in experimental studies. The method requires two 3D imaging input files: (1) a 3D model of the as-built assembly generated using a 3D reconstruction technique such as LADAR and (2) the tolerance specifications as represented by the 3D CAD design file. The files are input into a three stage algorithm,
1. **Preprocessing**: involves converting the input 3D imaging files into a standard point cloud format and object of interest isolation from the as-built cluttered point cloud.

2. **Registration**: begins by importing the two input point clouds into a common 3D space. Since the input files do not share a common origin, they need to be aligned through a combination of course registration using principal component analysis and fine registration using iterative closest point (Bosché 2012; Besl and McKay 1992).

3. **Dimensional non-compliance detection and quantification**: analyzes the deviations between the superimposed files using a 3D cube local neighborhood-based metric and outputs discrepancies between the two files in a number of different formats (ex. rotation at joints, extensions/contraction of members) depending on user preference.

The experimental study that validated the method within the paper used ideal as-built data with complete surface coverage of the object of interest.

**1.5 Practical Implications of Tool Implementation**

Transferring knowledge and technology from universities to industry is extremely challenging because of the inherent gap between basic research at universities and industrial exploitation (Griffiths and Röhrbein 2013). University-industry collaborations attempt to increase and test the robustness of basic laboratory proven technologies to ensure their suitability for application in complex industrial environments. If applied in a fabrication facility, an automated dimensional compliance checking tool would need to be capable of generating meaningful outputs from non-ideal data inputs. Non-ideal data collection conditions and resulting incomplete point cloud inputs are an unfortunate reality because of: random assembly occlusions causing blind spots in sensing setup, budgetary constraints limiting the purchase of sensing equipment/viewpoints, and random hardware or software failures resulting in corrupt data (Seversky and Yin 2012).

In order to progress the tool presented in (Nahangi and Haas 2014) towards application in industry, its ability to accurately detect and quantify dimensional non-compliance from incomplete point cloud inputs should be evaluated.

**2 METHODOLOGY AND EXPERIMENT**

**2.1 Laboratory Setup and Equipment**

To evaluate the performance of the methodology proposed in (Nahangi 2015) under incomplete point cloud input conditions, a series of experiments were conducted at the University of Waterloo’s Ralph Haas Infrastructure Sensing and Analysis Laboratory. The researchers collected data using a reconfigurable pipe spool (Figure 1), and a FARO LS 840 HE (Table 1). The pipe spool has custom connections that allow controlled displacements and rotations in order to deviate the assembly from its design compliant state.

Two controlled rotations were introduced into the assembly: 2.5 degrees on Branch 1 (B1) and 15 degrees on Branch 2 (B2) (Figure 2). These rotations simulated a state of design non-compliance that was held constant for 7 laser scans. A plan view layout of the locations of the laser scanner for the 7 laser scans can be found in Figure 1.
Figure 1: a. Reconfigurable pipe spool with two areas of interest; b. Laser scanner locations relative to pipe spool layout plan view

Table 1: Technical specifications of laser scanner

| Laser Properties          |  |
|---------------------------|  |
| • Power: 10.5 mW          |  |
| • Wavelength: 785 nm      |  |
| • Phase based measurement |  |

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>0.6-40 m</td>
<td>0.6 mm (@ maximum resolution)</td>
</tr>
<tr>
<td>Field of View</td>
<td>Horizontal: 360°; Vertical 320°</td>
<td>Horizontal: 0.009°; Vertical 0.00076°</td>
</tr>
</tbody>
</table>
2.2 Preprocessing

7 laser scans were collected of the pipe spool in its design non-compliant state. The scans were then merged in different combinations to obtain a set of point clouds with varying pipe spool surface coverage. The point clouds were imported into Meshlab (Cignoni et al. 2014), and through surface reconstruction, a surface area of coverage was calculated and compared to total surface area. Surface coverage is used as a metric for point cloud completeness. The mesh generated from scan 1 data points can be seen in Figure 3. The surface area calculated indicates 44% total pipe spool surface area coverage and 30% surface area coverage of the design non-compliance indicators (NCI) (pipe spool features distinguishing non-compliant state from design state).

Results of preprocessing can be found in Table 2. Total surface coverage ranges from 26% to 100% for the set of point clouds. Point cloud 1 was created by modifying scan 2 to simulate a large obstruction such as a welding screen, occluding half of the pipe spool (Figure 4). In point cloud 3, the NCI for B2 was fully occluded.

Figure 3: Point cloud 5, scan 1, mesh representing point cloud surface coverage of pipe spool and design non-compliance indicators

Figure 4: Point cloud 1, scan 2 modified to simulate a large obstruction occluding half of the pipe spool
Table 2: Point cloud surface coverage of pipe spool

<table>
<thead>
<tr>
<th>Point Cloud</th>
<th>Scan Sources</th>
<th>Surface Coverage: Total</th>
<th>Surface Coverage: B1 Non-compliance Indicator</th>
<th>Surface Coverage: B2 Non-compliance Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 modified*</td>
<td>26%</td>
<td>27%</td>
<td>60%</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>33%</td>
<td>13%</td>
<td>30%</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>34%</td>
<td>0%</td>
<td>30%</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>38%</td>
<td>27%</td>
<td>75%</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>44%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>6</td>
<td>1,3</td>
<td>55%</td>
<td>52%</td>
<td>61%</td>
</tr>
<tr>
<td>7</td>
<td>3,4</td>
<td>57%</td>
<td>16%</td>
<td>67%</td>
</tr>
<tr>
<td>8</td>
<td>1,7</td>
<td>58%</td>
<td>52%</td>
<td>84%</td>
</tr>
<tr>
<td>9</td>
<td>2,4</td>
<td>60%</td>
<td>27%</td>
<td>80%</td>
</tr>
<tr>
<td>10</td>
<td>2,5</td>
<td>66%</td>
<td>34%</td>
<td>65%</td>
</tr>
<tr>
<td>11</td>
<td>1,3,4</td>
<td>68%</td>
<td>47%</td>
<td>79%</td>
</tr>
<tr>
<td>12</td>
<td>1,2,4</td>
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<td>42%</td>
<td>87%</td>
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<td>13</td>
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<td>53%</td>
<td>88%</td>
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<td>14</td>
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<td>76%</td>
<td>75%</td>
<td>94%</td>
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<tr>
<td>15</td>
<td>1,2,3,4,5,6,7</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Point cloud 1 modified to simulate a large obstruction occluding half of the pipe spool Figure 4

3 RESULTS

The incomplete as-built point clouds were analysed for dimensional non-compliance using the methodology described in section 2.3. Monitoring both the total surface area coverage and NCI surface area coverage of the pipe pool by the as-built point clouds, the relationship between these factors and the accuracy of the corresponding dimensional compliance assessments was explored. As seen in Figure 5, the detection rate of the controlled rotation in B1 was 100% (i.e. all point cloud instances were able to detect the presence of the rotation). As well, the quantification of the controlled rotation in B1 ranged from 2.41 to 2.53 degrees, representing a maximum error of 4% for point cloud from a single scan, 1.6% from two scans, and 3.2% from three scans (relative to the quantification from Point Cloud 15, 2.51 degrees).

The detection rate of the controlled rotation in B2 was 93%. The point cloud which was unable to detect the rotation had 0% surface area coverage of the B2 NCI and was not included in the quantification stage of the methodology. The quantification of the controlled rotation in B2 ranged from 8.61 to 28.63 degrees representing a maximum error of 90% for point cloud from a single scan, 42.9% from two scans, and 20.9% from three scans (relative to the quantification from Point Cloud 15, 15.08 degrees). All data suggests an inverse correlation between error of non-compliance quantification and surface coverage by point cloud.
Prefabrication errors are a significant source of costly rework on heavy industrial projects. Researchers have developed and validated dimensional compliance control algorithms that have the potential to improve quality control in prefabrication environments by using data from LADAR and concepts from computer vision. However, these tools need to be subjected to additional rigorous testing for robustness to non-ideal data inputs before successful deployment in the field can be achieved. Several scans were collected of an experimental pipe spool, and a surface area of assembly coverage metric was used to gauge the quality of input point clouds. Processing the data using the methodology described in section 2.3, a relationship between input data quality and the accuracy of detection and quantification of dimensional non-compliance was explored.

The result was a 100% dimensional non-compliance detection rate in the experimental study, with the exception of the case in which the NCI (pipe spool feature distinguishing non-compliant state from design state) was fully occluded. Thus, reliable detection of non-compliance is possible from a single scan, but the output is susceptible to false negatives resulting from assembly occlusion. In order to mitigate this risk and improve the methodology's robustness, at least two scan perspectives should be used to ensure dimensional non-compliance detection.

The accuracy of quantifying the detected dimensional non-compliance improved as the input as-built point cloud's coverage of the assembly's surface area increased. The error of quantification for the rotation in B2 (branch 2 of the experimental pipe spool) was greater than the error for B1 (branch 1 of the experimental pipe spool), which could be attributable to the smaller surface area of the NCI. However, the error in B2 was substantially reduced as point cloud surface coverage increased. Thus if accurate
quantification is desired, it can be achieved by using additional scans in the analysis. Quantification in B1 was consistently accurate.

Future work should build on our present understanding of other pertinent variables in the methodology, particularly those involved in the manual portions of the process, in order to better determine the source of error and variability in output accuracy.

Acknowledgements

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References


DEVELOPMENT OF MECHANISMS BY USING CONCEPTUAL SYSTEM DYNAMICS MODELS TO RESOLVE DELAY IN CONSTRUCTION PROJECTS

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Abstract: A major concern in the construction industry remains with the non understanding of the mechanisms that cause delay in construction. Therefore, the objective of the paper is to evolve mechanisms, which could assist in identifying activities and events, comprehend and foresee the causal feedback relations among the variables that cause delay, and take appropriate actions to resolve the challenges of delay. A survey was conducted among 120 stakeholders from various construction projects in India. Evaluation of the major control parameters were done by using Likert scale. Subsequently, conceptual models were developed by using System Dynamics modelling principles. The important causal feedback relations from the conceptual models were used to evolve mechanisms to understand the events and chain of actions that lead to delay; which could assist in evolving policy/strategic interventions to resolve the challenges. It was observed that most of the client, contractor, consultant and design related variables are the major causes of occurrence of delay. However, policy/strategic interventions based on the four dynamic hypotheses; such as, the causal feedback relationships among (1) communication, decision-making, progress in payment and construction delay; (2) effective planning and scheduling, planning for finance and budget ahead, adoption of construction methods, contingencies in planning for rework and exigencies by the contractor and construction delay; (3) appointment of highly competent consultant and design team, delay in producing the design documents and delay in construction; and (4) provision of effective communication mechanism, conflict resolution and delay in construction, would able to assist in resolving delay in construction.

1 INTRODUCTION

Delay is a major cause of concern in almost all construction projects. The reasons of delay could be generally classified under broad issues related to client/owner, contractor, design, construction, materials, equipment and project management (Alaghbari, Razali, Kadir, Ernawat 2007, Assaf, and Al-Hejji 2006, Chan and KumaraSwamy 1997, Desai and Bhatt 2013; Kaming, Olomolaiye, Holt, Harris 1997, Odeh and Battaineh 2002; Stumpf 2000). However, the main concern remains with the non understanding of the mechanisms and not foreseeing of the unwarranted events by the stakeholders and project management team, which lead to delay. Over the years there are plenty of investigations made regarding to the causes, and various methods of analysis of construction delay. But, investigations relating to development of interventions or mechanisms to resolve the challenges of delay in construction projects are observed to be scarce. Taking into account the significant impacts of delay, there is an argument that development of mechanisms by considering various components and stakeholders would assist to foresee the chain of events that cause delay and to resolve the challenges (Alaghbari et al. 2007, Sweis, Sweis, Hammad, Abu 2008). Therefore, the objective of the paper is to evolve mechanisms, which could assist the project stakeholders to identify the activities and events, comprehend and foresee the causal
feedback relations among the variables that cause delay, and take appropriate actions to resolve the challenges of delay. The investigation was conducted by using a survey research methodology and System Dynamics (SD) modelling approach. A total of 120 stakeholders and professionals from large and medium projects in India, which includes project managers, architects, engineers, skilled technicians, consultants, designers, quantity surveyors, contractors and clients, were surveyed through semi-structured interview method to comprehend the major control variables causing delay in construction projects. Followed by, conceptual models were developed based on the causal feedback relations among the major variables influencing delay by using SD modelling principles. The important causal feedback relations in the conceptual models were used to comprehend the mechanisms that could enable understanding of the events and chain of actions that lead to delay; and to evolve policy/strategic interventions to resolve the challenges. It was observed that variables relating to client, contractor, consultant and design are the major causes of delay. These variables are interlinked with each other and function in causal feedback mechanisms creating a chain of actions, which influence the occurrence of delay. The mechanisms developed based on these causal feedback relations among the variables will act as a tool to assist the stakeholders, such as clients, contractors, consultants and project management team to foresee the challenges of delay ahead at each and every stage of construction projects and take appropriate actions to resolve them.

2 LITERATURE REVIEW

Delay in construction can be defined as the time overruns either beyond the contract date specified in a contract, or beyond the date that the parties agreed upon for delivery of a project. Generally, it is the additional days of work for completion of project/ activity or as a delayed start of an activity (Assaf, Al-Hejji 2006; Stumpf 2000). Since the construction process is subject to many variables and unpredictable factors, delays are found to be inevitable and become integral part of the project’s construction life. Even with the availability of advanced technology, and understanding of the project management techniques, construction projects continue to suffer delays (Stumpf 2000). The sources of delay are varied, which include the performance and involvement of stakeholders, resources availability, environmental conditions, contractual relations, and so on (Alaghbari, Razali, Kadir, Emawat 2007, Kaming, Olomolaiye, Holt, Harris 1997, Odeh and Battaineh 2002, Stumpf 2000). Besides, scholars like Al-Barak (1993), Al-Momani (2000), Chan and Kumaraswamy (1997), Kaming et al. (1997), Kumaraswamy and Chan (1998) and Noulmanee, Wachirathamrojn, Tantichattanont, Sittivijan (1999) have studied the causes of delay in different projects.

From these studies it is found that causes of delay vary with context and project environment. For instance, Chan and Kumaraswamy (1997) found five principal factors: poor risk management and supervision, unforeseen site conditions, slow decision making, client-initiated variations, and work variations. According to Kaming, et al. (1997) two different set of factors influence differently for cost overruns and time overruns. The major factors influencing cost overrun are material cost increase due to inflation, inaccurate material estimation and degree of complexity. For time overrun, the most important factors responsible are design changes, poor labour productivity, inadequate planning, and resource shortages. Some attribute the reason to bias of different industry groups and difference in perception by different groups as to what causes delay (Kumaraswamy and Chan 1998). According to Noulmanee et al. (1999), although delays can be caused by all parties involved in projects, the main causes come from the inadequacy of sub-contractors, organization that lacks sufficient resources, incomplete and unclear drawings, deficiencies of consultants and contractors, and differences between consultants and contractors. Similarly, Al-Momani (2000) observed that delay is related to designer, user changes, weather, site conditions, late deliveries, economic conditions and increase in quantity. Al-Barak (2000) concluded that lack of experience, poor estimation practices, bad decisions in regulating company’s policy, and national slump in the economy are the severe factors, which cause delay. Also, Aswathi and Thomas (2013) observed that contractors, rather than consultants and owners, were the most responsible party for the delays in construction projects (Ndekugri, Braimah and Gameson 2007). However, the role of owners in causing delay is no way meagre. In summary, factors like delay in progress of payments by owner, delay to furnish and deliver the site to the contractor by owner, change orders by owner during construction, late in revising and approving design documents by owner, delay in approving shop


drawings and sample materials, poor communication and coordination by owner and other parties, slowness in decision making process by owner, unavailability of incentives for contractor for finishing ahead of schedule, suspension of work by owner cause delay (Desai, Bhatt 2013, Assaf, Al-Hejji 2006). Similarly, inappropriate design, design changes, mistakes in design, late inspection, late design works, late approval, insufficient inspectors, incapable inspectors could cause delay (Alhomidan 2013, Desai and Bhatt 2013). However, causes like accidents, temporary stoppage, rework, extra work, external factors like weather conditions, unavailability of utilities, government law and regulations, etc., cannot be undermined (Iyer, Chaphalkar, Joshi 2008). Overall, the attributes can be classified into project, owner, contractor, consultant, design, material, equipment, labour and external related factors. Although, it is seen that many of the factors are interlinked and have cause and effect relationships (Assaf and Al-Hejji 2006, Chan and Kumaraswamy 1997, Frimpong et al. 2003, Manavizha and Adhikariib,2002, Odeh and Battaineh 2002, Sambasivan and Soon 2007), studies relating to such aspects are found to be limited. So, scholars like Alaghbari et al. (2007) stressed the importance of early identification of construction delays and development of major delay-reducing remedies (Sweis, Sweis, Hammad, Abu 2008).

A number of methods and techniques have been developed over the years to understand or analyse delay in construction industry (Braimah 2013). Yeats (2007) developed a decision support system (DAS) for delay analysis in construction projects, which could consider factors like equipment, external delay, labour, material, owner, contractor, management, subcontractor and weather (Odeh, Battaineh, 2002). Terry (2003) studied the standard methods currently available for assessing extension of time delays on major projects, and issues around such assessment, and used network causal mapping and system dynamics approach to study the impact of delays on a project. The other methods used are the frequency index (FI), severity index (SI), importance weight (IW), importance index (II), average weight (AW), influence value and activity duration. Some of the investigations have also used Monte Carlo simulation to derive delay reduction interventions (Aswath, Thomas 2013) and Fuzzy logic for delay computations (Pandey, Dandotiya, Trivedi, Bhadoniya, Ramasesh 2012). However, many of these methods do not explicitly consider the causal feedback relationships among the factors, which cause delay.

3 METHODOLOGY

A survey research methodology was employed to collect primary data from the various stakeholders in construction projects in India. A total of 120 questionnaires were administered, of which 102 were returned (approximately 85% response rate). Professionals and stakeholders from large and medium projects in India, which includes project managers, architects, engineers, skilled technicians, consultants, designers, quantity surveyors, contractors and clients/owners, were surveyed through semi-structured interview method. The respondents were asked to provide their opinions on the various parameters that cause delay and to rate the challenges in a scale of 1 to 5 (1= not influential, 2 = less influential, 3 = somewhat influential, 4 = significantly influential and 5 = most influential in causing delay) from the experiences in the projects they were involved in. The simple random sampling technique was used in the selection of samples for the survey.

Quantitative descriptive statistics analysis and Cronbach's alpha test of the data collected were conducted to observe the reliability of the data. Likert scale (Gravetter and Wallnau 2008) was employed to measure the relative influence causing delay through development of a delay index (DI) for the variables; and their general rank and rank under each major factor. Followed by, conceptual models by using SD modelling principles based on the systems thinking process (Von Bertalanffy 1974) were developed. The construction project was considered as the system or environment while developing the model. The influential variables, their positive and negative influences on the related variables and the causal relationships among them were used to develop the conceptual SD models. The causal relationships among the variables within and across the major parameters were developed based on the discussions and experiences of the professionals surveyed. While developing the causal relationships, initially the variables, such as, information, decision and action and environment (system) variables (Olaya 2012) were identified. The variables were then connected with simple one way causality in terms of one way linkages of information – decisions – actions – impact on the environment with their influence (i.e., information assisting in evolving decisions (policy interventions), decisions leading to appropriate
actions, and actions influencing the environment (system)) (El Halabi, Doolan, Cardew-Hall 2012, Veniix1996). Once the one way causalities were established the feedback relationships were checked and established. The constructed causal feedback relations were then discussed with the professional and experts in the field to check the veracity of the causal diagrams and relevant modifications with respect to the variable names, their polarity and causal relations as need be were made. The valid causal feedback diagrams (causal loop diagrams) were then employed to develop the conceptual SD models.

4 RESULTS, CONCEPTUAL SD MODELS AND DISCUSSION

4.1 Major Factors Causing Construction Delay

Table 1 presents the factors and their level of influence in construction delay. The various factors were grouped under project, client/owner, contractor, consultant, design, materials, equipment and labour related factors. However, external factors, such as, weather, availability of basic utilities, regulations, accidents, etc., have been kept out of the scope of the analysis. The acceptable standard deviation (SD) values and high Chronbach α (0.93) value show the reliability and acceptability of the data. The delay index (DI) and their general rankings revealed that majority of the factors belonging to client, contractor and consultant and design aspects of the projects have significantly higher delay indices compared to the factors belonging to materials, equipment and labour aspects. Thus, client/owner, contractor, consultant and design aspects have significant influence on construction delay. Similarly, the ranking in the groups show that delay in progress of payments by owner, slowness in decision making process by owner, change orders by owner during construction, poor communication and coordination by owner and other parties, delay in approving shop drawings and sample materials by the owner are the major client/owner related factors, which cause delay. Factors like delay in furnishing and delivering the site to contractor, suspension of work and lack of incentives to contractors for completion of the work ahead of schedule have lower impact. Similarly, difficulties in financing project by contractor, delay in financing project by contractor, conflicts between contractor and other parties (consultant and owner), rework due to errors during construction, ineffective planning and scheduling of project by contractor are the major contractor related causes of delay. Factors like poor communication and coordination by contractor with other parties, improper construction methods implemented by contractor, and delay in site mobilization also influence delay although to a lesser extent. Under consultant related factors, late in reviewing and approving design documents, delay in performing inspection and testing, delay in approving major changes in the scope of work, poor communication/coordination between consultant and other parties, inflexibility of consultant are the significant causes of delay, whereas delays in producing design documents, complexity of project design, mistakes and discrepancies in design documents, and unclear and inadequate details in drawings are the design related factors, which are the causes of concern. However, despite being relatively less influential delay due to delivery of material and late procurement of material, shortage of equipment, equipment breakdown, shortage of labour and unqualified labour force do cause delay in construction although they can be attributed to contractor or client related factors.

Table 1: Significance of elements and factors influencing delay in construction

<table>
<thead>
<tr>
<th>Group</th>
<th>Factors</th>
<th>Delay Index (DI) (Mean Score in Likert scale)</th>
<th>SD</th>
<th>Rank in the group</th>
<th>General Rank across the groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>Original contract duration is too short</td>
<td>3.32</td>
<td>0.23</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Legal disputes between various parties</td>
<td>2.79</td>
<td>0.17</td>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Ineffective delay penalties</td>
<td>3.45</td>
<td>0.31</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Client/Owner</td>
<td>Delay in progress payments by owner</td>
<td>4.35</td>
<td>0.34</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Owner</td>
<td>Delay to furnish and deliver the site to the contractor by the owner</td>
<td>3.65</td>
<td>0.27</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Change orders by owner during construction</td>
<td>4.10</td>
<td>0.32</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Late in revising and approving design documents by owner</td>
<td>3.95</td>
<td>0.33</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Column</td>
<td>Description</td>
<td>Score</td>
<td>Sigma Value</td>
<td>Rank</td>
<td>Value</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>-------</td>
<td>--------------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td>Delay in approving shop drawings and sample materials</td>
<td>3.85</td>
<td>0.38</td>
<td>6</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Poor communication and coordination by owner and other parties</td>
<td>4.05</td>
<td>0.35</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Slowness in decision making process by owner</td>
<td>4.20</td>
<td>0.32</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Unavailability of incentives for contractor for finishing ahead of schedule</td>
<td>2.85</td>
<td>0.26</td>
<td>9</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Suspension of work by owner</td>
<td>3.20</td>
<td>0.22</td>
<td>8</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td><strong>Contractor</strong></td>
<td><strong>Difficulties in financing project by contractor</strong></td>
<td>4.25</td>
<td>0.36</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Rework due to errors during construction</strong></td>
<td>4.10</td>
<td>0.32</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Conflicts between contractor and other parties (consultant and owner)</strong></td>
<td>3.70</td>
<td>0.28</td>
<td>5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td><strong>Poor site management and supervision by contractor</strong></td>
<td>3.20</td>
<td>0.28</td>
<td>9</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td><strong>Poor communication and coordination by contractor with other parties</strong></td>
<td>3.65</td>
<td>0.31</td>
<td>6</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td><strong>Ineffective planning and scheduling of project by contractor</strong></td>
<td>3.90</td>
<td>0.33</td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td><strong>Improper construction methods implemented by contractor</strong></td>
<td>3.45</td>
<td>0.26</td>
<td>8</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td><strong>Delay in site mobilization</strong></td>
<td>3.60</td>
<td>0.34</td>
<td>7</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td><strong>Delay in financing project by contractor</strong></td>
<td>4.15</td>
<td>0.38</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td><strong>Consultant</strong></td>
<td><strong>Delay in performing inspection and testing by consultant</strong></td>
<td>3.85</td>
<td>0.34</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td><strong>Delay in approving major changes in the scope of work by consultant</strong></td>
<td>3.95</td>
<td>0.31</td>
<td>2</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td><strong>Inflexibility (rigidity) of consultant</strong></td>
<td>3.25</td>
<td>0.25</td>
<td>6</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td><strong>Poor communication/coordination between consultant and other parties</strong></td>
<td>3.80</td>
<td>0.28</td>
<td>4</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td><strong>Late in reviewing and approving design documents by consultant</strong></td>
<td>4.10</td>
<td>0.32</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Conflicts between consultant and design engineer</strong></td>
<td>3.20</td>
<td>0.22</td>
<td>7</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td><strong>Inadequate experience of consultant</strong></td>
<td>3.65</td>
<td>0.25</td>
<td>5</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td><strong>Mistakes and discrepancies in design documents</strong></td>
<td>4.15</td>
<td>0.35</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Delays in producing design documents</strong></td>
<td>4.20</td>
<td>0.38</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>Unclear and inadequate details in drawings</strong></td>
<td>4.25</td>
<td>0.39</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Complexity of project design</strong></td>
<td>4.10</td>
<td>0.29</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Insufficient data collection and survey before design</strong></td>
<td>3.75</td>
<td>0.25</td>
<td>5</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td><strong>Misunderstanding of owner’s requirements by design engineer</strong></td>
<td>3.60</td>
<td>0.24</td>
<td>6</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td><strong>Changes in material types and specifications during construction</strong></td>
<td>3.60</td>
<td>0.27</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td><strong>Delay in material delivery</strong></td>
<td>3.90</td>
<td>0.30</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td><strong>Damage of sorted material while they are needed urgently</strong></td>
<td>2.60</td>
<td>0.21</td>
<td>5</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td><strong>Delay in manufacturing special building materials</strong></td>
<td>3.10</td>
<td>0.27</td>
<td>4</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Late procurement of materials</strong></td>
<td>3.85</td>
<td>0.30</td>
<td>2</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td><strong>Late in selection appropriate materials due to availability of many types</strong></td>
<td>2.45</td>
<td>0.19</td>
<td>6</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td><strong>Equipment</strong></td>
<td><strong>Equipment breakdowns</strong></td>
<td>3.45</td>
<td>0.25</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td><strong>Shortage of equipment</strong></td>
<td>3.75</td>
<td>0.27</td>
<td>1</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Conceptual Model and Mechanisms

Considering the influence of the factors as discussed above conceptual SD models have been developed to comprehend the dynamic causal feedback relationships among the factors, which cause delay and develop the possible mechanisms that can assist in reducing the delay. In the model, the causal feedback relations (loops), which essentially balance or disrupts the system (construction projects), and consequently augment delay are identified by balancing loops (B). On the other hand, the causal feedback loops, which reinforce the smooth functioning of the system and consequently assist in reducing or eliminating delay, are identified by reinforcing loops (R). While developing the models, only client, contractor, consultant and design aspects were considered because of their higher influence. Consultant and design related factors were taken together because of their strong inter-linkage and interdependence. The other factors belonging to materials, equipment and labour aspects were integrated to the client, contractor and consultant and design aspects according to their relationship and importance.

4.2.1 Client Related Aspects

As mentioned above delay in progress of payments by owner, slowness in decision making process by owner, change orders by owner during construction, poor communication and coordination by owner and other parties, and delay in approving shop drawings and sample materials by the client are the major client/owner related factors, which cause delay although others factors contributes to lesser extent. It is observed that there exists cause and effect relationships among these factors, and they work through a feedback mechanism. Figure 1 manifests the conceptual SD model based on such causal feedback relationships. As shown in the figure, slowness in decision making leads to delay in progress in payment, which cause delay and disrupts the system through balancing loop OB1. Also, poor communication leads to slowness in decision making and vice versa through another balancing causal feedback sub loop OB1A. So balancing sub loop OB1A aggravates the balancing loop OB1. Besides, factors like change in orders during construction, delay in approving the drawing and materials, late approval of revision of designs and delay in furnishing the site delivery by the client are influenced by slowness in decision making and vice versa. On the other hand, effective communication among stakeholders (which can be enhanced by coordination among them) will assist in decision making that will facilitate timely payment and consequently will assist in reducing the construction delay from client’s side.
However, to achieve this, measures, such as, coordination among stakeholder that would lead to effective communication; availability of requisite information to aid timely decision making, and availability of adequate fund and budget allocation that would allow timely payment are necessary.

Thus, the feedback mechanism involving effective communication, timely decision making and timely payment will reinforce reduction in delay through reinforcing loop OR1. As a result, the disrupting effects of feedback mechanisms (OB1 and OB1A) are balanced or negated by feedback mechanism OR1. So, the causal feedback relationship among communication, decision-making, progress in payment and construction delay is the dynamic hypotheses, which influence delay and need to be attended to alleviate the problem.

4.2.2 Contractor Related Aspects

Contractors form important parts of construction project. They are essentially responsible for the actual construction activities. As evident from this investigation, difficulties in financing project by contractor, delay in financing project by contractor, conflicts between contractor and other parties (consultant and owner), rework due to errors during construction, and ineffective planning and scheduling of project by contractor are the major contractor related causes of delay. However, factors like poor communication and coordination by contractor with other parties, improper construction methods, and delay in site mobilization also influence delay although to a lesser extent. The causal feedback relationships among the factors and delay in the SD model (Figure 2) reveal that ineffective planning and scheduling has a direct linkage with construction delay through a feedback mechanism (balancing loop CB1). While ineffective planning, essentially may happen because of poor communication, it can influence the construction activities through delay in site mobilization, poor management of site and supervision, and rework because of lack of contingencies in time schedule for such occurrences. Similarly, difficulty in financing the project by contractor, which can lead to delay in financing the project will cause construction delay through feedback mechanism (CB2) and disrupts the project. However, adoption of best practices of the industry through (1) planning for finance and budget ahead (CR1A), which can lessen the burden of difficulty in financing; (2) provision of effective communication and coordination, which can reduce ineffective planning and scheduling (CR1B); (3) use of appropriate construction methods (CR1C); and (4) provision for rework and exigencies (CR1D), which can reduce the rework, will enable reduction of delay in construction.

![Figure 2: SD model based on causal feedback relations among the contractor related factors causing delay](image-url)
Therefore, reduction of delay will occur through reinforcing loop CR1 between adoption of best practices and construction delay (through reinforcing sub loops CR1A, CR1B, CR1C, and CR1D). Thus, the disruptive mechanisms through CB1 and CB2 can be balanced or negated by reinforcing mechanism CR1. Therefore, causal feedback mechanism involving effective planning and scheduling, planning for finance and budget ahead, adoption of construction methods, and contingencies in planning for rework and exigencies by the contractor and construction delay is the dynamic hypothesis, which should be considered while developing policy interventions to reduce delay in construction.

4.2.3 Consultant and Design Related Issues

The consultant and design related issues are more or less integrated, and therefore both of them are considered together while developing the conceptual model. As seen from the Table 1, late in reviewing and approving design documents by consultant, delay in performing inspection and testing by consultant, delay in approving major changes in the scope of work by consultant, poor communication/coordination between consultant and other parties, inflexibility (rigidity) of consultant are the significant causes of delay, whereas delay in producing design documents, complexity of project design, mistakes and discrepancies in design documents unclear and inadequate details in drawings are the design related causes, which are responsible for delay in construction. The conceptual SD model is presented in Figure 3. The causal feedback mechanisms manifest that complexity of the project influence the delay in production of the design document by consultant, which essentially cause construction delay through balancing loop DB1. Complexity in design also can lead to mistakes and discrepancies in design document, which can lead to unclear and inadequate detail drawings through balancing sub loop DB1A. Similarly, delay in production of design document is influenced by delay in performing inspection and testing by consultant, delay in approving major changes in the scope of work of the consultant by the client, and late reviewing and approving the document by the consultant. Therefore, complexity of design can disrupt or cause construction delay through balancing feedback mechanism DB1 supported by feedback loop DB1A. However, on the other hand, appointment of highly competent consultant and design team will able to meet the challenges of complex design as well as eliminate the problems of mistakes and errors and enhance clarity in detail drawings through feedback mechanism (sub loop DR1A). Consequently, it will reinforce the reduction of delay by reducing the delay in producing the design documents through feedback mechanism DR1.

![Figure 3: SD model based on causal feedback relations among the consultant and design related factors causing delay](image-url)
Thus, causal feedback mechanism DR1A reinforces causal feedback mechanism DR1. Further, provision of an effective communication mechanism between consultant and other stakeholders will assist in conflict resolution among client, contractor, design team and consultant, and thereby reduces delay through causal feedback mechanism DR2. Besides, DR2 will be further reinforced by feedback mechanism DR2A, as effective communication will eradicate the challenges created by poor communication like misunderstanding of client's requirement leading to reduction in the challenges of complexity of design. Thus, the feedback mechanism DB1 causing construction delay will be balanced or negated by the feedback mechanisms DR1 and DR2. So, the causal feedback mechanisms involving appointment of highly competent consultant and design team, delay in producing the design documents and delay in construction; and provision of effective communication mechanism, conflict resolution and delay in construction are the dynamic hypotheses, which need to consider while developing policy interventions for reducing delay from consultant and design point of view.

5 CONCLUSION

Delay in construction projects is a menace. It leads to both appreciable cost and time overruns, which affect both socially and economically to the society. Although, there were plenty of studies conducted to investigate the causes of the delay, which differ depending on contexts, yet there are several causes which are observed to be common in most of the projects. However, there is scanty literature available regarding the mechanisms, which could aid in developing policy interventions to reduce or eliminate construction delay. This challenge has therefore warranted the investigation. The investigation was conducted by using a survey research methodology. A survey was conducted among the various stakeholders and professionals belonging to medium and major projects in India to understand the various causes, their level of influence and causal relations. Followed by, causal feedback mechanisms and consequent conceptual SD models were developed by using SD modelling principles, which lead to evolving of dynamic hypotheses to resolve the challenges of delay in construction.

It is evident from the results that parameters belonging to client/owner, contractor, consultant and design aspects have major influence on the occurrence delay, whereas material, equipment and labour related issues have lesser significance. However, the causal feedback mechanisms revealed that there are four dynamic hypotheses, which need to be considered while developing policy interventions to resolve the challenges of delay in construction. They are (1) the causal feedback relationship among communication, decision-making, progress in payment and construction delay; (2) the causal feedback mechanism involving effective planning and scheduling, planning for finance and budget ahead, adoption of construction methods, contingencies in planning for rework and exigencies by the contractor and construction delay; (3) the causal feedback mechanisms involving appointment of highly competent consultant and design team, delay in producing the design documents and delay in construction; and (4) the provision of effective communication mechanism, conflict resolution and delay in construction.

The paper has its limitations. The obvious limitation is that the modelling was done conceptually, although the basic premise behind it was to see the challenges of delay in a more critical way. However, there is a need for the quantitative modelling to examine the extent to which construction delay can be reduced or eliminated under different scenarios of strategic/policy interventions based on the dynamic hypotheses, which is the further scope of this research. Despite the limitation, this study can assist construction project managers, leaders and stakeholders to analyse and diagnose construction delay challenges by using the dynamic hypotheses in their projects and derive plausible strategic/policy interventions to reduce or eliminate delay in construction projects.

References


AN IMAGE-BASED DATA MODEL FOR SUBWAY CONDITION ASSESSMENT

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\(^2\) thikradawood2002@yahoo.ca

Abstract: The Canadian Urban Transit Association (CUTA) estimated that transit infrastructure needed a total of 53 Billion Canadian Dollars in 2013. Subway networks form an essential part of the public transportation infrastructure. Several surface defects may develop on subway infrastructure facilities, of which the most commonly identified are cracks, scaling, spalling, delamination, moisture marks, and efflorescence. These distresses participate not only in degrading the structure aesthetically, but in increasing the deterioration mechanisms of its components, taking into account the severe environmental conditions and continuous heavy loads that the structure is subjected to during its service life. High deterioration rates may cause the closure of subway system, therefore condition assessment of subway networks represents a crucial yet challenging task in the sustainability of a sound concrete infrastructure. Visual inspection techniques are considered the principal methods used in the condition evaluation of civil infrastructure. These methods are time-consuming, expensive, and depend inherently on subjective criteria. Several models have been proposed by previous researchers to assess the condition of subway systems. However, all of the developed methods were dependent on the visual inspection reports, hence they lacked the objectivity in quantifying and estimating the severity of defects. Therefore, a robust model that can detect the distresses and compute their severity needs to be developed. This paper defines the details of the recently introduced procedure based on image processing and assessment techniques. A five phased process is presented for accurate condition assessment of subway networks. The developed methodology utilizes data acquisition tools for collecting images of different elements in subway networks. Multiple algorithms are utilized to detect, interpret and measure surface defects, such as binary transformation, histogram equalization, image dilation, and hole filling. A case study from Montreal subway system was used to exemplify the application of the developed method. The results prove the potential benefits of the proposed methodology in identifying and quantifying surface defects. This research concludes the reliability of image-based data model in terms of accuracy, efficiency, and ease of analysis.

Keywords: Image Processing, Subway System, Inspection, Condition Assessment

1 INTRODUCTION

Public transit infrastructure plays a vital role in the economy, prosperity and the well-being of people. Subway networks form a fundamental constituent of the public infrastructure. Statistics show that the amount of passengers choosing the subway system for their daily travel is on the rise. According to the American Public Transportation Association (APTA) Fourth quarter report (APTA, 2013), in New York
City, 2.7 billion trips took place in 2012, while in the case of Montreal, that number reached around 357 million trips. (APTA 2013).

The increasing demand for underground transportation in addition to other factors will participate in the deterioration of subway systems. These factors include but are not limited to, the aging of infrastructure facilities, harsh environmental conditions, heavy loading, and deferred maintenance and rehabilitation plans. The high deterioration rates and the growing demand on metro systems, make the condition assessment procedure a critical safety issue. Accordingly, a reliable condition assessment method has become a vital task yet a necessity to ensure the sustainability of the structure.

Condition assessment of subway networks provides inputs for planning future maintenance activities. In both Canada and the United States, the main approach to evaluate the condition of subway systems, is based on visual inspection (VI), which is time-consuming, expensive, and depends regularly on subjective criteria. Automating the current practice is expected to provide more objective, accurate, quantitative results which will eventually lead to enormous savings in time and money. Among several damage detection techniques, the use of optical devices such as digital cameras and image processing methods are promising methodologies. One automation aspect is the detection of spall defects which develop on the surfaces of concrete structure. This paper aims at developing an automated assessment model for subway networks based on image processing algorithms and non-destructive evaluation (NDE) technologies. The model performs damage identification and quantification of spalling on the external surface of concrete. It provides a systematic approach for the identification of spall areas through different image enhancement algorithms, such as histogram equalization, image thresholding and mask processing. The output of this research is a decision support tool, expected to assist the infrastructure managers and civil engineers in their future plans and decision making.

2 BACKGROUND AND LITERATURE REVIEW

In the literature review, several efforts have been made to evaluate the condition of subway networks. Semaan (2006) has developed a condition assessment model to diagnose and assess the conditions of subway stations. This model has defined functional criteria and applied the Analytic Hierarchy Process (AHP) to calculate their weights. Then, the Preference Ranking Organization Method of Enrichment Evaluation was used to find the aggregation of weights and scores, and finally Station Diagnosis Index (SDI) was calculated using the Multi-Attribute Utility Theory (MAUT), and a condition scale for the evaluation of each station was proposed. This model was applied later on Montreal Metro stations. Another model was proposed by Semaan (2011). This model was developed to assess the performance of subway network, it has started by the hierarchy identification of subway network. Then, the physical and functional performances of each component in the network were assessed and integrated into one performance index using the AHP and MAUT theory. Performance prediction curves for all the components in the network were constructed using a Weibull reliability function. Moreover, this model has evaluated the performance of various systems, lines and the whole network by the use of the series-parallel system technique and was implemented in the Montreal subway network.

Kepaptsoglou et al. (2012) have developed a model to evaluate the functional condition of subway stations, this model was applied to Athens Metro systems. Several criteria and sub-criteria were allocated to every station. The AHP and Fuzzy AHP were utilized to rank the sub-criteria according to their significance to the station’s operational phase. The sub-criteria were weighted according to their significance to the station’s operational phase and they were evaluated on a scale of 0-5 by Athens transit authority. Then, their scores were aggregated with the use of MAUT to get the Metro’s Condition Index. This model was developed solely for the condition assessment of subway stations. In order to improve the previous model and achieve the interdependencies among its criteria, Gkountis and Zayed (2013) have applied the Analytic Network Process (ANP) and have used the same 0-5 scale. The additive MAUT was implemented to acquire the station’s condition index.

Abu-Mallouh (1999) has developed a “Model for Station Rehabilitation Planning” so called “MSRP” in an effort to improve the “Point Allocation Model” implemented by the MTA NYCT. The MSRP has considered the same functional and social criteria used by New York Transit Authority. The Analytic Hierarchy Process (AHP) technique was applied to obtain weights for the stations. For rehabilitation planning, a
powerful optimization technique (Integer Programming) was used to allocate budget for stations. The weights and budget allocation were later used to prioritize stations for rehabilitation. In fact, the MSRP is a budget allocation model rather than a condition assessment or a deterioration model and it is only limited to the evaluation of stations. Furthermore, it did not use real collected data for the validation process. Faraan (2006) has proposed a model “maintenance and rehabilitation planning for public infrastructure” known as “MRPPI” and implemented in the Montreal subway stations. This methodology has considered the life-cycle cost analysis of the structural elements in the infrastructure. It has applied Markov Chains theory to evaluate the deterioration of the elements and used transition probability matrices as input variables to the model. Consequently, Genetic Algorithm optimization technique was utilized to minimize the life cycle cost after considering a series of intervention actions.

Derrible and Kennedy (2010) have developed a model, the objective of which was to improve the efficiency and ridership of Toronto Metro network by assessing its performance as well as comparing it to other subway networks. The model was developed by computing three major factors including coverage, directness and connectivity. Numerous variables were considered in the computing process, including covered area, ridership, possible transfer options and number of lines. Marzouk and Abdel Aty (2012) have proposed a Building Information Modeling (BIM) framework for the maintenance of subway infrastructure. Various asset management indicators were included in the body of this research, such as structural integrity, mechanical systems, HVAC systems, electrical system and user-related indicators. The model has aimed at offering a solid ground by proposing BIM flowchart that considers the indicators as prepared inputs to a comprehensive BIM/Asset management model.

Abouhamad (2014) has developed a risk-based asset management framework for subway networks. The study has proposed two main models namely; fuzzy risk index model and risk-based budget allocation model. In the first main model, risk was evaluated using three sub models; probability of failure, consequences of failure and criticality index. Probability of failure for several structural components was evaluated based on inspection reports and Weibull reliability function. Consequences of failure were evaluated through seven attributes, such as revenue loss, replacement/repair cost, etc. Consequently, criticality index was computed using seven criteria, such as number of lines, number of exits, etc. And finally, the second main model was proposed which is a budget allocation model. It has delivered recommendations to prioritize stations for rehabilitation action and applied two sets of variables.

In all of the aforementioned studies, the models were subjective and dependent on the visual inspection reports. Therefore, they have lacked the objectivity in quantifying and estimating the severity of defects. As a result, more accurate condition assessment techniques are essential in order to acquire reliable results and improve the quality of inspection in concrete infrastructure. This paper presents an auto inspection system that is capable of accurately detecting, analyzing, and evaluating the condition, as well as reducing the inspection time and cost in subway systems. The frame work of the methodology is based on image processing techniques.

3 RESEARCH METHODOLOGY

The main concept of the imaging data model is to acquire digital images of surface defects in subway network, and apply different image processing techniques to make these defects more distinguishable and suitable for computing purposes. Figure 1 presents the model architecture which is based on applying different image processing algorithms.
Figure 1: Image data analysis and assessment model
Step 1
Images of the components of subway system were obtained using a digital camera. The images contained different visible defects on the structure’s surface, such as cracks, moisture marks, scaling, spall ...etc. as shown in Figure 2. A digital camera (Canon EOS Rebel XS, 10.1-magapixel) with a high resolution of 2592x3888 pixels was employed to acquire images for concrete surfaces. Afterwards they were transferred to the computer to be processed. This research takes spall defects that are visible on subway concrete surfaces as an example for the proposed methodology.

![Images showing different surface defects](image1.png)

(a) Cracks on lower slab  (b) Moisture marks on upper slab

(c) Scaling on upper slab  (d) Spall on lower slab

Figure 2: Different surface defects in subway networks

Step 2
The term “image” could be defined as a two dimensional (2D) function $f(x, y)$, where $f$ denotes the gray-level or intensity of the image at spatial coordinate point $(x, y)$ which corresponds to each pixel in the image (Gonzalez and Woods 2008). A digital image could be represented as a matrix which includes a large number of elements called pixels. Generally, the images are either gray-level images or color images. A gray-level image is a black-and-white image which has one matrix only, and the elements of the matrix represent pixels’ intensity values. Normally, matrix values in a digital image range from 0 to 255. A color image is an RGB image which is formed of three planes; red, green, and blue as depicted in Figure 3. It is necessary to split the RGB image into three planes in order to choose the plane which demonstrates the best visualization and to facilitate image enhancement and detection processes. The acquired images in this research were RGB images, they have been split into the three planes and the red plane was selected so that it can be processed later.

![RGB image planes](image2.png)

Red Plane  Green Plane  Blue Plane

Figure 3: The three planes of RGB image
Step 3

One of the most significant methods is thresholding the image through segmentation. Thresholding is the method of separating the object of interest from the background of the image. It is a binary transformation of the gray-level into either black or white intensity levels. Accordingly, matrix elements of a binary image have either zero or one value. Figure 4 shows a binary transformation of an image.

![Figure 4: Binary transformation of the image](image)

The selection of the best threshold value of a gray-level image is correlated to plotting its histogram. Therefore, the position of best threshold value will be specified. Figure 5 illustrates a histogram of a gray-level image. The horizontal axis represents the intensity of gray-level and the vertical axis is the frequency of occurrence of a pixel value in the image.

![Figure 5: Gray-level image and its histogram](image)

Step 4

It is quite useful to apply some morphological algorithms on the binary image, especially for the detection of boundaries. There are other techniques and filters which can be used concurrently with these algorithms, such as hole filling, thinning, thickening, etc. One of the basic algorithms which is used for filling holes in the image is developed on incorporating dilation, complementation, and intersection. Dilation is the process of thickening the boundaries of an object in a binary image (Gonzalez and Woods 2008), hence the object will be clearly visualized. Figure 6 depicts the processed image after using different morphological operations on the binary image including thinning, dilation, and hole fillings.
Before evaluating the condition of any element using image analysis, the images should be calibrated by setting the appropriate scale. A commercially available software ImageJ was used for processing and scaling the images. Prior to uploading, processing and scaling the images by the software, the length of spall (object) has been measured in situ so that it can be set as an entry data in the software. Thereby pixel values will correlate with actual measurements allowing all possible measurement to be done on the image. Subsequent to scaling the image, the defect has been selected, hence it is possible to obtain feature attributes such as area, percentage area, perimeter, width, lengths of major and minor axes, mean, standard deviation, etc. Figure 7 illustrates scaling the image and selecting the defect using the analysis software. For the purpose of evaluating the condition of a component in this research, only the spall area and its percentage in that component were taken into consideration.

**4 RESULTS FROM MODEL**

The proposed imaging data model was applied on a station in Montreal’s subway network. A total of 50 images were acquired for the upper and lower slab surfaces of the station for the objective of quantifying and measuring the defect (spalls). Table 1 summarizes the assessment results for a sample of 10 images acquired for the station slabs. These images targeted spall distress which is visible on the components'
surfaces. The defect (spall) area and spall percentage in each image were calculated using the proposed model. For example, from table 1, image number 6 which has been used in the image processing of this research, was processed by the model and demonstrated the largest area of 224 cm$^2$, thereby acquiring 57% of the whole slab area and considered a severe defect. Whereas, image number 3 showed the smallest area of 6.88 cm$^2$, thus acquiring 1% of the whole slab area and considered as a minor defect. The proposed assessment methodology was validated by taking actual measurements for the spall defects in Montreal subway station. Then area and spall percentage calculations were performed on each defect and compared to the calculations obtained from the model. The results showed that image-based model had an accuracy of 98% in detecting, measuring and evaluating surface defects in subway infrastructure.

Table 1: Assessment results of a subway station in Montreal

<table>
<thead>
<tr>
<th>Image number</th>
<th>Slab location</th>
<th>Spall Area (cm$^2$)</th>
<th>Spall percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Upper</td>
<td>10.20</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Upper</td>
<td>57.33</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>Upper</td>
<td>6.88</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Lower</td>
<td>111.27</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>Upper</td>
<td>34.14</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Lower</td>
<td>224.00</td>
<td>57</td>
</tr>
<tr>
<td>7</td>
<td>Lower</td>
<td>30.29</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>Upper</td>
<td>88.54</td>
<td>22</td>
</tr>
<tr>
<td>9</td>
<td>Upper</td>
<td>27.67</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>Lower</td>
<td>158.64</td>
<td>40</td>
</tr>
</tbody>
</table>

5 SUMMARY AND CONCLUSION

This paper presented a framework which applies image processing techniques for the detection and quantification of surface defects in subway networks. The imaging data model was realized by following five steps, each step comprised the utilization of several algorithms. In the first step, images for different surface defects have been acquired by a digital camera, then they were transferred to the computer to be processed. Step two included exploring the color space and extracting three planes for the purpose of selecting the best visualized plane to be further processed. Thresholding the gray-scale image and plotting its histogram was the approach applied in the third step to be followed by using some morphological operations such as image thinning, dilation and hole filling in the fourth step. And finally, the image has been calibrated and feature vectors such as area, percentage area, width, etc. were obtained. The proposed methodology was applied on segments of Montreal's subway system. The case study results were compared to the results taken from ground measurements, thus demonstrated a high accuracy of 98% in assessing the severity of defects. This proves the robustness of the proposed model in enhancing the quality and consistency of condition assessment, as well as, reducing the cost and time required to inspect subway networks.

References


FACTORS IMPACTING SELECTION OF CONSTRUCTION SUBCONTRACTORS

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Abstract: A considerable portion of the work in construction projects is carried out by subcontractors. The current lowest bid practice, in which the main contractor offers a subcontract to the bidder who submits the lowest price, is considered to leave subcontractors with very low profit margins, and with a lack of motivation to provide high quality work. Selecting appropriate subcontractors is consequently seen as contributing significantly to a project's success. Although subcontractors are mainly selected by the main contractor, as one of the influential contributors to the project, the choice of subcontractor will also affect other project stakeholders such as owners and consultants. The goal of this study is to identify the factors that different project stakeholders consider important when selecting subcontractors, and the extent to which their professional background affects the way they view selection factors used for subcontractors. To this end a questionnaire was designed and distributed among construction industry experts in Alberta, Canada, from three groups of general contractors, owners, and consultants with various professional backgrounds. The survey results verified that the factors identified in the survey were in fact those that were considered in the selection of subcontractors. Based on statistical analysis of the survey results in most cases, respondents from the contractor group associated a different degree of importance to each selection factor compared with consultants and clients. The level of importance associated to each selection factor was found to be more similar among the latter two groups. Interestingly the lowest bid price was not necessarily ranked highest by professionals within all background groups.

1 INTRODUCTION

A considerable portion of the work in construction projects is carried out by subcontractors. Consequently, selecting appropriate subcontractors contributes to a project's success (Hartmann et al. 2009). The literature around selection criteria has been mostly focused on choosing main contractors. These studies mainly focused on the selecting based on the low bidding price versus considering multi-criteria selection method.

A research study conducted in Singapore examined the relative importance of different factors in selecting a subcontractor by the main contractor. A survey was conducted to ask contractors which of the four factors of price, technical know-how, quality, and cooperation would affect their decision in selecting a subcontractor. Professionals from 221 construction firms in Singapore responded to the survey. In order to find out if these criteria play an important role in selecting subcontractors, contractors were asked to rank the level of importance they associated to the four selection factors. Based on the survey results, contractors perceived all four factors important in selecting subcontractors. They were then asked to do a discrete choice experiment and express their preference based on a number of hypothetical scenarios.
Interestingly, the discrete choice survey results showed that price is a predominant basis for the choice decision. While low bidding price accounted for 50% of the contractor’s decision, a subcontractor’s attractiveness could be increased by the other three factors of quality of the work, its cooperation and technical know-how respectively. In addition, it was shown that under equal conditions, previous relationship with the main contractors could work to subcontractor’s advantage (Hartmann et al. 2009).

A study in Pakistan examined the overall contractors’ satisfaction with the quality of services provided by subcontractors (Choudhry et al. 2012). A survey was conducted to investigate the extent and involvement of construction firms in subcontracting, reasons for subcontracting, and the selection criteria of subcontractors. The study found that the most widely used method for selecting a subcontractor was using a preference list that individual contractors prepared, generally based on the previous working experience with subcontractors. The second most common method was negotiation, while open bidding was the least preferred method. This study also found that out of five selection factors of price, quality, ability to complete work on time, subcontractors’ resources, and personal relationship, the most important criterion was the bid price, followed by the ability to complete the work on time and the quality of the work, respectively. Moreover, the study identified a high level of consistency in the opinions of the three groups (clients, consultants, and contractors) on the selection criteria of subcontractors (Choudhry et al. 2012). The objective of this study is to identify the factors that are deemed important in selecting subcontractors in Canada. The study will examine these factors not only from contractors’ perspective, but also from the perspective of experts from client and consultant organizations. This will enable a comparison of how experts at different roles in the industry view these selection factors.

2 METHODOLOGY

With the objective of the study in mind, a survey questionnaire was designed, consisting of two parts: The first part of the questionnaire contained general questions to identify the respondents’ professional background, including the relevant industry sector and segment, and level of experience. This part included seven questions which were considered independent variables in the consequent statistical analysis. The second section consisted of the proposed subcontractors’ selection factors. Twelve factors were surveyed in this section. Respondents were requested to rank them on a scale of 1 to 5 as shown in Table 1 below. These factors were treated as dependent variables.

<table>
<thead>
<tr>
<th>Scale</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>Very Unimportant</td>
<td>Unimportant</td>
<td>Good to have</td>
<td>Important</td>
<td>Very Important</td>
</tr>
</tbody>
</table>

The questionnaire was used to survey different professionals involved at various roles in the construction industry in Alberta, and the collected data was then statistically analyzed. A total number of 137 professionals from different walks of industry were surveyed. The participants were contacted through three modes of communications: in person (34.3% of responses), by email (62% of responses), and by regular mail (3.6% of responses). The following two sections provide summary of the survey results for the two parts of the questionnaire.

3 SURVEY SUMMARY: DESCRIPTIVE STATISTICS

3.1 Part I: Professional Background

In the first part of the survey, participants were asked seven questions regarding their professional background. Below is the summary of their responses:

**Industry sector [P1]:** 32.8% of the respondents were from the public sector and the remaining 67.2% from the private sector.
Role of the organization [P2]: 31.4% of the respondents worked for a client (owner) organization, 49.6% for contractors and 19% were from consulting firms.

Construction segment [P3]: 13.9% of the participants were involved in projects related to the residential construction 18.3% in non-Residential construction, 26.3% in heavy infrastructure construction, and 65% in industrial construction. As it can be inferred from the distributions, some participants were active in more than one section.

Years of experience in the construction industry [P4]: 29.9% of the participants had less than 5 years of experience in the construction industry; 31.4% had between 5 to 10 years of experience and the remaining 38.7% had more than 10 years of experience.

Years of experience in Alberta [P5]: 44.5% of the participants had less than 5 years of experience in Alberta’s construction industry; 32.8% had 5 to 10 years and 22.6% had more than 10 years of experience. A comparison of these percentages with those of the previous question can reflect the share of participants with larger years of experience in construction (more than 5 years) who have moved to Alberta.

Involvement in selecting subcontractors in projects [P6]: About 60% of the respondents were involved in selecting subcontractors in less than 10 projects and the remaining 40% in more than 10 projects.

Direct experience in working with subcontractors [P7]: 78.8% of the participants had experienced directly working with a subcontractor, and the remaining 21.2% lacked such experience.

3.2 Part II: Subcontractor Selection Criteria

In the second part of the survey, the respondents were asked to rank the importance of twelve factors in the selection of subcontractors on a scale of 1 to 5 as shown in Table 1. Below are the results of the second part of the survey:

Subcontractor’s experience in similar projects (F1): 0.7% ranked this factor very unimportant, 2.9% good to have, 38.7% important and 57.7% very important.

Subcontractor’s familiarity with the local market (F2): 0.7% ranked this factor very unimportant, 9.5% unimportant, and 42.3% good to have, 34.3% important and 13.1% very important.

Subcontractor bidding for the lowest price (F3): 10.2% considered this factor unimportant, 35.8% good to have, 24.1% important, and 29.9% very important.

Compliance of the subcontractor’s submitted schedule with the project’s overall schedule (F4): 1.5% considered this factor very unimportant, 22.6% unimportant, 11.7% good to have, 33.6% important, and 30.7% very important.

Subcontractor’s financial strength (F5): 23.4% ranked this factor very unimportant, 5.1% unimportant, 18.2% good to have, 36.5% important, and 16.8% very important.

Subcontractor’s available resources (F6): 1.5% ranked this factor very unimportant, 2.9% unimportant, 8% good to have, 54% important, and 33.6% very important.

Subcontractor’s reputation in the construction industry (F7): 2.9% considered it unimportant, 38% good to have, 39.4% important, and 19.7% very important.

Presentation of a solid execution plan in subcontractor’s proposal (F8): 3.6% ranked this factor very unimportant, 15.3% unimportant, 29.9% good to have, 34.4% important, and 19.7% very important.

Subcontractor having a well-defined quality assurance and quality control (QA/QC) program (F9): 1.5% categorized this factor as very unimportant, 1.5% unimportant, 31.4% good to have, 41.6% important, and 24.1% very important.
Subcontractor’s past safety record and having a health and safety program (F10): 2.2% ranked this factor very unimportant in their selection, 7.3% unimportant, 27% good to have, 23.4% important, and 40.1% very important.

Qualification of the key project personnel (F11): 5.1% ranked this factor very unimportant, 8% unimportant, 16.15% good to have, 45.3% important and 25.5% very important.

Previous positive business relation with the subcontractor in other projects (F12): 3.6% considered it very unimportant, 15.3% unimportant, 33.6% good to have, 33.6% important and 13.9% very important. Figure 1 shows the mean score of rankings for the above twelve factors. It is interesting to note that the mean score for all the questioned criteria ranges from 3 to 4.5. This shows that the participants found all the identified factors relevant to the selection of subcontractors, and therefore, provide an indication that they were selected appropriately.

![Figure 1: Mean score of factors impacting the selection of subcontractors](image)

4 ANALYSIS OF THE SURVEYED DATA

In order to examine the existence of significant relationships between the respondents’ professional background and how they ranked factors that affect the selection of subcontractors, a cross tabulated analysis of the survey data was carried out. Depending on the number of choices available to answer a question related to an independent variable, either t-test or ANOVA test were used. Whenever the number of choices in answering a question related to the professional background (independent variables) was limited to two mutually exclusive groups (e.g. P1-Industry Sector: Public or Private), t-test was applied to identify whether the difference in the answers of these two groups were statistically significant. For example, the average score that professionals from the two groups of Public and Private sectors (P1) gave to the importance of subcontractor’s experience on similar projects (F1) was 4.53 and 4.52, respectively. Therefore t-test was used to see if the 0.1 difference in their average scores is statistically meaningful or it was created by randomness. However, when the independent variable was composed of more than two mutually exclusive groups, (e.g. Role of respondent’s organization (P2): owners, contractors, or consultants), ANOVA test was applied to examine statistically significant difference between their opinions on a specific selection factor. If the result of the ANOVA test proved that there is significant difference, then the groups’ responses were compared two by two using the t-test to
find out which group’s opinion was significantly different than the others. The statistical analysis was conducted using the statistical package for social science (SPSS).

In total, 142 tests were conducted to examine the existence of significant relationships between the independent and dependent variables in the survey. At a 95% confidence level, 69 of the examined relationships were statistically significant. In other words, 5% possibility of type I error was accepted in this study which is what is commonly accepted in the similar studies (Winer 1971). Table 2 summarizes those relationships with P values less than 0.05. This section provides a brief explanation of the significant relationships organized based on the independent variables.

Table 2: Relationships with statistical significance (P<0.05)

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F8</th>
<th>F9</th>
<th>F1</th>
<th>F12</th>
</tr>
</thead>
<tbody>
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<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>Organization type</td>
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<td>.00</td>
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<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
</tr>
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<td>Segment: Residential</td>
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<td>.04</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
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<td>.01</td>
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<td>.01</td>
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<td>Non residential</td>
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<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>Heavy infrastructure</td>
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<td>.02</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.01</td>
<td>.00</td>
<td>.01</td>
<td>.00</td>
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<td>.00</td>
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<tr>
<td>Industrial</td>
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<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
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<td>.00</td>
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<tr>
<td>Experience in constr</td>
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<td>.00</td>
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<td>.01</td>
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<td>.00</td>
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<tr>
<td>Experience in Alberta</td>
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<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
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<td>.00</td>
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<tr>
<td>Involved in selecting sub.</td>
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<td>.02</td>
<td>.00</td>
<td>.00</td>
<td>.04</td>
<td>.00</td>
<td>.00</td>
<td>.02</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>Working with subcontractor</td>
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<td>.01</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
<td>.00</td>
</tr>
</tbody>
</table>

4.1 Industry Sector [P1]

As it can be inferred from Table 3, the public and private sectors had different opinions about the importance of the most of factors influencing the selection of subcontractors. The mean values in Table 3 indicate that professionals from the public sector ranked schedule compliance (F4), financial strength (F5), execution plan (F8), QA/QC plan (F9), safety record (F10), qualification of the key project personnel (F11), and previous business relationship with subcontractor (F12) higher than those professionals from the private sector. On the other hand, professionals from the private sector put higher importance for the low bidding price (F3) than their counterparts in the public sector.

4.2 Role of the Organization [P2]

As shown in Table 4, this study could not find a correlation between the type of organization that the respondents worked and their ranking for the importance of subcontractors’ experience in similar projects (F1), available resources (F6), and safety reputation (F9). Professionals working in contractor organizations ranked the importance of lowest bid price higher (μ= 4.2) than those from clients and consultant organizations (μ= 3.28, μ=3.19, respectively). Those from owner organizations associated a higher importance to compliance to the schedule (F4), safety record of the subcontractor (F10), and qualification of the subcontractor personnel. Interestingly, professionals from the consultant firms associated a higher value to all the factors except for the lowest bidding price. In general, it appears that professionals from consultant and owner organizations associated closer importance to most of the factors compared to those from contractor organization (see average values in Table 4).

4.3 Construction Industry Segment [P3]

Since respondents could be involved in projects that belonged to more than one construction segment (Residential buildings, Non-residential buildings, Infrastructure, and Industrial projects), they could select more than one answer for this question (i.e. answers were not mutually exclusive). Therefore four separate t-tests were carried out to identify possible relationships between the involvement in each
industry segments and the ranking of the factors (Tables 5). Professionals from the residential segment associated a high importance to almost all factors except for familiarity with the location market (F2) and lowest bid price (F3). Those involved in non-residential building construction found compliance of the subcontractor’s schedule with the project schedule (F4) and subcontractor’s execution plan (F8) were the most important factors. Professionals from heavy construction segment also found compliance to project schedule (F4) an important factor, along with subcontractor’s safety record (F10), and qualification of the personnel (F11). Those from industrial construction projects considered all factors as good to have.

Table 3: Respondents’ industry sector and ranking of the factors impacting selection of the subcontractor

<table>
<thead>
<tr>
<th>Factor</th>
<th>Dependent variables</th>
<th>Public</th>
<th>Private</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N=45</td>
<td>N=92</td>
<td>N=137</td>
</tr>
<tr>
<td>F1</td>
<td>Experience in similar projects</td>
<td>4.53</td>
<td>4.52</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.544</td>
<td>0.920</td>
</tr>
<tr>
<td>F2</td>
<td>Familiarity with the local market</td>
<td>3.60</td>
<td>3.45</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.953</td>
<td>0.270</td>
</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>3.27</td>
<td>3.42</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.97</td>
<td>0.23</td>
</tr>
<tr>
<td>F4</td>
<td>Compliance of schedule</td>
<td>4.24</td>
<td>3.27</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.42</td>
<td>1.225</td>
</tr>
<tr>
<td>F5</td>
<td>Financial strength</td>
<td>3.87</td>
<td>2.85</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.14</td>
<td>0.27</td>
</tr>
<tr>
<td>F6</td>
<td>Available resources</td>
<td>4.27</td>
<td>4.10</td>
<td>0.799</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.799</td>
<td>0.60</td>
</tr>
<tr>
<td>F7</td>
<td>Reputation</td>
<td>3.91</td>
<td>3.68</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>3.68</td>
<td>0.851</td>
</tr>
<tr>
<td>F8</td>
<td>Execution plan</td>
<td>3.91</td>
<td>3.27</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.007</td>
<td>0.27</td>
</tr>
<tr>
<td>F9</td>
<td>QA &amp; QC program</td>
<td>4.07</td>
<td>3.72</td>
<td>0.765</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.765</td>
<td>0.60</td>
</tr>
<tr>
<td>F10</td>
<td>Safety record</td>
<td>4.40</td>
<td>3.68</td>
<td>1.079</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.68</td>
<td>0.894</td>
</tr>
<tr>
<td>F11</td>
<td>Qualification of personnel</td>
<td>4.22</td>
<td>3.57</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.102</td>
<td>0.850</td>
</tr>
<tr>
<td>F12</td>
<td>Previous relationship</td>
<td>3.82</td>
<td>3.17</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.096</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 4: Respondent’s organization role and ranking of the factors impacting selection of subcontractors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Dependent variables</th>
<th>Owner N=43</th>
<th>Contractor N=68</th>
<th>Consultant N=26</th>
<th>Total Df (2,134)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Experience in similar projects</td>
<td>4.53</td>
<td>4.50</td>
<td>0.533</td>
<td>4.58</td>
</tr>
<tr>
<td>F2</td>
<td>Familiarity with the local market</td>
<td>3.58</td>
<td>3.19</td>
<td>0.902</td>
<td>4.15</td>
</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>3.28</td>
<td>4.24</td>
<td>0.932</td>
<td>3.19</td>
</tr>
<tr>
<td>F4</td>
<td>Compliance of schedule</td>
<td>4.21</td>
<td>3.12</td>
<td>1.223</td>
<td>4.38</td>
</tr>
<tr>
<td>F5</td>
<td>Financial strength</td>
<td>3.84</td>
<td>2.43</td>
<td>1.529</td>
<td>4.08</td>
</tr>
<tr>
<td>F6</td>
<td>Available resources</td>
<td>4.23</td>
<td>4.06</td>
<td>0.790</td>
<td>4.27</td>
</tr>
<tr>
<td>F7</td>
<td>Reputation</td>
<td>3.93</td>
<td>3.44</td>
<td>0.780</td>
<td>4.31</td>
</tr>
<tr>
<td>F8</td>
<td>Execution plan</td>
<td>3.86</td>
<td>3.04</td>
<td>0.953</td>
<td>4.00</td>
</tr>
<tr>
<td>F9</td>
<td>QA &amp; QC program</td>
<td>4.00</td>
<td>3.71</td>
<td>0.774</td>
<td>4.00</td>
</tr>
<tr>
<td>F10</td>
<td>Safety record</td>
<td>4.42</td>
<td>3.43</td>
<td>1.041</td>
<td>4.38</td>
</tr>
<tr>
<td>F11</td>
<td>Qualification of personnel</td>
<td>4.14</td>
<td>3.35</td>
<td>1.103</td>
<td>4.31</td>
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<td>F12</td>
<td>Previous relationship</td>
<td>3.74</td>
<td>2.91</td>
<td>1.000</td>
<td>4.04</td>
</tr>
</tbody>
</table>
4.4 Years of Experience in the Construction Industry [P4]

An interesting split was observed when studying the effect of years of experience on ranking the factors considered in selecting the subcontractors. As it can be seen in Table 6, respondents with low experience (less than 5 years) and those with high experience (more than 10 years) had a more similar opinion than those with medium experience (5 to 10 years). The latter group ranked the lowest bidding price (F3) higher than their counterparts with higher and lower years of experience (µ= 4.19 versus 3.43 and 3.66). Conversely, respondents with both less (less than 5 years) and higher experience (more than 10 years) associated higher level of importance on a good number of factors including the subcontractor’s familiarity.

Table 6: Respondent’s years of experience in the construction industry and ranking of the factors impacting selection of the subcontractors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Dependent variables</th>
<th>Years of experience in construction industry</th>
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</thead>
<tbody>
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<td>5-10</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>Sd.</td>
</tr>
<tr>
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</tr>
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<td>F2</td>
<td>Familiarity with the local market</td>
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</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>3.66</td>
<td>0.794</td>
</tr>
<tr>
<td>F4</td>
<td>Compliance of schedule</td>
<td>4.07</td>
<td>0.877</td>
</tr>
<tr>
<td>F5</td>
<td>Financial strength</td>
<td>3.68</td>
<td>0.960</td>
</tr>
<tr>
<td>F6</td>
<td>Available resources</td>
<td>4.17</td>
<td>0.834</td>
</tr>
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<td>F7</td>
<td>Reputation</td>
<td>3.85</td>
<td>0.792</td>
</tr>
<tr>
<td>F8</td>
<td>Execution plan</td>
<td>3.88</td>
<td>0.842</td>
</tr>
<tr>
<td>F9</td>
<td>QA &amp; QC program</td>
<td>3.93</td>
<td>0.755</td>
</tr>
<tr>
<td>F10</td>
<td>Safety record</td>
<td>4.10</td>
<td>1.044</td>
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<td>F11</td>
<td>Qualification of personnel</td>
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</tr>
<tr>
<td>F12</td>
<td>Previous relationship</td>
<td>3.63</td>
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Table 5: Respondent’s construction segment and factors impacting selection of the subcontractors

<table>
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<th>F</th>
<th>Dependent variables</th>
<th>Construction segment</th>
<th>Mean</th>
<th>Sd.</th>
<th>Sig.</th>
<th>Mean</th>
<th>Sd.</th>
<th>Sig.</th>
<th>Mean</th>
<th>Sd.</th>
<th>Sig.</th>
<th>Mean</th>
<th>Sd.</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Experience相似 projects</td>
<td>Residential (N=19)</td>
<td>4.74</td>
<td>0.4</td>
<td>0.049</td>
<td>4.64</td>
<td>0.9</td>
<td>0.318</td>
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<td>0.8</td>
<td>0.5</td>
<td>4.51</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-residential (N=25)</td>
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<td>0.6</td>
<td>0.049</td>
<td>3.56</td>
<td>0.6</td>
<td>0.620</td>
<td>3.81</td>
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<td>3.36</td>
<td>0.9</td>
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<tr>
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<td></td>
<td>Heavy (N=36)</td>
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<td>0.001</td>
<td>3.24</td>
<td>0.7</td>
<td>0.002</td>
<td>3.42</td>
<td>0.9</td>
<td>0.0</td>
<td>3.93</td>
<td>1.0</td>
<td>0.0</td>
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<tr>
<td></td>
<td></td>
<td>Industrial (N=89)</td>
<td>4.47</td>
<td>0.6</td>
<td>0.000</td>
<td>4.20</td>
<td>0.9</td>
<td>0.006</td>
<td>4.14</td>
<td>1.0</td>
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<td>1.2</td>
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<tr>
<td>F2</td>
<td>Familiarity相似 projects</td>
<td>Residential (N=19)</td>
<td>4.00</td>
<td>0.7</td>
<td>0.000</td>
<td>3.84</td>
<td>0.8</td>
<td>0.000</td>
<td>3.83</td>
<td>1.1</td>
<td>0.0</td>
<td>2.89</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-residential (N=25)</td>
<td>4.26</td>
<td>0.6</td>
<td>0.523</td>
<td>4.28</td>
<td>0.9</td>
<td>0.385</td>
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<td>0.8</td>
<td>0.5</td>
<td>4.09</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>Residential (N=19)</td>
<td>4.32</td>
<td>0.6</td>
<td>0.001</td>
<td>3.96</td>
<td>0.7</td>
<td>0.166</td>
<td>3.94</td>
<td>0.6</td>
<td>0.0</td>
<td>3.63</td>
<td>0.8</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-residential (N=25)</td>
<td>4.11</td>
<td>0.8</td>
<td>0.007</td>
<td>4.00</td>
<td>0.9</td>
<td>0.006</td>
<td>3.67</td>
<td>1.2</td>
<td>0.2</td>
<td>3.30</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>F4</td>
<td>Compliance of schedule</td>
<td>Residential (N=19)</td>
<td>4.32</td>
<td>0.7</td>
<td>0.011</td>
<td>3.88</td>
<td>0.9</td>
<td>0.867</td>
<td>4.00</td>
<td>1.0</td>
<td>0.2</td>
<td>3.70</td>
<td>0.7</td>
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<tr>
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<td>Non-residential (N=25)</td>
<td>4.47</td>
<td>0.7</td>
<td>0.004</td>
<td>4.28</td>
<td>0.9</td>
<td>0.064</td>
<td>4.28</td>
<td>0.9</td>
<td>0.0</td>
<td>3.69</td>
<td>1.0</td>
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</tr>
<tr>
<td>F5</td>
<td>Financial strength</td>
<td>Residential (N=19)</td>
<td>4.37</td>
<td>0.7</td>
<td>0.010</td>
<td>3.96</td>
<td>1.0</td>
<td>0.360</td>
<td>4.22</td>
<td>0.8</td>
<td>0.0</td>
<td>3.53</td>
<td>1.1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-residential (N=25)</td>
<td>3.79</td>
<td>0.9</td>
<td>0.060</td>
<td>3.56</td>
<td>0.8</td>
<td>0.350</td>
<td>3.72</td>
<td>0.8</td>
<td>0.0</td>
<td>3.18</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
with the local market (F2), schedule compliance (F4), financial strength (F5), reputation in the industry (F7), safety record (F10), previous business relationship (F12). The less experience professionals ranked having a well defined execution plan (F8) higher than those with more experience. The rest of the factors had the same level of importance for the surveyed professionals regardless their years of experience.

4.5 Years of Experience in Alberta [P5]

Similar to the years of experience in previous section, statistical analysis, as summarized in Table 7, revealed that respondents with less (less than 5 years) and those with higher experience (more than 10 years) in Alberta had a more similar opinion about the importance of factors than those with medium experience (5 to 10 years). The first two groups ranked subcontractor’s schedule compliance (F4), financial strength (F5), and previous relationship (F12) higher than professionals with medium experience in Alberta (5 to 10 years). Similar to previous section, the latter group ranked the lowest bidding price higher than their counterparts with less and more experience in Alberta. Subcontractor’s execution plan (F8) was more important to respondents with less than 5 years experience in Alberta and the remaining selection factors had equal degree of importance for respondents from all three groups. Therefore, in general it appears that the experience in Alberta will not significantly change the ranking of factors compared to experience from other parts of the world.

Table 7: Respondent’s years of experience in Alberta and ranking of the factors impacting selection of the subcontractors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Dependent variables</th>
<th>Years of experience in Alberta</th>
<th>N=61</th>
<th>N=45</th>
<th>N=31</th>
<th>Total DF (2,134)</th>
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</thead>
<tbody>
<tr>
<td>F1</td>
<td>Experience in similar projects</td>
<td>&lt; 5</td>
<td>4.48</td>
<td>0.566</td>
<td>4.53</td>
<td>0.548</td>
</tr>
<tr>
<td>F2</td>
<td>Familiarity with the local market</td>
<td>5 - 10</td>
<td>3.62</td>
<td>0.897</td>
<td>3.38</td>
<td>0.860</td>
</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>10 &lt;</td>
<td>3.64</td>
<td>0.932</td>
<td>4.09</td>
<td>0.973</td>
</tr>
<tr>
<td>F4</td>
<td>Compliance of schedule</td>
<td>Total</td>
<td>3.95</td>
<td>1.056</td>
<td>3.22</td>
<td>1.241</td>
</tr>
<tr>
<td>F5</td>
<td>Financial strength</td>
<td></td>
<td>3.49</td>
<td>1.220</td>
<td>2.56</td>
<td>1.575</td>
</tr>
<tr>
<td>F6</td>
<td>Available resources</td>
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<td>4.21</td>
<td>0.733</td>
<td>4.02</td>
<td>0.812</td>
</tr>
<tr>
<td>F7</td>
<td>Reputation</td>
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<td>3.79</td>
<td>0.777</td>
<td>3.58</td>
<td>0.753</td>
</tr>
<tr>
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<td>Execution plan</td>
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<td>3.75</td>
<td>0.830</td>
<td>3.16</td>
<td>1.186</td>
</tr>
<tr>
<td>F9</td>
<td>QA &amp; QC program</td>
<td></td>
<td>3.93</td>
<td>0.772</td>
<td>3.84</td>
<td>0.796</td>
</tr>
<tr>
<td>F10</td>
<td>Safety record</td>
<td></td>
<td>3.98</td>
<td>1.057</td>
<td>3.73</td>
<td>1.074</td>
</tr>
<tr>
<td>F11</td>
<td>Qualification of personnel</td>
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<td>3.80</td>
<td>1.030</td>
<td>3.56</td>
<td>1.119</td>
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<tr>
<td>F12</td>
<td>Previous relationship</td>
<td></td>
<td>3.56</td>
<td>0.87</td>
<td>2.98</td>
<td>1.06</td>
</tr>
</tbody>
</table>

4.6 Involvement in Selecting Subcontractors [P6]

Professionals who were involved in selecting subcontractors in more than 10 projects ranked the importance of lowest bid price (F3) slightly higher (µ= 3.98) than those involved in selection of subcontractors in less than 10 projects (µ= 3.57). However, the rest of the factors received a higher score from professionals with less involvement in selecting subcontractors. Particularly in cases of compliance of schedule (F4) and financial strength (F5), the gap of opinions was considerable (Table 8).

4.7 Direct Experience in Working with Subcontractors [P7]

Respondents’ without direct experience in working with a subcontractor put more importance on the subcontractor’s familiarity with the local market (F2), financial strength (F5), having a solid execution plan (F8) and a positive relationship than those with direct experience in working with subcontractor (Table 9).
Those with direct experience in working with subcontractors ranked the lowest bidding price (F3) higher. However, both groups had the same idea on the importance of the remaining selection factors.

Table 8: Respondent's involvement in selecting subcontractors in projects and ranking of the factors impacting selection of the subcontractors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Dependent variables</th>
<th>No. of projects involved in selecting subcontractors</th>
<th></th>
<th></th>
<th>T</th>
<th>Df</th>
<th>Sig.</th>
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<tr>
<td></td>
<td></td>
<td>&lt; 10</td>
<td>&gt; 10</td>
<td>Total</td>
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<td>N=55</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>Sd.</td>
<td>Mean</td>
<td>Sd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Experience in similar projects</td>
<td>4.51</td>
<td>0.689</td>
<td>4.55</td>
<td>0.538</td>
<td>-0.30</td>
<td>13</td>
</tr>
<tr>
<td>F2</td>
<td>Familiarity with the local market</td>
<td>3.66</td>
<td>0.820</td>
<td>3.25</td>
<td>0.886</td>
<td>2.74</td>
<td>13</td>
</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>3.57</td>
<td>0.903</td>
<td>3.98</td>
<td>1.097</td>
<td>-2.29</td>
<td>10</td>
</tr>
<tr>
<td>F4</td>
<td>Compliance of schedule</td>
<td>4.02</td>
<td>1.088</td>
<td>3.20</td>
<td>1.129</td>
<td>4.28</td>
<td>13</td>
</tr>
<tr>
<td>F5</td>
<td>Financial strength</td>
<td>3.59</td>
<td>1.175</td>
<td>2.58</td>
<td>1.536</td>
<td>4.11</td>
<td>95</td>
</tr>
<tr>
<td>F6</td>
<td>Available resources</td>
<td>4.22</td>
<td>0.889</td>
<td>4.05</td>
<td>0.650</td>
<td>1.25</td>
<td>13</td>
</tr>
<tr>
<td>F7</td>
<td>Reputation</td>
<td>3.88</td>
<td>0.727</td>
<td>3.58</td>
<td>0.875</td>
<td>2.08</td>
<td>10</td>
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<tr>
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<td>Execution plan</td>
<td>3.73</td>
<td>1.007</td>
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<td>1.100</td>
<td>3.42</td>
<td>13</td>
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<tr>
<td>F9</td>
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<td>3.60</td>
<td>0.852</td>
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<td>13</td>
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<tr>
<td>F10</td>
<td>Safety record</td>
<td>4.09</td>
<td>1.102</td>
<td>3.67</td>
<td>1.001</td>
<td>2.23</td>
<td>13</td>
</tr>
<tr>
<td>F11</td>
<td>Qualification of personnel</td>
<td>3.99</td>
<td>0.988</td>
<td>3.47</td>
<td>1.136</td>
<td>2.74</td>
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<tr>
<td>F12</td>
<td>Previous relationship</td>
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<td>3.18</td>
<td>1.090</td>
<td>1.94</td>
<td>13</td>
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</table>

Table 9: Respondent's direct experience in working with subcontractors ranking of the factors impacting selection of the subcontractors

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<th>Dependent variables</th>
<th>Direct experience in working with subcontractors</th>
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<th></th>
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<th>Df</th>
<th>Sig.</th>
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<td>N=137</td>
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<td>Sd.</td>
<td>Mean</td>
<td>Sd.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>Experience in similar projects</td>
<td>4.58</td>
<td>0.532</td>
<td>4.31</td>
<td>0.891</td>
<td>1.58</td>
<td>34</td>
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<tr>
<td>F2</td>
<td>Familiarity with the local market</td>
<td>3.40</td>
<td>0.842</td>
<td>3.86</td>
<td>0.875</td>
<td>-2.61</td>
<td>135</td>
</tr>
<tr>
<td>F3</td>
<td>Lowest price bid</td>
<td>3.84</td>
<td>1.015</td>
<td>3.34</td>
<td>0.857</td>
<td>2.42</td>
<td>135</td>
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<td>F4</td>
<td>Compliance of schedule</td>
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<td>4.00</td>
<td>1.069</td>
<td>-1.70</td>
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<td>F5</td>
<td>Financial strength</td>
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<td>3.72</td>
<td>0.882</td>
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<td>76</td>
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<td>Available resources</td>
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<td>0.750</td>
<td>4.24</td>
<td>0.988</td>
<td>-0.66</td>
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<td>Reputation</td>
<td>3.72</td>
<td>0.807</td>
<td>3.90</td>
<td>0.772</td>
<td>-1.04</td>
<td>135</td>
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<td>F8</td>
<td>Execution plan</td>
<td>3.32</td>
<td>1.075</td>
<td>4.07</td>
<td>0.923</td>
<td>-3.72</td>
<td>50</td>
</tr>
<tr>
<td>F9</td>
<td>QA &amp; QC program</td>
<td>3.80</td>
<td>0.829</td>
<td>4.07</td>
<td>0.923</td>
<td>-1.54</td>
<td>135</td>
</tr>
<tr>
<td>F10</td>
<td>Safety record</td>
<td>3.83</td>
<td>1.072</td>
<td>4.24</td>
<td>1.057</td>
<td>-1.83</td>
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</tr>
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<td>F11</td>
<td>Qualification of personnel</td>
<td>3.75</td>
<td>1.060</td>
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<td>1.145</td>
<td>-0.65</td>
<td>135</td>
</tr>
<tr>
<td>F12</td>
<td>Previous relationship</td>
<td>3.27</td>
<td>1.038</td>
<td>3.83</td>
<td>1.258</td>
<td>-2.67</td>
<td>135</td>
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</table>
5 SUMMARY AND CONCLUDING REMARKS

This study presented a survey of the factors that are deemed important when selecting subcontractors for construction projects. 137 construction industry professionals were surveyed. About two-thirds (67%) of the participants were from the private sector and the remaining from the public sector. The majority of participants were from contractor organizations, accounting for almost half of the population, followed by those from the owner organizations. Most of the participants were active in the industrial construction segments (64%), followed by the heavy infrastructure. While more than two thirds (70%) of the participants had above 5 years of experience in the construction industry, only slightly over half of the participants (55%) had more than five years of experience in Alberta. This gap can be reflective of the percentage of immigration of experienced professionals to this province. Around 40% of respondents were involved in selecting subcontractor in more than 10 projects and about 80% had direct experience in working with subcontractors, which may support the reliability of their responses.

Based on the survey result, the lowest bid price was the most important selection factor for participants from construction contractors and professionals with medium range (5-10 years) of experience in the construction industry in Alberta, those involved in selecting a subcontractor in more than 10 projects and with direct experience in working with subcontractors. Experience in similar projects was most important to professionals from residential segment. Familiarity with the local market was deemed most important by those from the consultant firms. Compliance to the project schedule was seen important by professionals from public sector, those from owner and consultant firms, those involved in residential segment, less than 5 years of experience in construction industry and involved in selecting subcontractors in less than 10 projects. Financial strength and reputation of subcontractor was scored highest by professionals from consultant firms and those involved in residential segment. Professionals from public sector, those with owner and consultant firms, those involved in residential segment, those with little experience in selecting subcontractors found the quality assurance program of subcontractors an important factor. Safety records and qualification of the personnel was scored highest by public sector, owner and consultant firms, residential and heavy segment, and those with little experience in selecting subcontractors. Interestingly, the consultants were the only group that associated a high important to the previous relationship with the subcontractor.

References

A STATISTICAL SAFETY CONTROL MODEL FOR CONSTRUCTION SITES USING LOCATION SYSTEMS

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Abstract: A statistical safety control model is presented that utilizes data from a Real Time Location System of relatively low accuracy, to alert of unsafe situations at construction sites. Based on the Statistical Process Control methodology, predefined statistical rules are used to detect trends of increasing exposure to hazards, and provide proactive alerts before a critical exposure takes place. An initial verification of the performance of the model was carried out through extensive laboratory tests.

1 INTRODUCTION

Various studies indicate that the incidence rate of fatal workplace accidents in the building industry, with an estimated 60,000 fatal casualties a year around the world, is higher than in any other industrial sector (Aires et al. 2010). The most common cause for fatal accidents on construction sites is usually falling from heights (Aneziris et al. 2012; Wu et al. 2010). In recent years, a number of studies have been dedicated to the improvement of safety on construction sites through the application of a Real Time Location System (RTLS) in order to track the movement of workers and prevent accidents from occurring (e.g. Nattichia et al. 2013; Maalek and Sadeghpour 2013). The main purpose of the RTLS is to facilitate an alert when a worker enters an area that has been defined as being of "high risk". Such an approach can be considered deterministic, and requires a highly accurate tracking system in order to be able to detect in real-time when a worker moves from a low risk area to a high risk area.

Highly accurate indoor tracking systems such as Ultra Wide Band (UWB) (i.e. systems that, unlike standard GPS, can be used inside buildings that are under construction) are relatively expensive technologies that require significant time and effort to deploy (Khoury and Kamat 2009). Other, less expensive technologies such as WLAN-based tracking systems are economical but provide a much lower accuracy (i.e. 1.5 to 2 m, as opposed to centimeter level positioning accuracy for UWB). Such a low accuracy is not compatible with a deterministic approach, in which any penetration into a high risk area needs to be immediately identified.

An additional factor that needs to be taken into account, in the application of a RTLS to improve worker safety on construction sites, is the high uncertainty that typically exists regarding expected worker locations. This uncertainty stems from the fact that the project plan often does not reflect in real time decisions on changes that are made by the project management team (Isaac and Navon 2013). In addition to that, even an accurate and up-to-date project plan cannot fully reflect the complexity and unpredictability of worker movements, which often deviate from expected work envelopes (Isaac and Navon 2013).
The use of a RTLS on construction sites can therefore enhance worker safety. However, the economic rationale for using a cheap but inaccurate RTLS, and the uncertainty regarding actual worker behavior onsite, means that one might not be able to rely solely on the definition of safe work areas with clear-cut boundaries, and deterministic alerts in case these boundaries are crossed. In fact, the uncertainty regarding worker behavior may imply that improving the accuracy of real-time location measurements is likely to be less beneficial than is often assumed. Transgressions on the site are likely to be frequent, due to both workers entering dangerous areas, and the location of those areas changing in ways that differ from the project plan. One solution could be to compensate for the expected inaccuracy and uncertainty by significantly enlarging the areas defined as being of high risk, and therefore off-limits for most workers on site. However, this would reduce the efficiency of the construction processes.

An additional limitation of the current deterministic approach for applying RTLS systems to enhance construction worker safety is the fact that for some safety risks, the temporal dimension is of importance. In other words, the duration of risk exposure has to be taken into account. For example, in case of a hazardous noise exposure, the duration of exposure is an essential factor. The current deterministic approach for using a RTLS for safety control on construction sites therefore has three main limitations:

1. It requires highly accurate and expensive tracking systems
2. It is not fully compatible with the highly uncertain nature of construction projects
3. It does not take into account the duration of risk exposure, which is of importance for certain hazards.

In order to provide an answer to these limitations, the present research is based on a statistical approach that complements the existing deterministic methods. Specifically, this research deals with the development of a statistical safety control model that utilizes data from a RTLS, with the objective to alert of unsafe situations at construction sites of multistory buildings. An unsafe situation is defined here as one that causes workers to be exposed to hazards which were initially created by other teams of workers. While there are many methods and models available to assess the risks that the workers’ own activities pose to themselves, few studies have dealt with the hazards derived from the concurrent activities of other workers on site to which workers are also frequently exposed (Hallowell et al. 2011).

2 THE PROPOSED STATISTICAL SAFETY CONTROL MODEL

The proposed model is implemented in four modules, as follows:

1. Identification of hazards which are related to the execution of an activity;
2. Risk assessment according to a structured method (though sufficiently flexible to accommodate different types of hazards);
3. Division of the site into risk areas according to predefined parameters of injury level and distance from hazard;
4. Definition of safety zones using a statistical methodology.

In the first module, an identification of potential hazards, based on the construction site layout and the project's schedule, is required before carrying out an activity. The related hazards are those to which other teams might be exposed. This stage contains several sub-stages. Preliminary Hazards Analysis breaks down the activity into a chain of actions. This list of actions makes it easier to detect the hazards. Following this, the required work area is analyzed in terms of the type of space, and the expected worker movement patterns. This is done in order to identify the potential teams that might be exposed to the related hazards.

In the second module, a risk assessment of the identified hazards is carried out. The assessment is defined by 2 parameters: 1) the level of the potential injury when an accident occurs, based on the classification of the Israel Institute for Occupational Safety and Hygiene; 2) The distance from the
hazards, taking into account different factors such as the RTLS accuracy, the movement velocity of the workers, data processing by the RTLS, worker reaction time to alerts, etc.

In the third module, the construction site is divided into risk areas. This division is a product of the risk assessment. The combination of assessments regarding injury level and distance from hazards creates a matrix which defines the risk level at a certain location. There are several risk area categories, as follows: very high, high, medium and low risk. The main applicable difference between those areas is the level of hazard exposure to which non-authorized teams are allowed. In fact, the risk area classification defines the level of tolerance towards the presence of non-authorized workers in a certain risk area. Therefore, each worker must be familiar with the risk area classification.

In the fourth module, statistical safety zones are defined. This stage is related to the statistical operation. Therefore, statistical alerts rely on this division. The main impact of the division is the definition of a “medium risk” area, where the proposed statistical model can provide benefits not provided by deterministic models. The medium risk area may appear to be "free" of hazards, since the risk is not defined there as critical or immediate. However, a continuous exposure to a certain hazard may harm a worker, or might increase the probability that that worker will penetrate into the high risk area. Therefore, the model contains several statistical rules that detect an increasing exposure to a hazard, and that provide alerts before a critical exposure occurs.

The remainder of this paper will focus on the fourth module, which is based on an existing methodology of process management, called Statistical Process Control (SPC).

3 STATISTICAL PROCESS CONTROL (SPC)

SPC is a statistical methodology for process management, which has been mainly used for quality control in manufacturing. SPC uses statistical tools to observe specific characteristics of the manufactured product, and identify significant variations in those characteristics. Instead of defining deterministic rules for rejecting a product that does not meet certain specifications, SPC assumes that some variation in the process is to be expected, and that only a statistically significant variation needs to be addressed, and the factors causing it identified. The assumption in SPC is that the measured characteristic of a specific object has a normal distribution, which distributes symmetrically around the Mean ($\mu$), with three zones defined according to the Standard Deviation ($\sigma$):

1. Zone1: ~68% of population, which defined as: $\mu \pm \sigma$;
2. Zone2: ~95% of population, which defined as: $\mu \pm 2\sigma$;
3. Zone3: ~99% of population, which defined as: $\mu \pm 3\sigma$;

An application of the SPC methodology for safety control on construction sites, instead of for quality control in manufacturing, obviously requires significant adjustments. Firstly, it is assumed, based on the Central Limit Theorem, that the distribution of the movements of workers will be normal relative to the main “work” location. Secondly, the division into zones is based on safety aspects. Thus, Zone1 is related to a low risk area, Zone2 and Zone3 are related to a medium risk area, and all locations above Zone3 are related to a high risk area. The hypothesis of the present research is that a statistical model can deal with issues such as the relatively low-level accuracy (2m) of a cost effective RTLS and the high uncertainty regarding workers’ movements, by providing alerts based on a statistical analysis of locations within medium risk areas, in addition to the existing deterministic alert when a worker enters a high risk area. In practice, such medium risk areas would constitute buffers between planned work areas and areas identified as being of high risk to the workers.

The application of SPC for quality control is based on certain statistical rules. The rules that are nowadays commonly used in the manufacturing industry were defined in the middle of the 20th century by an American company called Western Electric Company (Western Electric Co. 1958). These rules can be used to detect statistical trends relative to the desired mean, based on the expected normal distribution.
For example: measurements that fall within Zone3 have a low probability (under 1%), and are therefore considered abnormal. Other rules are based on sequential measurements related to the predefined zones and their probabilities. For example: the probability of four out of five consecutive measurements being in Zone2 or Zone3 is about 3%, and therefore considered to be statistically significant.

An advantage of the statistical approach is thus the ability to detect trends of increasing exposure to hazards by calculating sampling rates, either for a single worker or an entire crew. This supports proactive actions in the form of alerts, which are received before a critical exposure takes place. As will be demonstrated, the model can ensure that alerts will not be ignored, by using such statistical rules to avoid an excessive number of alerts, and by discerning who should be the client of an alert. We can thus increase both safety and efficiency (in terms of multiple teams working simultaneously on site). This, on contrast to the present situation, in which areas with moderate risk exposure levels are either ignored (therefore increasing safety risks), or included in deterministic no-entry zones (therefore reducing the efficiency of the construction processes).

4 IMPLEMENTATION OF THE MODEL

The implementation and initial verification of the model was based on laboratory tests that were carried out at the Structural Engineering Department at Ben-Gurion University of the Negev, Israel. Simulated movements of workers were monitored in the department using a Wi-Fi-based RTLS that was installed for this purpose. The RTLS included Access Points, Low Frequency tags and a software platform. The accuracy of the RTLS was 2 meters, and it was chosen due its low cost, which is expected to increase the likelihood that it will be used in actual construction projects. In fact, this type of RTLS is based on a regular Wi-Fi network that is installed in any case in most buildings. The only extra costs would therefore be those of the tags, which can be reused from one project to another. It was assumed that the implementation of a statistical model would make it possible to overcome the relatively low accuracy of the RTLS.

For the tests, one floor of the department was divided into three different zones and a high risk area. The location of those zones changed in the tests according to different scenarios of construction activities that were defined. The definition of the zones according to one such scenario is shown in Figure 1. Zone1 (related to a low risk area) is shown in green, Zone2 and Zone3 (related to a medium risk area) are shown in yellow, and the high risk area is shown in red. During the tests, teams of participants carrying tags moved around the department and their locations were tracked. These locations were then converted into their distance from a simulated hazard location, according to the scenario.

Using the model, different types of alerts were provided. These included alerts related to a penetration into a high risk zone, as well as statistical alerts according to the predefined rules. The model was used to track movements and provide statistical alerts at 3 different levels:

- At the level of a single worker (Figure 2);
- At the level of a team of workers (Figure 3);
- At the project level (Figure 4).
The trend charts in Figures 2-4 present the locations of the tags that were tracked in tests, relative to the statistical zones. The horizontal axis is the time axis, whereas the vertical axis presents the location of a tag relative to the predefined statistical zones. Black marks indicate locations for which statistical alerts were provided. These alerts depend on the definition of the statistical zones, which depend, in turn, on the structured risk assessment that was carried out. The alerts can be related to a single worker (when the location of that worker deviates from the safe work area), to an entire team (for example, when the team starts working in a medium risk area), or to all the teams (when a certain event or management decision puts them in danger). Accordingly, the clients of such alerts can be the worker, a site manager, or the company administration.

![Trend chart of employee #4 in one of the tests](image1)

**Figure 2: Trend chart of employee #4 in one of the tests**

![Trend chart of Team #2 in one of the tests](image2)

**Figure 3: Trend chart of Team #2 in one of the tests**

![Trend chart of all the Teams](image3)

**Figure 4: Trend chart of all the Teams**

The verification criteria for the testing of the statistical model were based on a comparison of the alerts provided by the model, with a manual measurement of the duration for which participants were located in
a certain zone. The results of this comparison reveal that about 7% of the samples in the medium risk area were mistakenly identified as being in a high risk area (i.e. a false alert) (Table 1). In addition, about 12% of the samples in the high risk area were mistakenly identified as being in a medium risk area. One might assume that in those cases in which the second type of error occurred, the risk potential was high, since there wasn’t any deterministic alert of the participant entering a high risk area. However, all of those cases were in fact detected through the statistical rules in the model, and statistical alerts were accordingly provided. Therefore, all of the events in which a worker would have been exposed to a high risk, were either warned of through a deterministic alert of a penetration into a high risk area (~88% of the events), or through a statistical alert that was provided according to the predefined rules in the model (the remaining ~12% of the events). Nevertheless, it should be noted that an implementation of the model in a real project, would of course include an adjustment of the model’s parameters in order to improve its accuracy.

Table 1: Comparison of the model’s output with manually collected data

<table>
<thead>
<tr>
<th>Color of manually identified zone</th>
<th>Identification by model - type of mistake</th>
<th>% of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>No mistake</td>
<td>90</td>
</tr>
<tr>
<td>Green</td>
<td>Yellow instead of Green</td>
<td>10</td>
</tr>
<tr>
<td>Yellow</td>
<td>No mistake</td>
<td>87</td>
</tr>
<tr>
<td>Yellow</td>
<td>Green instead of Yellow</td>
<td>6</td>
</tr>
<tr>
<td>Yellow</td>
<td>Red instead of Yellow</td>
<td>7</td>
</tr>
<tr>
<td>Red</td>
<td>No mistake</td>
<td>88</td>
</tr>
<tr>
<td>Red</td>
<td>Yellow instead of Red</td>
<td>12</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

A statistical model was developed in this research, with the objective to alert of unsafe situations on construction sites. The model utilizes data from a cost-efficient, yet relatively low-accuracy RTLS, to prevent workers from being exposed to hazards which were initially created by other teams of workers. The statistical approach complements existing deterministic models by detecting trends of increasing exposure over time to hazards, and providing proactive alerts that are received before a critical exposure takes place. This enables it to deal with issues such as a high uncertainty regarding workers’ movements on construction sites, which is usually not observed in other types of industry.

The results of the laboratory tests show that the model has the ability to overcome the medium accuracy of the RTLS, based on the division of the site into statistical zones. In addition, it was found that the percentage of errors in zone identification is about 10%. Nevertheless, the statistical rules were found to be efficient, since all the critical zone detection errors that were related to a penetration into a high risk area would have been prevented by alerts provided according to the predefined statistical rules, and this in turn would have prevented the entrance of workers into a high risk area. Obviously, these results still have to be confirmed through an implementation in a real construction project.

References


A ROUTING ALGORITHM TO CONSTRUCT CANDIDATE WORKZONES WITH DISTANCE CONSTRAINTS

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Abstract: As highways deteriorate over time, it is necessary to execute preventive interventions to ensure that they continue to provide an adequate level of service. As the execution of interventions on highways almost invariably results in the interruption to traffic flow, it is often beneficial to group interventions. By grouping interventions into workzones, there is, for example, less lane changing required by vehicles traveling on the highway and, therefore, perhaps fewer accidents. The objects included in the optimal workzones depend on many factors, such as the condition/performance of the objects, the length of the workzone, the traffic configuration within the workzone, the length of time required to execute the interventions, and the budget available. Recent research by Hajdin & Lindenmann (2007) and Lethanh et al. (2014) has been focused on the development of optimization models to solve such problems. One difficulty with them though is the construction of the set of possible combinations, which was done manually. Once large networks are to be analyzed this is no longer possible. In this paper, a routing algorithm is presented that can be used together with these optimization models to automatically establish the combination matrix, taking into consideration constraints on the length of the workzone and the distance between workzones. The algorithm is developed in Matlab and empirically tested on a real world road network, with 671 km of roads and 567 objects including bridges, tunnels, and road sections. The state of each object is classified on a discrete scale of 5, with 1 being the best and 5 being the worst. Several scenarios based on setting constraints on maximum workzone length, and minimum distance between two adjacent workzones are used to verify the robustness of the algorithm. It is found that the algorithm is both efficient and fast for all scenarios investigated. The development potential, in particular with respect to integration in GISs, is discussed.

1 INTRODUCTION

Road networks are comprised of different types of objects, such as road sections, bridges, and tunnels. These objects are subjected to deterioration and, therefore, interventions (e.g. repair, rehabilitation, replacement) need to be executed to ensure that they continue to provide adequate levels of service. When an intervention is executed on an object, a workzone has to be set up to ensure that the intervention can be executed. When there are more than one object on which interventions are to be executed there is the possibility of grouping multiple objects within one work zone. Whether or not they are included, however, depends on their closeness to each other, the benefits of grouping them together as opposed to establishing separate work zones and constraints, such as the amount of funding
available, the maximum allowed length of a work zone, and the minimum allowed distance between workzones. An infrastructure manager is, of course, interested in determining the set of workzones.

The importance of having an optimal set of workzones can be simply explained with the following fictive road link consisting of 2 lanes comprised of five objects (Figure 1). Object 1, 3, and 5 are in states in which interventions are required while object 2 and 4 are in states in which no interventions are required.

![Figure 1: Possible sets of workzones (WZ) for a road link of five objects](image)

With 3 objects on which interventions are to be executed, there are 9 possible sets of workzones. The sets of workzones from 1 to 4 are possible when there is sufficient amount of budget. Whilst, in the sets from 5 to 9, a workzone might not include objects that require intervention due to limitation in the amount of budget. It is assumed that within a workzone, one lane is closed while the other lane is opened with a restriction on speed. In workzone set 1, there are 3 workzones. However, in workzone set 2, there are 2 workzones and one of the workzone includes objects 1, 2, and 3. In this workzone, there is no intervention on object 2 because it is still in good state. However, restriction on speed limit of vehicles is still applied. This is because it is not feasible with regard to the capacity of traffic control to allow 2 lanes of traffic flows in opposite directions in a short distance. Evidently, the impacts on stakeholders are different for each set of workzone, e.g. with workzone set 1, the owner of the road would have higher setup costs than with workzone set 2, where the users if the road could have higher additional travel time costs.

The problem of determination of optimal workzones undoubtedly becomes challenging when: 1) there is no longer a road link of only a few objects but a network of hundreds or thousands objects; 2) objects are not homogeneous sets but they are a mix of many different types of objects; 3) there are more than one intervention type or traffic configuration to be considered for each object (e.g. traffic flows for a road section of 4 lanes can be formed with more than one configuration).

Recently, research work focused on solving this problem has been conducted, but there are still improvements to be made before implementation is possible. One of the pioneer research was the work of Hajdin & Lindenmann (2007) and Hajdin & Adey (2005), which presented a linear optimization model to determine a single workzone, but not multiple workzones. In setting up the model, it is a must to construct two matrices: the continuity matrix and the combination matrix. These two matrices have to be setup so that input parameters (e.g. intervention cost, long-term benefits) related to each object and to any possible workzone can be estimated when the optimization model runs. In Hajdin & Lindenmann (2007), the authors verified the robustness of the model with a simple example of a road link with 36 objects. They setup the two matrices manually and thus it was possible with the size of the example. However, it is a tedious process and thus not possible if the size of the link becomes a network of hundreds or thousands objects and with a network having looping structure. This was done similarly in Hajdin & Adey (2005).

\footnote{a set of workzones can either be a single workzone or a group of multiple workzones}
The approach emphasized in these two papers was extended from one work zone to multiple work zones in the work presented by Lethanh et al. (2014), using a mixed-integer linear model. This also involved the introduction of maximum length of a workzone and minimum distance between two adjacent workzones constraints. This work was, however, also done by setting up the continuity and combination matrices manually.

In order to overcome the limitation of having to do this, it is necessary to develop a routing algorithm that allows a computer program to generate the two matrices giving only initial information such as the numbers of objects, numbers of nodes, maximum workzones length, and minimum distance between two adjacent workzones. The goal of the work presented in this paper was to develop such an algorithm.

The remainder of the paper is set-up as follows. The optimization model of Lethanh et al. (2014), which is the model that this work is based on, is described in the following section. Section 3 contains the developed routing algorithm. An example on a road network with 567 objects is shown in Section 4. The last section concludes the paper with highlighted points and elaborates recommendations for future extension of the work.

2 THE MODEL

The objective function is

\[ \text{Maximize } Z = \sum_{n=1}^{N} \sum_{k=1}^{K} \delta_{n,k} \cdot (B_{n,k} - C_{n,k}) \]

where \( \delta_{n,k} \) is a binary variable, which has a value of 1 if an intervention of type \( k \) is executed on road segment \( n \) and 0 otherwise. \( B_{n,k} \) and \( C_{n,k} \) are the long term benefit and cost of executing an intervention of type \( k \) on object \( n \), respectively.

Subject to the following constraints:

Continuity

\[ \sum_{n=1}^{N} \sum_{k=1}^{K} \delta_{n,k} = 1 \]

This constraint enforces the model to select only one intervention of \( k \) on object \( n \).

Budget

\[ \sum_{n=1}^{N} \sum_{k=1}^{K} \delta_{n,k} \cdot C_{n,k} \leq \Omega \]

The budget for executing interventions on the network is in general limited. The total cost of all interventions on the network cannot exceed a certain threshold \( \Omega \) for a given planning period.

Maximum workzone length

\[ \sum_{l=a_l^w}^{e_l^w} \sum_{n=a_n^w}^{e_n^w} \lambda_{l,n} \leq \Lambda_{\text{MAX}} \forall w \]

where \( \lambda_{l,n} \) is the length of the object \( [l,n] \); \( a_l^w \) \((l=a_l^w, n=a_n^w)\) is the first object of the workzone \( w = (1,...,W) \), and object; \( e_l^w \) \((l=e_l^w, n=e_n^w)\) is the last object in the workzone. \( \Lambda_{\text{MAX}} \) is the maximum length of the workzone.
Minimum distance

\[ \sum_{l=1}^{d_l} \sum_{m=1}^{d_m} \lambda_{l,m} \geq \Lambda^{MIN} \quad \forall d \]

where \( a^d \left( l = a^d_i, n = a^d_n \right) \) is the first object the default section \( d \); \( e^d \left( l = e^d_i, n = e^d_n \right) \) is the last object of the default section \( d \); \( \Lambda^{MIN} \) is minimum distance between two workzones.

Combination of maximum workzone length and minimum distance

The maximum workzone length and the minimum distance between workzones constraint is merged into one constraint by defining a combination matrix of objects within the network that cannot be subjected to an intervention simultaneously.

\[ \sum_{n=1}^{N} \sum_{k=1}^{K} \delta_{n,k} \cdot \gamma_{n,k,i} \leq 1 \quad \forall i \]

\( \gamma_{n,k,i} \) is a 1-by-J matrix, with I is the total number of rows and each row contains an object combination that cannot be selected simultaneously.

3 THE ROUTING ALGORITHM

The algorithm was described in this section using an example of a network comprised of 45 objects and 31 nodes with an equal length of 5 km per object (Figure 2). The maximum length of any workzone and the minimum distance between two adjacent workzones are 15 km.

In Figure 2, objects and nodes are indicated by numbers with no circles and numbers with circles, respectively. This network is different from the examples used in Hajdin & Adey (2005); Hajdin & Lindenmann (2007); and Lethanh et al. (2014) in that it has loops. The looping structure of the network becomes an obstacle when having to construct the combination and continuity matrices, which represent all possible ways to form a workzone starting from the first object in the workzone. The main task of the proposed algorithm is to calculate all the possible paths in the network taking into consideration both maximum workzone length and minimum distance between two adjacent workzones. Matlab code for each step is publicly available at Github repository\(^2\).

3.1 Maximum workzone length

For a given object \( n \) in the network, the algorithm calculates all paths starting with this object (max-paths). The lengths of these paths are defined as the sum of the lengths of the objects. The paths are then stored

\(^2\) https://github.com/namkyodai/workzone-routing-algorithm
in a matrix format. For example, with object 1, there are in total 6 paths that can be formed (solid thick lines in Figure 3 and combination of objects in Table 1).

### Table 1: Possible paths starting from object 1 satisfying maximum length

<table>
<thead>
<tr>
<th>Paths</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>1</td>
<td>1</td>
<td>1</td>
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<td>4</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3: All paths starting from object 1](image)

### 3.2 Minimum distance between two adjacent workzones

The algorithm calculates, for a given object \( n \), all paths starting with this object (min-paths). Objects are added to a min-path as long as the min-path's length is smaller than the minimum distance between workzones. The length of a min-path is defined as the sum of the lengths of its objects minus the length of the first object in the path. Thus the number of objects in the paths for the minimum distance is defined as the sum of the lengths of its objects minus the length of the first object in the path. The total number of paths starting with an object for the minimum distance constraint is significantly larger than the total number of paths starting with that object for the maximum work zone length. The following figure and table illustrate the matrix formation for the minimum distance constraint.

### Table 2: Possible min-paths starting after object 1

<table>
<thead>
<tr>
<th>Paths</th>
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</table>

![Figure 4: All paths starting after object 1](image)
It can be seen that a min-path has its total length greater than the maximum workzone path. For example, path 10 is comprised of objects 3, 6 and 8 with its total length of 15 km. Then if the object 1 is selected to be in a workzone, the other workzone can only be formed after object 8.

3.3 Impossible object combinations

After all max-paths and min-paths for all objects in the network have been identified, the algorithm searches for a set of impossible object combinations. Impossible object combinations are pairs of network objects that violate the maximum workzone length constraint if they are to have interventions simultaneously. For example, if object 1 is part of a workzone, impossible object combinations are objects that are too far away to be part of the same workzone as object 1, but too close to be part of an adjacent workzone (they are objects 8, 11, 12, 15, and 18 (Table 3)).

Table 3: Impossible object’s combination starting from object 1

<table>
<thead>
<tr>
<th>Constrains</th>
<th>Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum length</td>
<td>1 2 3 4 5 6 7 10 - - - -</td>
</tr>
<tr>
<td>Minimum distance</td>
<td>1 2 3 4 5 6 7 8 10 11 12 15 18</td>
</tr>
<tr>
<td>Invalid combination</td>
<td>- - - - - - 8 - 11 12 15 18</td>
</tr>
</tbody>
</table>

3.4 The combination matrix

The combination matrix is a m-by-n matrix where m is the number of constraints and n is the sum product of all the objects in the network and the number of intervention. The number of impossible object combinations and thus the number of constraints depends on the difference between the thresholds for the minimum distance between work zones and the maximum work zone length constraints. With increasing difference between these two thresholds, the number of impossible object combinations grows greatly with the number of constraints. Below is an example of the formulation of linear constraints for the impossible combinations with respect to object 1.

Table 4: Combination matrix starting from object 1

| Objects 1 1 2 2 3 3 4 4 5 5 6 6 7 7 8 8 9 9 10 10 11 11 12 12 12 |
|---------------------------|---------|
| Interventions 0 1 0 1 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 0 1 2 |
| Binary 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 |

| WZs 1-8 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 |
| WZs 1-11 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 |
| WZs 1-12 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 |

In Table 4, the interventions to be executed on multiple objects can be seen. There are 2 types of interventions for objects 1, 2, denoted 0 and 1, and 3 types of intervention for objects 7, 8, 10, 11, and 12, denoted 0, 1 and 2. Interventions denoted as "0" are the “do-nothing” interventions, i.e. there is no physical intervention executed and there is no change to the traffic configuration. Interventions denoted 1 and 2 are combinations of a physical intervention type and a traffic configuration. If intervention 1 or intervention 2 is selected, then the object is included in the workzone. Otherwise it is not. The binary values appeared in the combination matrix (refer to Eq. [6]) become 1 when it is impossible to form two workzones adjacent to each other. This binary value will be multiplied with the binary in the upper part of the table to give a possible workzone. This means that in Table 4, objects 1 are in a work zones, and objects 8, 11 and 12 are not in a work zone.

3.5 The continuity matrix

The continuity matrix ensures that exactly one intervention is selected for every object in the network. The continuity matrix is a p-by-n matrix where p is the number of objects in the network and n is the sum product of all the objects in the network and the number of intervention.
Table 5: Continuity matrix

| Interventions | 0 | 1 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 |
| Binary        | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 |

The right hand side of the continuity matrix shows the number of connections for every object. For example, object 1 is connected to two adjacent objects and object 2 is connected to four adjacent objects.

3.6 Example results

The optimal set of workzones for the simplified example is illustrated in Figure 5. Workzones (shown with thick lines) have been identified and all constraints have been satisfied.

![Figure 5: Result of the simplified example](image)

4 Example

To demonstrate the robustness and efficiency of the routing algorithm, it was used to determine optimal work zones for a road network comprised of 567 objects with a total length of 671 km was tested.

4.1 Intervention types and condition states

Table 6: Condition states-cost and benefit of intervention (per 1 km)

<table>
<thead>
<tr>
<th>CS</th>
<th>Road description</th>
<th>Low Benefit</th>
<th>High Benefit</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Like new</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Good</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Acceptable</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Insufficient</td>
<td>4</td>
<td>8</td>
<td>1,5</td>
</tr>
<tr>
<td>5</td>
<td>Bad</td>
<td>8</td>
<td>16</td>
<td>1,5</td>
</tr>
</tbody>
</table>
For every object, three types of interventions can be executed: 1) Intervention type 0: Do nothing; 2) Intervention type 1: Low benefit intervention; 2) Intervention type 2: High benefit intervention. All objects are considered to be in one of five discrete states, with worsening physical condition from state 1 to state 5. Executing interventions on objects in state 1 yield low benefits whereas intervening on objects in state 5 yield high benefits. The exact values are given in Table 6. States for objects were randomly generated, but once determined, they were used for all investigated scenarios.

4.2 Scenarios and results

Four different scenarios were investigated by means of changes in the budget, the maximum workzone length and the minimum distance between workzones. The optimal sets of workzones were obtained by running the optimization model for these scenarios (Table 7).

<table>
<thead>
<tr>
<th>Results</th>
<th>Budget (mus(^3))</th>
<th>Maximum workzone length</th>
<th>Minimum distance</th>
<th>Number of objects selected</th>
<th>Objective function</th>
<th>Total number of constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>[ MU/1'000 m]</td>
<td>[ m]</td>
<td>[ m]</td>
<td>[ -]</td>
<td>[ MU ]</td>
<td>[ -]</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>50</td>
<td>5'000</td>
<td>5'000</td>
<td>23</td>
<td>483.3</td>
<td>2'911</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>50</td>
<td>5'000</td>
<td>8'000</td>
<td>29</td>
<td>456.2</td>
<td>6'109</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>40</td>
<td>6'000</td>
<td>8'000</td>
<td>17</td>
<td>386.6</td>
<td>5'196</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Unlimited</td>
<td>5'000</td>
<td>8'000</td>
<td>176</td>
<td>872.3</td>
<td>6'108</td>
</tr>
</tbody>
</table>

In scenario 1, the budget is restricted to 50 mus, the maximum workzone length and the minimum distance between workzones are set to 5'000 m. For this scenario, the final version of the optimization model contains a total of 2'911 constraints, and once run the interventions to be executed in the optimal work zones are determined to provide a benefit of 483.3 mus.

In scenario 2, the budget and the maximum workzone length remain unchanged (with respect to scenario 1), whereas the minimum distance between workzones is increased to 8'000 m. Due to this increase, the gap between the minimum distance between workzones and the maximum workzone length increases. The larger gap (3'000 m) between those two workzone constraints causes the number of combination constraints to rise and the total number of constraints reaches 6'109. The number of continuity constraints remains the same for all four scenarios. A slight drop in the value of the objective function is observed from 483.3 to 456.2.

In scenario 3, the minimum distance between workzones remains constant (with respect to scenario 2). The budget is lowered to 40 mus and the maximum workzone length is increased to 6'000 m. This increase reduces the gap between both work zone constraints from 3'000 to 2'000 m and thus the number of impossible object combinations drops again. Scenario 3 has a total of 5'196 constraints. The decrease in the value of the objective function is caused by the reduction in the available budget.

In scenario 4, both workzone length constraints are equal to scenario 2, whereas the budget constraint is lifted. The total number of constraints decreases from 6'109 to 6'108 (no budget constraint).

A strong increase in the total number of objects to have an intervention from 29 to 176 is observed due to the unlimited budget. However, the value of the objective function rises only by a factor of 2. This is because, in the first three scenarios, the objects to have an intervention are mainly in condition states 4 and 5. In scenario 4, a lot of objects in good condition states and thus lower benefits are subject to interventions because of the unrestricted budget.

In all scenarios, computational time was less than 5 minutes on a normal lap top computer (32 bits, 4 GB RAM, Dual-Core Intel 2.53 GHz). This infers the power of computation and robustness of the model with

\(^3\) mus stands for monetary units
respect to the size of network, especially when comparing with the manual setup, which might not be feasible with such a network.

4.3 Graphical representation of optimal workzones

Figure 6 illustrates parts of the optimal sets of workzones for the four scenarios. The nodes represent interventions and they are notated in the format of xx.yy, with xx being the object number and yy being the intervention. Workzones are highlighted in rectangular boxes. It can be seen how the optimal workzones changes with the changes mentioned in the previous section.

![Graphical representation of optimal workzones](image)

Figure 6: Sets of workzones under 4 different scenarios

5 CONCLUSION

In this paper an efficient routing algorithm to be used to formulate two matrices (the continuity and combination matrices) for a mixed-integer linear optimization models is presented. Such an algorithm is

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4 Intervention includes physical intervention types and traffic configuration
beneficial if models developed to solve network problems, such as those developed by Hajdin & Adey (2005); Hajdin & Lindenmann (2007); and Lethanh et al. (2014) are to be expanded to large networks and networks that contain loops. Setting up the combination and continuity matrices, if done manually, is not possible when there are hundreds and thousands of objects in a road network. However, with the developed algorithm (coded in Matlab), they can be generated with ease. In addition, the algorithm allows construction of these two matrices taking into consideration looping structures of a road network.

The algorithm was verified with examples of two simplified road networks: one with a small size network with only 45 objects to describe the algorithm step by step; the other with a large scale network of 567 objects to demonstrate the robustness and efficiency of the algorithm.

With the development of this algorithm a substantial barrier to the implementation of these types of optimisation models has been removed, in the effort to automate the determination of optimal work programs, which are made of work zones, for large road networks. Further work will be focused on testing this algorithm and much larger networks and integrating it into geographical information systems.

References


EVOLUTIONARY STABLE STRATEGY FOR POST-DISASTER INSURANCE: A GAME THEORY APPROACH

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Abstract: Natural disasters leave the impacted regions with financial burdens both on the individual and governmental levels. Thus, the goal of the associated stakeholders is to maximize the host communities' welfare through minimizing their post-disaster financial burdens. Accordingly, this paper attempts to find a post-disaster insurance plans equilibrium so as to mitigate the financial impacts associated with the natural disasters. Utilizing an evolutionary game theory approach, the equilibrium is investigated between three different players including: resident families purchasing insurance plans; insurance companies offering different insurance plans; and the government agency that implements post disaster relief financial plans. The authors determined a set of decision actions as well as utility functions for the aforementioned stakeholders. Moreover, the authors created a hypothetical sample of 1,000 heterogeneous income level resident families, three insurance companies offering three unique and different insurance plans per company and two post disaster financial relief plans to be utilized by the government agency. The proposed model was implemented on NetBeans IDE 7.4 platform using JAVA programming language on the hypothetical case study simulating resident family evolutionary learning process in reaching an equilibrium. The results indicate that: (1) resident families tend to prefer insurance plans with the least premium value and coverage; (2) insurance plans with the most comprehensive coverage received the least demand; and (3) the evolutionary stable strategy path oscillates between chosen plans and insurers over time as a result of the stochastic and dynamics nature of the factors associated with disaster management. Currently, the authors are working to develop the model further to better account for simultaneous actions by all stakeholders (not only resident families), population growth and changes in financial and income standards. Ultimately, this evolutionary game theory model will be tested on real post natural disasters data representing physical damages in coastal Mississippi Counties post Katrina, so as to determine the significant increase in the host community welfare.

1 INTRODUCTION

Mitigation of the financial impacts associated with natural catastrophes is becoming a focal issue at both the national and international levels as the rate and magnitude of natural disasters are increasing. According to Climatic Change Science Program (2008) and the National Association of Insurance
Commissioners (2005), recent examples in the United States include (1) Hurricane Andrew in 1992 which caused $20.9 billion in insured losses; (2) the Northridge earthquake in 1994 which resulted in insured losses of $15.9 billion; (3) the four Hurricanes Charlie, Ivan, Frances and Jeanne in 2004 which caused $21.9 billion in insured losses; (4) Hurricane Wilma and Rita in 2005 which resulted in insurance losses of $11.9 billion; (5) the devastating Hurricane Katrina in 2005 which caused economic losses approaching $125 billion; (6) Hurricane Ike in 2008 that resulted in $19.3 billion in property damages; and (7) Hurricane Sandy in 2012 which incurred damages more than $68 billion.

Disaster insurance plays a significant role in the mitigation and preparedness phases of the emergency management. However, there are important gaps in the knowledge-base for emergency management and financial disaster mitigation. Past studies have primarily addressed the challenge of disaster risk management by segregation of the problem without concern of the integration of how these parts fit into a decision making tool that integrates the goals, objectives, perceptions, and beliefs of multiple agents in determining a set of social optimum strategies to mitigate the financial impact of future disaster damage.

2 GOALS AND OBJECTIVES

Using an evolutionary game theory approach, this paper aims to find an equilibrium profile of post-disaster insurance plans purchased by resident families, sold by insurance companies, and ex post disaster relief implemented by a government agency. This should identify the optimal balance between: (1) number of plans offered by insurance companies; (2) types of plans that should be selected by each type of resident family based on their income level; and (3) compensation ratio that the government will pay for each resident family to offset the post-disaster damages. This dynamic integrated assessment minimizes the total losses for the three aforementioned associated stakeholders, thus maximizing welfare within natural disaster host community systems.

3 BACKGROUND INFORMATION

Natural hazards damages have reached a record level causing around 800,000 fatalities last decade as well as damages in the infrastructure of over a trillion dollars (Economics of Climate Adaptation Working Group 2009; Stern 2006). Decision makers nationwide, in both public and private sectors, are concerned about the vulnerability of their economy to natural hazards. They face investment choices in a stochastic environment with overlapping risk factors. These risk factors consist of wind, flooding, fire, and earthquakes, as well as climate change and their effects on investments. Also, as population and economies continue to grow, the total value at risk from natural hazards will increase (Climatic Change Science Program 2008). Research has been conducted by governmental, private, non-profit and academic organizations and institutions to study, assess, and solve problems associated with disaster financial mitigation. Most of these valuable efforts generally fall into three main streams including loss estimation models, computational engineering approaches, and risk management using insurance.

3.1 Loss Estimation Models

Since the 1980s, a number of major impact assessment models have been developed to support disaster preparedness and recovery efforts. For example, HAZUS-MH is a hazard prediction software program developed by the Federal Emergency Management Agency under a contract with the National Institute of Building Sciences to estimate potential losses from earthquakes, hurricane winds, and floods (HAZUS-MH 2007; Pradhan et al. 2007). Loss estimation models provide increasingly comprehensive estimates of regional risk, but offer little guidance about how to use that information to make damage mitigation resource allocation decisions (Dodo et al. 2005). These models can estimate losses in relation to structural damage, contents damage, time-based impacts, and only a small set of predefined mitigation alternatives can be considered (Grossi and Kunreuther 2006). However, they are not able to account for the stakeholders’ side including costs of the alternatives, the budget, and the specific objectives and priorities of each stakeholder (Federal Emergency Management Agency 2003; Dodo et al. 2005).
3.2 Computational Engineering Approaches

Computational engineering approaches have been used extensively for studying and mitigating the financial impacts from natural catastrophes including:

- **Deterministic Net Present Value (NPV):** Altay et al. (2002); and Kuwata and Takada (2003) calculated the avoided loss as the difference between the losses estimated with and without implementation of the mitigation alternatives.

- **Stochastic NPV:** Englehardt and Peng (1996) estimated probability distribution of the benefits associated with revising hurricane requirements and compared it with the cost of implementing the revision. Werner et al. (2002) compared various levels of proposed seismic design or upgrade on both means and standard deviations of losses.


- **Optimization Models:** Augusti et al. (1994) used dynamic programming to select structural mitigation alternatives. Researchers at the International Institute for Applied Systems Analysis (IIASA) developed a spatial-dynamic stochastic optimization model to select the insurance policy design that maximizes profits and minimizes risk of insolvency for insurance companies (Ermoliev et al. 2000; Ermolieva et al. 2001; Brouwers et al. 2001). Dodo et al. (2005) developed linear program for resource allocation in earthquakes that incorporates spatial correlation among a set of mitigation alternatives, associated probabilities, and decision timing.

3.3 Risk Management Using Insurance

Insurance is utilized to spread the financial risk of loss resulting from low frequency-high consequence disastrous events (Kunreuther and Michel-Kerjan 2007). Insurance companies have made significant changes in their approaches to provide coverage for natural hazards (Muller 2008; Mills 2007). Capital market participants developed catastrophe bonds, which are a type of securities that can be purchased by institutional investors to cover certain insurer risks (Cardenas 2006). Proposals have been made to Congress and regulatory agencies to take additional steps in changing the U.S. tax laws and accounting standards to allow insurers to set aside funds on a tax deductible basis and establish reserves for hazards (Smetters and Torregosa 2008; Cardenas 2006). However, these reserves lower federal tax receipts and do not necessarily bring about a meaningful increase in the capacity of the insurance industry. This is because insurers may substitute their reserves for other types of capacity (Shear 2005).

More analytically, Picard (2008) investigated the equity-efficiency trade-off faced by policy makers under imperfect information about individual prevention costs. His research highlighted the complementary relationship between individual incentives tax cuts and collective incentives grants to the local jurisdictions where natural hazard insurance plans are enforced. Chen et al. (2008) studied the determinants for the short-run position resulting from ex-ante insufficient premium and the long-run position resulting from ex-post insurance supply reductions. Greiving et al. (2006) studied the spatial limitations of the Natural Hazard Index for Mega Cities as well as the Total Place Vulnerability Index, and developed an integrated hazards map that combines regional hazards and vulnerability. Also, research revealed that while catastrophe insurance is more price elastic than non-catastrophe insurance in cities like New York, responsiveness to price is inelastic in the coastal areas because price increases only with mandatory purchase by mortgage borrowers (Grace et al. 2004; Kriesel and Landry 2004).

The aforementioned research illustrate several models that asses disaster damages and how to financially mitigate the impacts of disasters on the existing environment and host community. However, few to none discuss the social and individual decision process for selecting an insurance company given their preference for different disaster insurance plans. To this end, this research aims to utilize Evolutionary game theory to simulate residences’ post disaster learning to better guide the disaster...
insurance plans selection. This research will also guide insurers on how to determine an optimal array of plan premiums and coverages that will eventually be accepted by the community over time.

4 METHODOLOGY

In order to attain the aforementioned goal and objectives, the authors utilized the following three-step research methodology: (1) determined the set of possible actions and utility functions that govern the strategy profiles of the associated stakeholders including resident families, insurance companies, and government; (2) utilized the evolutionary stable strategy profile amongst the aforementioned players using game theory; and (3) applied the proposed model to a hypothetical dataset as a proof of concept.

5 ASSOCIATED STAKEHOLDERS: ACTIONS AND UTILITY FUNCTIONS

As previously mentioned, the stakeholders are resident families, insurance companies, and the government. The resident families and insurance companies will be represented by a population of players while the government is represented as a single player. Thus, it is worth noting that selecting a specific insurance plan will affect the resident family player through determining the amount of money spent on the premiums and the compensation obtained from insures in case of an occurrence of a natural disaster. This will also affect the insurer in term of earned revenue (i.e. the amount of premiums collected) and the amount of compensation paid out in case of a natural disaster event occurrence. Moreover, after calculating the post disaster damages for the residential sector, and taking into account the compensation by the insurer, the government compensation can be likewise calculated.

5.1 Resident Families

Each property owner player has a set of actions to choose from, \( A = \{a_{(n,i)}\} \), where \( A \) is the set of possible actions, and \( a \) is the chosen insurance coverage plan \( n \) offered by the associated company \( i \). In selecting a plan at each iterative step \( t \), each resident considers their current wealth, the indemnity received from the insurance company if a natural hazard causes damages to the residence building, the amount of tax paid and the compensation paid by the government post disaster as shown in Eq. (1).

\[
W_p(t) = W_p(t+1) - P(n,i) - T - D(t) + C(n,i) + G
\]

Where \( W_p(t+1) \) is the amount of wealth of a property owner \( p \) at time \( t+1 \), \( P(n,i) \) is the insurance premium paid by a property owner to insurance company \( i \) using plan \( n \), \( T \) is the taxes paid to the government, \( D \) is the damage cost by natural disaster at time \( t \), \( C(n,i) \) is the compensation paid by the insurance company \( i \) if the property owner is using plan \( n \), and \( G \) is the compensation paid by the government. Also, it is worth noting that utility does not govern actions. Generally speaking, players maximize their utility by choosing their optimal actions subject to their beliefs of the actions taken by their rivals. In evolutionary games, the players observe the payoffs of others and mimic those with superior outcomes.

5.2 Insurance Companies

A successful strategy for post disaster damage mitigation should decide on the type of coverage provided by the insurer and the premium structure (Jaffee et al. 2008). However, there are two main concepts that may negatively affect the optimum strategy profile. First, adverse selection as the pool will contain mostly high risk resident families and so the insurance company will keep the premium at a fair rate (Janssen and Karamychev 2005). It is noted though that insurers can change rates to overcome the problem of adverse selection. Second, moral hazard as losses will always be not in the favor of the insured pool and thus the insurance will not change the situation or mitigate the damage for the insured party (Lee and Ligon 2001; Breuer 2005; Doherty and Smetters 2005). This emphasizes the need of an optimum post-disaster insurance plan strategy profile where a selective value of premiums and coverage values should be determined as well. These issues can be handled by allowing the insurer to be myopic in their product offerings and learn from their rivals given the distribution of population types per contract. A decision for
each company is to determine the distribution and pricing of plans to offer the population of resident families. Accordingly, the insurer utility function is shown in Eq. (2).

\[ W_i(t+1) = W_i(t) + \sum R \]

Where, \( W_i(t+1) \) is the insurance company \( i \) wealth at time \( t + 1 \). \( R \) is the aggregate monetary utility gained by an insurance company by calculating the difference between the sum of the premiums paid by the residents and the sum of the indemnities paid to the residents when a natural hazard event occurs. Thus, \( R \) is equal to the \( P(n,i) - C(n,i) \) for every resident that purchased the insurance plan \( n \) from company \( i \).

5.3 Government

State protectionism is essential for a post natural disaster relief. This can be achieved by subsidizing the insurance costs on families or financially aiding families in reconstructing their damaged homes and reconstructing the state damaged infrastructure during the disaster event. The government action will determine the financial compensation for damaged houses post a natural disaster event. The government utility function is simplified to the difference between its current wealth, obtained through tax payments, and compensation paid to the families as showed in Eq. (3).

\[ W_G(t+1) = W_G(t) + \sum (T_p - G_p) \]

6 EVOLUTIONARY GAME THEORY

Game theory is the study of the ways in which strategic interactions among economic agents produce outcomes with respect to the preferences (or utilities) of those agents, where the outcomes in question might have been intended by none of the agents (Samuelson 1997). Since Von-Neumann and Morgenstern (1944), game theory has been used in many different research areas (i.e. economics, biology, engineering, political science, computer science, and philosophy) because of its advantage of a natural and plausible representation of strategic interaction between individuals, organizations, and countries (Son and Rojas 2011). In evolutionary games, a large population of individuals, each having their own actions and strategies, meet in an environment to determine their optimum strategy profiles depending on their payoffs (Samuelson 1997). In other words, evolutionary game theory allows imperfect players to learn from observations. The dynamics are based on the assumption that each strategy is played by a certain fraction of individuals at each moment of the game (Turocy et al. 2001). Inspired by Darwin theory of survival of the fittest, stakeholders having better than average payoff will be more successful and more likely to survive in the next round. Those players who chose strategies that result in less than average payoffs update their strategic choices to mimic (replicate) those making above average payoffs (Samuelson 1997). The replicator dynamics govern the law of motion for the game, and are unique to each stakeholder group. Thus, one would not expect a resident final payoff to equal that of the insurance company or government. A basic requirement in evolutionary games is that a set of strategies is evolutionary stable if for any mutant strategy (perturbation) in the game; the non-mutates must result in a higher payoff than the mutant strategy (Weibull 1995; Smith and Price 1973). Evolutionary game theory has been applied in Economics (Cressman 1995, Friedman 1998), and explored by mathematicians (Hofbauer and Sigmund 2003). However, as far as the authors’ knowledge, there is no implementation for the Evolutionary game theory in the construction management research.

7 PROPOSED MODEL: SOLUTION PROCESSES

The solution processes for the proposed model consider: (1) the post-disaster insurance plans selected by each resident family from the different insurance companies, (2) the premium value charged as per the distribution of contract types offered by each insurer for each plan, and finally (3) the government post-disaster damage compensation ratio. At this stage, as an initial step, the data associated with the three main stakeholders is entered into the model. For resident families, the model requires the population size, the ratio between different income families (i.e. poor, medium, and high), income and current wealth, and a random initial set of selected plans and insurance companies. For the insurance companies data about
the number of associated insurers, different plans offered, premiums, compensation ratios, and wealth of the insurance companies including relationship with reinsurance companies. For the government, the tax rate should also be set as well as an initial percentage of the collected tax amount to be dedicated to post natural disaster mitigation plan. Last, the nature, as a Pseudo player, should also be set in this step including determination of type of hazard accompanied with its characteristic parameter such as severity, frequency, and return period. This information will help the model to create an initial random population of players that have their own actions, and measuring their utility function after the disastrous event, and choose the fittest parents of the population for future evolution.

7.1 Updating Utility Functions for Associated Players

This step depends firstly on the occurrence of disaster or not, and the damage rate for each family residence. Determining that, the model can estimate the loss and calculate the associated compensation ratio by the insurers and the government. The total change of any player's utility will be equal to the difference of the utility function prior and after the disaster occurrence as shown in Eq. (4-6):

[4] For resident families: \[ \Delta W_p = W_p(t+1) - W_p(t) \]
[5] For the insurance companies: \[ \Delta W_i = W_i(t+1) - W_i(t) \]
[6] For the local government: \[ \Delta W_G = W_G(t+1) - W_G(t) \]

Through Eq. (4-6), the relative fitness of each player for every stakeholder can be calculated as shown in Eq. (7) & (8): This is carried out by dividing the player’s (resident family or insurer) change in the utility function’s value by the total change in the utility values for all the players of the same type. Thus, the players with higher positive changes in the utility values will have higher relative fitness values, so as other (lower relative fitness value) players will chose to mimic them – via replicator dynamics – by duplicating their actions and decisions in the next time steps. It is worth noting that there is no relative fitness for the local government as there is only one government player in the game.

[7] For resident families: \[ \text{Relative Fitness}_p = \frac{\Delta W_p}{\sum (\Delta W_p)} \]
[8] For the insurance companies: \[ \text{Relative Fitness}_i = \frac{\Delta W_i}{\sum (\Delta W_i)} \]

8 MODEL IMPLEMENTATION

The authors created a hypothetical sample including: (1) 1,000 resident families taking into account the different level of income; (2) three insurance companies with three different insurance plans available per company, each with different premium percentage to the family house value and different compensation ratio; and (3) two different type of government compensation plans for post disaster damage mitigation. Realizing how complex the evolutionary game theory model between the three associated stakeholders can be, and in order to focus more on the foundational and fundamental steps associated with the model development, the authors treated the resident families as the principal controller of the game’s environment and that insurance companies and the government are supportive players for analysis. The model was implemented on NetBeans IDE 7.4 platform using JAVA programming language.

To this effect, the resident family population is randomly created with 20% under poverty level, 60% of average income and 20% of high income level. The initial insurance plan and insurance company are created randomly for each family, where the three generated insurance companies’ premiums percentages as well as the coverage compensation ratios are given in Table 1. In addition, the government offers plan (A) of compensation percentages of 10%, 15% and 20% or plan (B) of a compensation percentage 15%, 20% and 25% of the damages to the property for the high, medium and poor level income families, respectively. Also, for the sake of simplicity for this model, the probability of windstorm occurrence per time period in the implementation process is set to 95% with damages
accounting for a minimum 10% of the house value up to totally damaged (100%). In addition, convergence was checked every 10 years as to find a similarly steady state when the number of families changing their plans does not exceed 15% of the total family number. The presence of a complete steady state is not practical as nature’s changing weather continuous to plagues the model’s attempts to converge into one.

<table>
<thead>
<tr>
<th>Plan A</th>
<th>Plan B</th>
<th>Plan C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premium%</td>
<td>Coverage%</td>
<td>Premium%</td>
</tr>
<tr>
<td>Insurer # 1</td>
<td>1.8</td>
<td>70</td>
</tr>
<tr>
<td>Insurer # 2</td>
<td>2.2</td>
<td>80</td>
</tr>
<tr>
<td>Insurer # 3</td>
<td>2.8</td>
<td>85</td>
</tr>
</tbody>
</table>

9 RESULTS AND ANALYSIS

The proposed model output for each of the three player types was extracted from the computer model and analyzed to determine the evolutionary stable strategy profile. As an overview, Figure 1 illustrates the evolution process of the families in their choices over the three insurers. To this end, it was clear that families tend to avoid the costly premium of insurer # 3 even though it gives the highest coverage rates to even a full coverage. Figures 2-4 illustrate the changes in selection of the insurers for each family level.

Figure 1 (left): Overall Families Choices of Insurance. Figure 2 (right): Insurers and Poor Income Families

Figure 3 (left): Insurers and Medium Income Families. Figure 4 (right): Insurers and High Level Families

Reviewing the results illustrated in Figures 2-4, it is obvious that both poor and medium income level families tend over time to avoid Insurer # 3 and prefer more Insurer # 1 than # 2, this is due to the high premium costs of insurer # 3’s plans that doesn’t pay off as well as the low ones by insurers #1 and #2. On the other hand, high income level families are found to be indifferent between the three insurers as the premium costs (high or low) cut only a small portion of their income and would all pay off similarly. Figures 5-7 illustrate the resident families’ choices of the different plans by each insurer. Through these
results, it is observed that insurance plans with the most comprehensive coverage received the least demand. Table 2 presents the targeted percentage of each resident type for each insurer company.

![Graphs showing population over time for different plans](image)

**Figure 5 (left): Insurer #1 Plans and Resident Family Choices. Figure 6 (Right): Insurer #2 Plans and Resident Family Choices**

![Graph showing population over time for different plans](image)

**Figure 7: Insurer #3 Plans and Resident Family Choices**

<table>
<thead>
<tr>
<th>Table 2: Families’ Choice Percentage over Insurance Companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family Income Level</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Insurance Companies</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

The aforementioned results illustrated the choices of the three income level family types over the insurance companies’ proposed insurance plans. The results make it advisable for the insurance companies to propose more of the least premium plans to both poor and medium level income families to increase their sales as they are the most demanded ones, as shown in Figure 5-7. As for the government, the choice between plan A and plan B varied through the first two thirds of the time period and settled on plan B as the evolutionary stable strategy profile, which is more or less the same period when the families players are getting deterministic on their plans.

### 10 CONCLUSION AND FUTURE WORK

Natural disaster damages have reached record levels and decision makers nationwide are concerned about the vulnerability of their economy to natural hazards. Their situation is extremely difficult as they are faced with making investment choices in an ever changing stochastic environment with overlapping risk factors. This study utilized evolutionary game theory to identify the optimal balance between: (1) number of plans offered by insurance companies; (2) types of plans that should be selected by each type of resident family based on their income level; and (3) compensation ratio that the government will pay for
each resident family to offset the post-disaster damages. To this end, the authors developed a computer model on NetBeans IDE 7.4 platform using JAVA programming language, and applied it to a hypothetical case study that involves resident families, insurance companies, and the government. Realizing how complex the evolutionary game between the three associated stakeholders can be, and in order to focus more on the foundational and fundamental steps associated with the model development, the authors treated the resident families as the principal controller of the game’s environment and that insurance companies and the government are supportive players for analysis. This proof-of-concept analysis revealed that: (1) resident families tend to prefer insurance plans with the least premium value and coverage; (2) insurance plans with the most comprehensive coverage received the least demand; and (3) the evolutionary stable strategy path oscillates between chosen plans and insurers over time as a result of the stochastic and dynamics nature of the factors associated with disaster management. Based on the results of the hypothetical case study, the authors will develop the model further to take into account simultaneous actions by all stakeholders as well as changes in the social parameters. Furthermore, more investigation will be carried out on the stakeholders' preferences and how they approach risk. Also, an effort will be directed towards integrating input from existing natural hazard prediction software systems (for example, HAZUS-MH) with the new evolutionary game theory model for a more precise simulation of the hazard characteristics. Moreover, based on the positive results associated with the model implementation, the authors are currently working to apply their model to data associated with Hancock County, Mississippi for a way more comprehensive analysis.

References


QUANTIFYING SOCIOECONOMIC DISRUPTIONS CAUSED BY CONSTRUCTION IN DENSELY POPULATED AREAS

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Abstract: Executing construction projects in densely populated areas can have significant impacts on the residents’ quality of life during the construction phase. The social and economic impacts of dense-urban construction are reported for projects undertaken in planned areas as well as unplanned areas (such as slums and squatters). These impacts include residents’ relocation, roads closure, loss of businesses’ income, high noise levels, and temporary disruptions to essential services. On the other hand, socioeconomic disruptions resulting from poorly planned projects in densely populated areas generate resistance among residents to the executed projects, which in turn affects the success of the these projects. The objective of this paper is to present an assessment model capable of estimating and quantifying the level of socioeconomic disruptions expected to be experienced by residents of densely populated areas. This assessment model utilized GIS capabilities and can evaluate candidate construction plans in order to support decision makers in planning for such challenging projects. To this end, this model incorporates four newly developed socioeconomic metrics that are designed to assess (1) the travel delays due to roads closure and detours; (2) number of relocated residents during construction; (3) loss of income due to businesses closure or reduced accessibility; and (4) inconvenience due to high noise levels. In order to demonstrate the model capabilities, its assumptions, and underlying computations, a case study of an upgrading project in a densely populated area in Giza, Egypt is presented.

1 INTRODUCTION

There is a continuous increase in the population density in urban areas, which in turn imposes new construction management requirements for urban construction (Maas and Gassel 2005; Guglielmetti et al. 2008). Nowadays, a significant number of construction projects take place in congested urban sites (Gilchrist et al. 2002), which result in affecting the social and economic welfare of the local residents during the construction phase. For instance, highway construction and repair projects are reported to cause traffic congestions in the surrounding areas leading to travel delays (Tighe et al. 1999; Gilchrist and Allouche 2005). Furthermore, the population density around construction sites introduces a series of socioeconomic challenges that impact the project success, which include the disruptions due to cutting services, road closures, businesses loss of income, and residents’ relocation (El-Anwar and Abdel Aziz 2014). Another challenge associated with construction operations and activities is the increasing levels of the ambient noise that have severe impacts on the nearby residents (Weixiong 2008).

Slums upgrading projects (as a major example for dense urban construction) is investigated in several previous studies (Abiko et al. 2007; The Cities Alliance 2008; and Viratkapan and Perera 2006). These
studies reported a number of social, economic, construction and logistics challenges in and around slums upgrading projects, which makes them quite distinct and complex than development projects in formal-sector urban areas. Abdel Aziz and El-Anwar (2010) and El-Anwar and Abdel Aziz (2011) proposed the use of multi-objective optimization methodologies to achieve three main objectives for slums upgrading projects, including (1) maximizing the project benefits; (2) minimizing the total project costs and durations; and (3) minimizing the social and economic disruptions for resident families. The practical use of these optimization methodologies is dependent on developing social and economic assessment models to alternative construction plans.

Recent research studies focused on the advances of social impact assessment as a means to address these challenges. Burdge and Vanclay (1996), Becker (2001), Burdge (2003), and Becker and Vanclay (2003) discussed the emergence and development of social impact assessment. Other studies aimed at minimizing the social and economic disruptions experienced by resident families and local businesses during construction. In a notable study, Gilchrist and Allouche (2005) proposed a socioeconomic impact costing system based on measuring the disruption caused by construction on (1) traffic; (2) economic activities; (3) pollution; and (3) ecological, social and health conditions. This costing process utilizes mathematical equations to valuate a number of disruption indicators, which include travel delay, loss of income, productivity reduction, health cost, etc. The later research used some valuation methods as measuring loss of productivity, human capital, replacement cost, and user delay cost. However, these valuation methods require significant amounts of data, which might not be readily available in the project planning phase. In a relevant research field, El-Anwar and El-Rayes (2007), El-Anwar et al. (2010) and El-Anwar and Chen (2013) proposed metrics to support minimizing the socioeconomic disruptions for relocated families after natural disasters. These metrics focused on measuring the quality of the new housing locations in terms of employment and educational opportunities, housing quality, displacement distance, accessibility to important facilities and services, and housing delivery time. Similar efforts are needed to quantify the socioeconomic impacts of dense urban construction projects given their unique nature and challenges.

Although most contributions managed to identify the sources and indicators of socioeconomic disruption, there exist limited attempts to assess and quantify socioeconomic disruptions imposed by candidate construction plans. For example, Tsunokawa and Hoban (1997) addressed the difficulty of valuating the losses associated with temporary or permanent loss of houses and businesses. As a result, there exist a need for a practical and comprehensive methodology capable of assessing and quantifying the level of socioeconomic disruption experienced by residents in proximity of dense urban construction projects. This research is a first step to fill this gap using a novel socioeconomic assessment model. The following sections present the proposed model formulation and implementation, and demonstrate the model capabilities using an application example from a current project.

2 MODEL FORMULATION

In this research, the proposed model processes basic data about the urban area and the construction project to evaluate the socioeconomic condition of the area during construction. The model utilizes four main socioeconomic disruption indicators, addressing (1) travel distance delay; (2) resident relocation; (3) business loss; and (4) noise inconvenience. Each indicator is calculated by adding the values of disruption experienced by each resident or business vulnerable to such type of disruption, where the disruption value for each resident or business can range from 0 (indicating no disruption) to 1 (indicating maximum disruption). Furthermore, the effect of the disruption duration is incorporated using an exponential function reflecting the effect of prolonged duration of disruption.

2.1 Travel delay indicator (Dd)

This indicator measures the increase in distance travelled by a dweller from his/her home to a certain service. This increase of distance originates from road closure and detours as a result of construction operations. It is common to estimate the disruption caused by the increased distance using the ratio of the increased distance (∆S) to the original distance travelled (S0) to a certain type of service. However, using this calculation results in an infinite range of results (as the value of increased distance is not...
limited and might exceed the original distance multiple times). Thus, and for the sake of normalizing the ratio to the range from 0 to 1, the formula is modified to calculate the ratio between the increased travel distance ($\Delta S$) to the final travelled distance ($S$) to a certain service. This modified ratio, however, will never reach a value of 1 (where this only occurs when $\Delta S$ approaches infinity, because $\Delta S$ is always smaller than the final distance $S$). As such, the model formulation enables decision makers to define a maximum distance ($S_{\text{max}}$) that if reached the resident is assumed to experience a maximum disruption value of 1. To this end, decision makers define a percentage ($\%s$), which is multiplied by the final distance ($S$) to reduce the upper bound of the travel distance from $S$ to $S_{\text{max}}$, as shown in Figure 1.

Furthermore, the model formulation enables decision makers to define a minimum domain ($\Delta S_{\text{min}}$), below which the increased travel distance has a negligible impact on residents (i.e. the ratio value is set to zero). For example, an increased distance of 100 metres may not produce any disruption. The proposed indicator can be calculated using Equations 1 and 2.

\begin{equation}
[D_{d,i}] = \begin{cases} 
0 & , 0 \leq \Delta S < \Delta S_{\text{min}} \\
\left(\frac{\Delta S - \Delta S_{\text{min}}}{S_{\text{max}} - \Delta S_{\text{min}}}\right)^k & , \Delta S_{\text{min}} \leq \Delta S < S_{\text{max}} \\
1 & , \Delta S \geq S_{\text{max}}
\end{cases}
\end{equation}

\begin{equation}
[S_{\text{max}}] = (\%s) \times S
\end{equation}

\[\text{Figure 1: Impact of the user-defined percentage ($\%s$) to reduce the domain upper bound from } S \text{ to } S_{\text{max}}\]

Where, $D_{d,i}$ is the value of disruption experienced by a dweller ($i$) due to travel delay to a certain type of service, $\Delta S$ is the increased travel distance measured for each resident dweller, $S_{\text{max}}$ is the imposed upper bound to the travel distance, $\%s$ is the percentage of the final distance ($S$) travelled by a dweller after disruption which results in a maximum disruption value of 1, the final distance ($S$) is calculated by adding the increased distance ($\Delta S$) to the original distance travelled before disruption ($S_0$), $S_{\text{min}}$ is the defined increase in travel distance that results in negligible disruption, and $k$ is a constant defining the incremental shape of the disruption function (i.e. $k = 1$ generates a linear function, $k < 1$ generates an exponential function, and $k > 1$ generates a logarithmic function).

Finally, the travel delay indicator ($D_d$) calculates the total value of travel delay disruption for all residents, as shown in Equation 3.

\begin{equation}
[D_d] = \sum_{i=1}^{n} D_{d,i}
\end{equation}
2.2 Resident relocation indicator \((D_r)\)

Various factors might require relocating residents during construction, such as road closure, houses entrance blockage, and houses structural instability. The residents relocation indicator \((D_{r,i})\) computes the number of residents who will be affected by the temporary displacement and its associated socioeconomic disruptions, as shown in Equation 4.

\[
D_r = \sum_{i=1}^{P} d_{r,i}
\]

Where, \(P\) is the original number of dwellers before construction, and \(d_{r,i}\) is a binary variable that equals 1 if resident \((i)\) is temporary relocated and equals 0 otherwise.

2.3 Business loss indicator \((D_l)\)

Local businesses suffer two types of impact. The first type is function in the number of reduced customers \((\Delta C)\), which is incurred due to dwellers relocation away from the business location or as a result of road detours (where some dwellers might choose the second nearest business offering the same service), as shown in Equations 5 and 6.

\[
D_{l,i} = \begin{cases} 
0 & , \ 0 \leq \Delta C < \Delta C_{\text{min}} \\
\left( \frac{\Delta C - \Delta C_{\text{min}}}{C_{\text{max}} - \Delta C_{\text{min}}} \right)^k & , \ \Delta C_{\text{min}} \leq \Delta C < C_{\text{max}} \\
1 & , \ \Delta C \geq C_{\text{max}}
\end{cases}
\]

\[
C_{\text{max}} = (\%c) \times C_0
\]

Where, \(D_{l,i}\) is the value of economic disruption suffered by a certain business \((i)\) as a result of customers reduction, \(\Delta C\) is the number of reduced customers measured for each business, \(C_{\text{max}}\) is the upper bound of reduced customers resulting in a maximum disruption value of 1 and calculated as a percentage \((\%c)\) of the original number of customers \((C_0)\) before disruption, \(\Delta C_{\text{min}}\) is the reduction in the number of customers that results in negligible disruption, and \(k\) is a constant defining the shape of the disruption function.

The second type of loss is function in the number of closed businesses resulting from business inaccessibility due to road closure. In this case, a closed business \((i)\) will have a maximum disruption value \((D_{l,i})\) of 1.

\[
D_l = \sum_{i=1}^{P} d_{l,i}
\]

Where, \(B\) is the original number of businesses before construction.

2.4 Noise inconvenience indicator \((D_n)\)

Although there are many adverse health issues associated with construction activities, noise has always been a major source of complaints among urban construction projects (Hanson et al. 2006). The value of noise disruption is proportional to the number of residents living in the zones within harmful noise levels.

To measure the intensity of noise at a certain distance from the noise source, sound attenuation has to be considered. Sound attenuation depends on a number of factors, including the distance to the noise source, noise directivity, average air temperature, average atmospheric humidity, presence of obstructions and sound reflection (Harris 1966; Piercy et al. 1977).
Neglecting the minor effect of noise directivity, noise obstruction and reflection, which will be difficult to
determine, the level of noise \((N_i)\) affecting a certain dweller \((i)\) as a result of a noise sources \((j)\) can be
calculated using Equation 8 (Lamancusa 2000). In the proposed model, dwellers subjected to the harmful
noise levels will have a noise disruption value \((H_i)\) equals to 1, while other unharmed dwellers take a
disruption value of 0. Accordingly, the noise inconvenience indicator \((D_n)\) is calculated using Equation 9.

\[
N_i = 10 \times \log \left( \frac{L_j \times 10^{-20 \log r_{ij} - 11 - A_{abs}}}{11} \right)
\]

\[
D_n = \sum_{i=1}^{R} H_i
\]

Where, \(L_j\) is the noise level in dB resulting from a source \((j)\), \(NS\) is the total number of active noise
sources, \(r_{ij}\) is the distance from noise source \((j)\) to dweller \((i)\) location in metres, \(A_{abs}\) is the atmospheric
absorption in dB which is function in source frequency and average atmospheric temperature and
humidity (Lamancusa 2000), \(H_i\) is the noise disruption value for each resident dweller \((i)\) and \(R\) is the total
number of residents in the impacted area.

2.5 Total socioeconomic disruption indicator \((D_T)\)

The total value of socioeconomic disruption \((D_T)\) is computed as the weighted average of the
aforementioned normalized indicators multiplied by a factor accounting for the time duration of disruption.
As such, the total value of socioeconomic disruption is given by Equation 10.

\[
D_T = (W_d \times D_d + W_r \times D_r + W_l \times D_l + W_n \times D_n) \times T^z
\]

Where, \(W_d, W_r, W_l\) and \(W_n\) are the relative weights of the four socioeconomic disruption indicators, and
the effect of disruption duration is incorporated using \(T^z\), which is the exponent of the disruption duration,
and \(z\) should be set to a value greater than 1 to indicate the exponential effect of prolonged
socioeconomic disruption.

To enable the practical use of the proposed assessment methodology, an automated model is developed
as described in the following section.

3 MODEL IMPLEMENTATION

The proposed model is implemented in three main steps, as shown in Figure 2.

3.1 Define Project Characteristics

The first step in the automated socioeconomic assessment model is to define the main characteristics of
the project and its surrounding area. GIS is used to plot road networks, residential buildings locations,
services locations and noise sources locations. A map layer is used to draft the area features, where
each road in the network is defined as a vector having a start point and an end point. Buildings are
defined as nodes each having a specific location. Services are also represented as nodes; but in addition
to the location attributes, the type of service is also defined. Finally, noise sources are defined as nodes
each having a location and noise source attributes.

A graphical user interface (GUI) is used to define additional variables, such as the total number of
residents, average daily number of visits for each service type, average atmospheric temperature, and
humidity. Moreover, the user defines construction-related data, including construction phasing, phases’
durations, road closure plan, and noise levels associated with different construction resources and
operations.
3.2 Input Socioeconomic Disruption Sources

The model studies the effect of two main socioeconomic disruption sources; (1) road closure, and (2) construction noise. Road closure has a direct effect on travel distances to services, the number of relocated residents, and businesses closure. Road closure has also an indirect effect on business loss through reduction in the number of customers due to their relocation away from the business location. Construction noise directly results in increasing the number of people exposed to harmful noise levels.

3.3 Measure Socioeconomic Disruption Value

Hoogendoorn (2003) shows that pedestrian’s route choice has an infinite number of paths options, but a certain pedestrian will mainly choose a path with minimum travel time or minimum travel distance to his target location. To this end, the model manipulates the GIS data, where the road vectors are first converted into road segments linked together using intersection nodes, as shown in Figure 3. Dijkstra’s Algorithm is used to calculate the shortest path travelled by a dweller to the nearest instance of each service type.

An initial (pre-construction) state is first generated to be compared to the different states corresponding to the candidate construction plans. In the initial state, each dweller node is associated with the ID of the nearest instance of each service type along with the travel distance. A backward calculation is then implemented using this data so that each service instance is associated with the initial number of customers (dwellers) visiting that service.
3.3.1 Measuring travel delay

To compute travel delay, the initial state is compared with the road closure scenario results. The significance of a certain travel pattern is inferred from the amount of its repetition due to the need to frequently visit a target service. The need to frequently visit services can be defined by the average number of monthly visits input for each type of service. For example, some services have higher rate of visits, such as groceries and bus stops, while others have limited number of visits.

3.3.2 Computing the number of relocated residents

A resident is assumed relocated if the road segment within which the resident’s home is located is completely closed for construction reasons. The GIS model is used to identify the buildings whose roads are closed, and accordingly the number of relocated residents is calculated. Currently, the model assumes an average number of residents in each building, which can be modified in future developments to allow for specific buildings occupancy data.

3.3.3 Measuring businesses loss

The GUI allows the user to define each service type in the area either as a business or a public service. The expected number of customers measured after a road closure scenario is compared to the initial business state. For each construction plan, the number of closed businesses is first computed by identifying road closures. Secondly, the change in the number of customers is computed for the remaining businesses taking into account route changes and detours because of the construction operations.

3.3.4 Measuring noise inconvenience

Noise received at each dweller’s location as a result of construction operations is calculated using the distances between the dweller’s location and noise sources. This data is obtained from the GIS model. The noise inconvenience indicator is then measured by counting the number of dwellers subjected to harmful noise levels.

4 APPLICATION EXAMPLE

The proposed socioeconomic assessment model is applied to a dense urban construction project in Giza, Egypt. A main sewage pipe was broken at a depth of about 7.5 metres under Imam El-Ghazaly Street in the District of Imbaba, where the leakage of soil into the pipe led to critical settlements in the surrounding buildings. Auger piles were used as side supports for the required excavation depth in the narrow streets. Imbaba is a highly populated area in Greater Cairo. Moreover, Imam El-Ghazaly Street is considered a main street in the area with high concentration of residents and services.

The area under consideration is about 33,000 m² with a simple road network of narrow streets and high buildings density. There are about 188 buildings distributed over the residential zone. The construction operations required the closure of some road segments, as shown in Figure 4. The services in the area are mostly of a basic nature, including two bus stops, eight groceries, two pharmacies, three retail shops, two bakeries, four household appliances shops, four restaurants, and four workshops. All the previously mentioned services are considered for business disruption calculation except for the bus stops; thus the total number of disrupted businesses in the area is 27. The average temperature in the area is 30°C and average humidity is 75%, and the harmful noise level is set to 85 dB. Two main sources of noise are present; the first is a fixed generator producing 80 dB at 1100 Hz, while the second is a moving bored pile rig producing a noise of 75 dB at 950 Hz. The contractor has only one piling rig which makes the piling activity critical.

There are three studied construction scenarios. In the first scenario, construction will be executed in two phases, as shown in Figure 4. The two phases will be executed in series, where the road segment of phase 2 will be closed only after opening the road segments closed during phase 1. Noise resulting from
the pile rig is assumed to occur at the midpoint of the closed road segment. The duration of executing each phase is about 6 months, where the site preparation and mobilization takes place in the first month of each construction phase. Accordingly, the total project duration is 12 months. The second scenario assumes that construction of the second phase will start one month before the end of phase one so that the mobilization and preparation period will overlap with the execution period of phase one. This will lead to a total project duration of 11 months. The third scenario assumes that construction will be executed in one phase by closing all the road segments for about 11 months. In this case, mobilization and site preparation will only occur once at the start of the project.

The variables of the travel distance delay function are assumed to have a minimum domain ($\Delta S_{\min}$) of 200 metres, a maximum domain of 95% of the final traveled distance (i.e. $S_{\max} = 95\% \times S$) and a logarithmic curvature (k) value of 2. The function of business loss is assumed to have a minimum domain of 0 customers, a maximum domain of 80% of the initial number of business customers (i.e. $C_{\max} = 80\% \times C$) and an exponential curvature (k) value of 0.8. The duration is very critical, so it is assumed to have an exponential value of (k) equals to 2. Moreover, the relative weights of the indicators are assumed to be 0.3 for dwellers relocation, 0.4 for business loss, 0.1 for travel distance delay and 0.2 for noise inconvenience indicators. The model enables the users to set the values of all these variables before running the socioeconomic analysis.

The model results show that the socioeconomic disruption indicators of the first and the second scenarios have near results which are much lower than those of the third scenario, as shown in Figure 5. The best scenario in this case is the second scenario which has the lowest total socioeconomic disruption indicator. The results also show that the highest impacts of this project are on noise inconvenience.

Figure 4: GIS Model of the project area showing the location of different types of services on the road network and the project phases
5 CONCLUSION

This paper presents a socioeconomic assessment model capable of quantifying the socioeconomic disruption experienced by residents in proximity to construction projects in dense urban settings. The model incorporates four important socioeconomic indicators; namely (1) Travel Distance Delay, (2) Residents Relocation, (3) Business Loss, and (4) Noise Inconvenience. The model enables decision makers to assign a relative weight to each of these four indicators and accounts for the impact of prolonged socioeconomic disruption when computing the total impact of any construction scenario.

![Bar chart showing SEDI values for different scenarios]

Figure 5: Model results

In order to ensure the practicality of the proposed model and its ease of use, the model computations are automated using a GIS-based system integrated with a VBA user interface. The automated system allows decision makers to break down the construction project into phases and define different scenarios for possible construction plans. The model then assesses the socioeconomic impact of each plan in order to support reaching an informed decision that accounts for the welfare of nearby residents. The main challenge to using the developed system is the need for users to set the values of different variables (such as the minimum travel distance $S_{min}$ that results in social disruption, etc.). Future research will address this limitation using sensitivity analysis to identify the significance of these variables.

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CONSTRUCTION PRODUCTIVITY MODEL USING FUZZY APPROACH

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Abstract: Productivity is one of the most important elements to manage construction projects especially with regards to the prediction of the activities’ durations. Uncertainty is an entrenched characteristic of most construction projects. Most research works in simulating construction productivity have focused predominantly on modeling and have neglected to study the effect of subjective variables on productivity of construction process. The unique nature of construction projects and uncertainty of the construction processes lead to a need of new generation of models that utilizes the historical data. The presented research develops, using Fuzzy approach, a model to utilize, analyze, extract and find the hidden patterns of the project data sets to predict the construction process productivity. The engine depends on finding the relation between quantitative and qualitative variables, which affect the construction processes, and productivity. The methodology of this research consists of six steps: (1) Investigate the factors affecting the productivity (2) select the critical factors that affect the productivity; (3) build Fuzzy sets; (4) generate Fuzzy rules and models; (5) build Fuzzy knowledge base; and (6) validate the effectiveness of the built model to predict the construction process productivity. The developed model is validated and verified using case study with sound and satisfactory results, 90.65 % average validity percent. The developed research/engine benefits both researchers and practitioners because it provides robust model for construction processes and a tool to predict the productivity of construction processes.

1 INTRODUCTION

Productivity is one of the most important elements to manage construction projects especially with regards to the prediction of the activities’ durations. Productivity is defined as “the ratio of output of required quality to the inputs” for a specific construction process (Al-Zwainy, et. al. 2013). Several studies applied many statistical methods in the construction management; regression, probability functions, stochastic techniques, and mathematical learning curves for simulation and/or optimization (Bee Hua, 2008).

Raw (i.e. dirty) data can cause confusion for the mining and modeling procedure that leads to unreliable output (Han and Kamber 2006). If users believe the data are dirty, they are unlikely to trust the results of any data mining that has been applied to it. Most research works in simulating construction processes have focused predominantly on modeling and neglected to prepare the data before mining process. Before dealing with the system building, the data problem should be identified. There are major two problems of data, which are missing data and outliers. The simple way that most research works deal with
is to remove incomplete data set and outliers. Knowledge Discovery in Database (KDD) is the nontrivial process of identifying valid, novel, potentially useful, and ultimately understandable patterns in data (Fayyad et. al 1996). Data mining is used to extract hidden knowledge from a data set that is not obtained by traditional methods as statistical analysis. The KDD is an interdisciplinary field involving concepts from machine learning, database query, statistics, mathematics and visualization (Anand et al. 1998). Most modern KDD tools have focused almost exclusively on building models (Cox and Wills 1997). A 60% of time goes into preparing data for mining; however, actual mining step typically constitutes about 10% of the overall effort (Cabena et al. 1998). Knowledge discovery in databases (KDD) and data mining consist of a series of steps including domain and data understanding, data preparation, data mining, and finally, pattern evaluation and deployment (Chapman et al. 1999). The KDD has been applied in the area of construction and facility management in recent research in response to the explosive growth of computerized historical databases (Buchheit et al. 2000; Soibelman and Kim, 2002). Chau et al. (2002) developed an application of data warehouse and decision support system to provide the information about and insight of existing data.

The previous studies show a lack of using the historical data and experts to build models/knowledge bases that help to predict the construction productivity.

2 RESEARCH OBJECTIVES

The overall objective of this research is to build a construction productivity model. To achieve this objective, the following sub-objectives are as follow:

1. Develop a data mining engine to utilize, analyze, extract, and model the hidden patterns from the project data.
2. Integrate the enormous amount of historical data and knowledge base design in order to predict construction productivity.
3. Verify and validate the proposed framework using a case study.

3 BACKGROUND

Construction management research used the fuzzy set theory, fuzzy logic, and hybrid fuzzy techniques (Chan, Chan, & Yeung, 2009). Therefore, many studies went through to combine the fuzzy set theory/ fuzzy logic with artificial intelligence systems as well as Gas, Ann, and PSO in order to create a hybrid model to implement model parameter optimization (Bee Hua, 2008). Several studies investigated the factors that affect the construction labors productivity variations; the National Electrical Contractors Association (NECA) studied the effects of humidity and temperature on labor productivity (Sonmez & Rowings, 1998). Another study developed a model using a methodology based on the regression and neural network modeling techniques to evaluate many factors on productivity for concrete pouring, formwork, and concrete finishing tasks from task to task (Sonmez & Rowings, 1998).

The theory behind learning curve models revealed that as the production quantity of any product doubles, the unit or average cost (hours, man-hours, dollars, etc.) will decreases by a fixed percentage of the previous unit or average rate (Thomas, et. al., 1986). A number of mathematical models were used to describe and predict the learning curve, including the straight line power model, cubic power model exponential model, and piecewise model (Thomas, Mathews, and Ward, 1986). Straight line power model is the most commonly used model in construction productivity, moreover, it provides the most reliable prediction of future performance (Everett and Farghal, 1994). Hildreth (2012) presented a case study of his construction students where they participated in virtual construction operation. The experiment resulted in excellent knowledge regarding learning curve theory and its application within construction industry.

Malyusz and Pem (2014) used mathematical algorithms to evaluate the predictive capabilities of various learning curve models and data presentation methods for labor intensive construction operations. The algorithms gave sequential predictions for future performance of construction activities.
Situation-based simulation models is a recently developed technique that is used to model the triggering situations in construction to predict productivity. Choy and Ruwanpura (2006) developed an application model that uses “root causes of productivity loss” as the situations. This model allows users to develop models based on the interactions of various situations and work types. A study by (Al-Zwainy et al., 2013) developed a model using Multivariable Linear Regression technique (MLR) to estimate construction productivity for marble finishing works of floors.

4 RESEARCH METHODOLOGY

This research consists of five phases that provides detailed explanation of the research methodology. A comprehensive literature review phase has been conducted that includes the state of the art review of construction productivity, data mining and knowledge discovery, as well as fuzzy knowledge base building and Design. The second section pertains to system development and implementation procedures that includes the following three stages: Variable Selection, Fuzzy Sets, Fuzzy Rule Induction, and Fuzzy Knowledge Base. The third phase focuses on data collection, which includes a case study to verify and validate the developed system. The fourth phase denotes verification and validation of the developed system using a case study. The final phase of this research propounds conclusions and recommendations for future work. What follows is a detailed explanation of the aforementioned five-study section and their sub sections.

5 PRODUCTIVITY DATA MINING ENGINE DEVELOPMENT

The productivity Data mining engine make the variable selection to build the knowledge base through Fazzification and fuzzy induction rules. The productivity data mining engine consists of five steps as follows:

5.1 Variables selection

In this step, the variables that affect the task productivity rate are selected using Fuzzy average method. The fuzzy curve will be built using Equation 1 and the variables will be ranked using equation 2.

I. Build the Fuzzy curve

For every input and output points \((X_i, Y_j)\) the equation 1 will be applied (Lin and Cunningham III 1995). If there is a completely random relationship between the input(s) and output(s), then, the fuzzy curve is flat and vice versa.

\[
C_i(x_i) = \frac{\sum_{j=1}^{n} y_j \mu_{ij}(x_i)}{\sum_{j=1}^{n} \mu_{ij}(x_i)}
\]  

(1)

Where:

- \(C_i(x_i)\): Curve points

II. Ranking the variables

Mean Square Error (MSE) will be used to rank the variables using Equation 2. The MSE value shows the significant; if the value is small that mean a high significance and vice versa.

\[
MSE_i = \frac{1}{M} \sum_{k=1}^{M} (c_i(x_i,k) - y_k)^2
\]  

(2)
5.2 Fuzzy sets (Fuzzification)

Crisp quantities are converted into fuzzy sets in this step using the Artificial Neural Network (ANN) technique. The ANN will be built from modeling data sets of the selected variables. The training will simulate the relationship between the coordinate locations and membership values. After the net is trained, its validity and efficiency can be checked using the testing data. Then it is ready and can be used to determine the membership value of input data set in the different regions.

5.3 Fuzzy rules induction

Rule induction creates a knowledge base of fuzzy if-then rules by modeling the embedded patterns in the data. This is a supervised knowledge discovery that use Fuzzy rule induction algorithm. The functional relationships between the independent and dependent variables are expressed as a set of fuzzy if-then rules. The inputs of this step are Fuzzy sets that will be isolated to data point mapping with the highest membership degree that could happen if there are two data sets in the same Fuzzy set, the higher degree would be selected. The final rules are selected from a pool of data pairs. The degree of effectiveness (E) for each rule will be computed. It selects the most effective rules amongst the candidate rules using Equation 3 (Cox, 2005).

\[ E(r_i) = \mu_x(v_1) \times \mu_y(v_2) \times \mu_z(v_3) \]  

(3)

5.4 Fuzzy knowledge base (FKB)

The collection of all the previous steps are forming Fuzzy knowledge base, which includes variables, fuzzy sets, and fuzzy rules. This collection of FKBs may form a solution to a complex system. FKBs are containers where they store the data definitions (variables) and the required rules to solve a set of outcomes associated with the system.

5.5 Validation

Prediction effectiveness of the developed engine will tested in this step using a mathematical validation. The average invalidity percent (AIP) and the Average validity Percent (AVP) will be calculated using Equation 4 and 5 respectively. If the AIP value is closer to 0.0, the model is sound and a value closer to 100 shows that the model is not appropriate to predict the productivity (Zayed and Halpin, 2005). Similarly, the Root Mean Square Error (RMSE) is estimated using Equation 6. If the value of the RMSE is close to 0, the model is sound and vice versa. In addition, the Mean Absolute Error (MAE) is defined as shown in Equation 7. The MAE value varies from 0 to infinity. However, the MAE should be close to zero for sound results (Dikmen et al. 2005).

\[ AIP = \left( \frac{1}{n} \sum_{i=1}^{n} \left| 1 - \left( \frac{E_i}{C_i} \right) \right| \right) \times 100/n \]  

(4)

\[ AVP = 100 - AIP \]  

(5)

\[ RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (C_i - E_i)^2} \]  

(6)
6 ANALYSIS OF DATA MINING ENGINE IMPLEMENTATION TO A CASE STUDY

In this study, data were collected through both on-site observation and digital camera monitoring system for Engineering, Computer Science and Visual Arts complex of Concordia University (Khan, 2005). The implementation to a case study will concern the productivity of concrete pouring operation. The factors that affect the productivity are shown in Table 1. A sample of case study data is shown in Table 2.

Variables selection

In this step, the variables that affect output variable (work task productivity) are selected. Two methods are used to select the variables that affect the productivity. The first is sorting factors according to Mean Square Error (MSE) as shown in Table 3. The second method is using Fuzzy curve. As shown in Figure 1 and Figure 2. The MSE method will be used to validate the Fuzzy curve method and how it selects and ranks critical variables. The ANN method is used to compare the ranking and selection efficiency using the selected variables as shown in the following sections.

Table 1: Concrete Pouring Process Variables

<table>
<thead>
<tr>
<th>No.</th>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature °C</td>
<td>Average of eight working hours of the day</td>
</tr>
<tr>
<td>2</td>
<td>Humidity (%)</td>
<td>Average of eight working hours of the day</td>
</tr>
<tr>
<td>3</td>
<td>Precipitation</td>
<td>Incorporated in terms of four numerical values as follows:</td>
</tr>
<tr>
<td>4</td>
<td>Wind Speed (km/h)</td>
<td>Average of eight working hours of the day</td>
</tr>
<tr>
<td>5</td>
<td>Floor Height</td>
<td>The floor number</td>
</tr>
<tr>
<td>6</td>
<td>Work Type</td>
<td>Two types of activities will be considered as follows: Slabs = 1 and walls = 2</td>
</tr>
<tr>
<td>7</td>
<td>Gang Size (workers)</td>
<td>Number of persons in the gang</td>
</tr>
<tr>
<td>8</td>
<td>Labor Percent (%)</td>
<td>The percentage of the labor (non-skilled workers) in the gang</td>
</tr>
<tr>
<td>9</td>
<td>Time (min)</td>
<td>Work Task Duration</td>
</tr>
</tbody>
</table>
Table 2: A Sample of Concrete Pouring Process Variables Data

<table>
<thead>
<tr>
<th>Temperature (ºC)</th>
<th>Humidity</th>
<th>Precipitation</th>
<th>Wind speed (K/h)</th>
<th>Gang size (workers)</th>
<th>Labor %</th>
<th>Floor level</th>
<th>Method</th>
<th>P (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4</td>
<td>35</td>
<td>0</td>
<td>13.5</td>
<td>12</td>
<td>57</td>
<td>4</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>-13.5</td>
<td>70</td>
<td>1</td>
<td>8</td>
<td>7</td>
<td>55</td>
<td>2</td>
<td>2</td>
<td>8.5</td>
</tr>
<tr>
<td>8</td>
<td>83</td>
<td>1</td>
<td>6</td>
<td>10</td>
<td>56</td>
<td>8</td>
<td>1</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Variables selection using the ANN method

The ANN method is used to validate the Fuzzy Average method of selecting and ranking critical variables. Ranking of input variables is required in order to determine the relative importance of each variable and those that have the most effect on the task duration. The contribution percentages are derived from analysis of weights of the trained neural network. The higher the number, the more that variable is contributing to the classification and/or prediction. Obviously, if a certain variable is highly correlated, the variable will have a high contribution percentage. Table 4 shows the contribution percentage (relative significance) of eight variables. By comparing the results of Fuzzy Average Method and ANN methods, it is clear that four out of eight variables are similar in the top of each ranking and the other variables have different ranking.

Table 3. Variables Ranking According to Mean Square Error (MSE)

<table>
<thead>
<tr>
<th>Variables</th>
<th>MSE</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(ºC)</td>
<td>6.4</td>
<td>2</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>8.5</td>
<td>4</td>
</tr>
<tr>
<td>Precipitation</td>
<td>8.9</td>
<td>5</td>
</tr>
<tr>
<td>Wind speed (K/h)</td>
<td>10.72</td>
<td>7</td>
</tr>
<tr>
<td>Floor level</td>
<td>10.5</td>
<td>6</td>
</tr>
<tr>
<td>Method</td>
<td>13.5</td>
<td>8</td>
</tr>
<tr>
<td>Gang Size(workers)</td>
<td>3.25</td>
<td>1</td>
</tr>
<tr>
<td>Labor Percent (%)</td>
<td>6.5</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 4. Variables Ranking Using ANN

<table>
<thead>
<tr>
<th>Rank</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Temperature</td>
</tr>
<tr>
<td>4</td>
<td>Humidity</td>
</tr>
<tr>
<td>8</td>
<td>Precipitation</td>
</tr>
<tr>
<td>5</td>
<td>Wind speed</td>
</tr>
<tr>
<td>7</td>
<td>Floor level</td>
</tr>
<tr>
<td>6</td>
<td>Method</td>
</tr>
<tr>
<td>1</td>
<td>Gang Size</td>
</tr>
<tr>
<td>3</td>
<td>Labor Percentage</td>
</tr>
</tbody>
</table>

**Fuzzy sets**

The Fuzzy clustered points are used to train and build the Neural Network. As shown in Table 5, a sample of Fuzzy membership values for data shown in Table 2. The ANN is used to predict and form the Fuzzy sets. The Fuzzification process involves assigning membership values for the given crisp quantities. Membership’s values are assigned using the Neural Network technique in order to model the relation between the fuzzy membership functions and productivity.

Table 5. A Sample of Fuzzy Membership Values

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4686</td>
<td>0.3416</td>
<td>0.1898</td>
</tr>
<tr>
<td>0.4438</td>
<td>0.314</td>
<td>0.2422</td>
</tr>
<tr>
<td>0.4764</td>
<td>0.3072</td>
<td>0.2164</td>
</tr>
</tbody>
</table>
Fuzzy rule induction

Rule induction creates a knowledge base of fuzzy if-then rules by modeling the embedded patterns in the data. This step aims at finding the functional relationships between variables and task duration defined as a set of “if-then” rules. Fuzzy Rule Induction Algorithm is used. A sample of Fuzzy rules is shown in Table 6. As the final rules are selected using only the highest degree of effectiveness (E).

Fuzzy knowledge base

Fuzzy knowledge base includes all the previous steps, i.e. the selected variables, fuzzy sets, and fuzzy rules. The FKB is a representation of a particular model of each process that means the FKB of concrete pouring process is separate from the loading process.

<table>
<thead>
<tr>
<th>Table 6: A Sample of Fuzzy Rules and Fuzzy Knowledge Base Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rule 1</td>
</tr>
<tr>
<td>Rule 2</td>
</tr>
<tr>
<td>Rule 3</td>
</tr>
</tbody>
</table>

Fuzzy knowledge base validation

The goal of this step is to test the engine prediction effectiveness. To test the effectiveness of the engine’s prediction, a validation data set is embedded into the developed engine to compare its results with actual data. As shown in Equation 4 and 5, the average validity percent (AVP) and the average invalidity percent (AIP) are used. The developed Knowledge base is validated by comparing the predicted results with the actual values for productivity using the validation data set. The results show that the average validity percent is 90.65 %, the RMSE is 1.5, and the MAE is 3. Therefore, the developed fuzzy knowledge base is acceptable and robust to predict the productivity of the work task.

7 CONCLUSIONS

The current research presents a construction productivity data mining engine to prepare, utilize, analyze and extract the hidden patterns from the project data to predict the work task productivity. The engine depends on preparing the historical data to be modeled and finding the relation between quantitative and qualitative variables, which affect the construction processes, and work task productivity. The developed data mining engine consists of the following steps: (1) select the factors that affect the construction process; (2) generate Fuzzy sets; (3) define Fuzzy rule and models; (4) build Fuzzy knowledge base; and (5) validate the effectiveness of the built knowledge base to predict the work task durations. The presented research shows the significant effect of qualitative and quantitative variables on the task durations. It shows the efficiency of Fuzzy approach to model the hidden patterns of construction project data. The developed engine is validated and verified using case study with sound and satisfactory results, 90.65 % average validity percent. The developed research/engine benefits both researchers and practitioners because it provides robust knowledge base for construction processes and a tool to predict the related task productivity for construction activities.
References


SCHEDULING OPTIMIZATION OF LINEAR PROJECTS CONSIDERING SPATIO-TEMPORAL CONSTRAINTS

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Abstract: Overall schedule optimization, considering all temporal, spatial and precedence constraints is a difficult task due to the complexity which is inherent in construction projects. The difficulties associated with modeling all aspects combined become more considerable when optimizing linear type of projects with high activities’ inter-relations. The progress of these projects highly depends on the productivity achieved from their resources which is directly dependent upon the space and time available to these resources. As a result, in order to practically optimize linear schedules, not only their achieved productivities need to be managed well, but also the spatio-temporal flexibilities and constraints are to be integrated into the optimization process. This paper aims to fill the gap in the current literature by proposing a practical approach for modeling and optimization of linear schedules while taking into account all the project-dependent constraints. For this purpose, the methodology is built on the new concept of Space-Time float for explicit consideration of spatio-temporal constraints of activities. The developed method uses constraint-satisfaction optimization approach to minimize duration of the generated schedules. As such, by having Space-Time floats for different activities’ resources and using such constraints, the schedule is optimized to get the minimum achievable duration for the total project. A numerical example is analyzed to present the proposed and developed method as well as its added benefits.

Key words: Schedule optimization; Spatio-temporal constraints; Constraint programming; Linear projects; Space-time float.

1 INTRODUCTION

Having accurate and up-to-date information of each activity and its respective resources has a large impact on effective project scheduling and control of linear construction projects (Roofigari Esfahan and Razavi, 2013, Roofigari Esfahan and Razavi, 2012, Andersson et al., 2007, Roofigari Esfahan et al., 2014). This is due to the fact that, in this class of projects, construction crews are often required to repeat the same work in various locations and therefore, move from one location to another. As a result, the spatio-temporal constraints of such movements need to be considered when scheduling each and any of the linear activities. As such, the schedule developed for these projects should first be enhanced taking into account all the logical precedence constraints of activities as well as spatio-temporal constraints on movement of resources (Hegazy, 2005, Moselhi and Hassanein, 2003, Polat et al., 2009, Yang and Chi-Yi, 2005, Song et al., 2009).
The current scheduling methods for linear projects do not consider spatio-temporal constraints for movement of activities' resources and the flexibility in their movement to enhance and improve the schedules. This subsequently causes them to overlook other possible whole range of productivity rates that can be achieved without delaying activities.

The limitations stated can be tackled by the new concept of Space-Time float prisms to generate and optimize schedules of linear projects. The scheduling framework presented here integrates location of construction resources through an innovative modification of Linear Scheduling Method LSM by adding the spatio-temporal constraints to the traditional LSM productivity. Using such constraints, the schedule is then optimized to get the minimum achievable duration for the total project.

The optimization phase of the proposed method takes a constraint-satisfaction approach to find the optimum productivity rates for activities that will lead to minimum achievable duration for the project. To achieve this goal, the objective of the optimization process is set as duration minimization, and the decision variables include the start date and productivity rates of linear activities. All the project precedence, and spatio-temporal constraints identified through using Space-Time float prisms are then used to limit the search space into practical solutions. The output of the optimization phase, i.e. the optimum schedule for the project and the optimum productivity rates of activities, are then used to visualize and track the progress of the project schedule.

The remaining of the paper is organized as follows: first, an overview of the current state of scheduling linear projects is presented. Subsequently, the new concept of Space-Time float prisms previously published by the authors (Roofigari Esfahan et al., 2014) is briefly introduced and the modification to traditional linear scheduling method using Space-Time float prisms is then described. In the next step, the optimization framework used to optimize the duration of the generated schedule is presented followed by the details of tracking and control of such schedules. Finally a numerical example is analyzed using the proposed framework to present the method as well as its added benefits.

2 BACKGROUND

Due consideration to space and time constraints and requirements should be given when it comes to scheduling linear construction projects. This is because the dynamic resources on sites of linear projects are more likely to interact with each other in a complex spatial-temporal manner. Current available network techniques and linear scheduling methods mainly consider technological constraints and resource requirements in generating schedules for repetitive and linear works. Such techniques and methods overlook the requirements of activities for the requisite work space for material storage and movement of manpower and equipment. The literature on scheduling and planning linear projects is rich. A number of methods including Linear Scheduling Method (LSM), Repetitive Scheduling Method (RSM), and Line of Balance (LOB) are presented in the literature to plan, schedule and control linear projects; e.g. ((O’Brien, 1975, Stradal and Cacha, 1982, Harmelink, 2001, Harmelink and Rowings, 1998, Harris and Ioannou, 1998, Johnston, 1981, Cosma, 2003). Much research also has been performed to predict the production rate of linear projects based on simulation, probability, or regression analysis (e.g.(Duffy et al., 2011, Watkins et al., 2009, O’Connor and Huh, 2005, Woldeisenbet et al., 2012, Jiang and Wu, 2007, Kuo, 2004).

The methods presented in the literature to optimize schedules of linear projects can be divided into four main categories: 1) the methods whose purpose is to minimize resource fluctuation of these projects (e.g. (Georgy, 2008, Mattila and Abraham, 1998, Tang et al., 2014a, Tang et al., 2014b, Shu-Shun and Chang-Jung, 2007); 2) methods that tend to minimize resource idle times (Vanhoucke, 2006, Gonzalez et al., 2013); 3) Methods that optimize project schedule considering minimization of project cost as objective (e.g. (Handa and Barcia, 1986, Senouci and Eldin, 1996, Hegazy and Wassef, 2001, Moselhi and Hassanein, 2003, Ezeldin and Soliman, 2009, Ipsilandis, 2007, Menesi et al., 2013); and 4) the methods which reduce the duration of the linear projects (Russell and Caselton, 1988, Fan and Lin, 2007, Bakry et al., 2013, Bakry et al., 2014, Cho et al., 2013).
There are also methods that attempted to visualize linear schedules, using 4D CAD (Staub-French et al., 2008) and MS-Excel (Lluch, 2009) as well as methods that consider variable productivity rates for linear activities; e.g., (Lucko, 2008, Lucko et al., 2014, Duffy et al., 2011). Yamin (Yamin, 2001) developed an approach to analyze the cumulative effect of productivity rate variability (CEPRV) on linear activities in highway projects. The focus of that study was to advance the risk analysis capabilities of linear scheduling to allow managers to forecast the probability of project delay. Duffy, et al.’s method (2011) divided linear schedules to areas of time and location for which unique production variables, called working windows can be assigned. Working windows display when and where production variables may change along the linear project’s timeline. Similarly, (Lucko et al., 2014) models linear schedules using singularity functions to model changes in productivity along the execution time of each activity. In a recent attempt, (Shah, 2014) aimed to provide the precise scheduling information of working locations, allocation of resources, and identification of time–space conflict on a weekly, particularly in the earthwork operations of road and railway construction projects.

However, none of these methods optimizes the schedule with due consideration to the whole range of possible production rates that are available to each activity at each point in time and space. The existing methods mainly focus on minimizing day to day resource usage fluctuations, not taking into account the range of achievable productivity rates of resources. As a result, they overlook possible production rates that can lead to minimum duration schedules. Furthermore, none of these methods considers the space available to the activities’ resources throughout their execution. This is a limitation that can be tackled by using Space-Time float, as introduced in the authors’ previous work (Roofgari Esfahan et al., 2014). As a continuation to the previous work, this paper proposes a constraint-satisfaction approach to optimize project duration of linear projects using space-time floats. The details of the method are presented in next section.

3 BACKGROUND

The methodology developed in the present study is based on: 1) the Linear Scheduling Method (LSM) (Harmelink and Rowings, 1998) as a resource-driven technique suitable for repetitive tasks; 2) explicit consideration of spatio-temporal constraints of activities; and 3) constraint-satisfaction integer optimization approach to minimize duration of the generated schedules.

The method integrates all the above mentioned tools in one framework and generates, optimizes, and visualizes linear project schedules. The system presented here has three essential integrated modules, namely: scheduling, optimization and visualization modules. Figure 1 shows the different modules of the proposed method.

![Scheduling and Optimization Framework](image)

Figure 1: Framework of the proposed method
3.1 Scheduling Module: Scheduling Linear Projects using Space-Time Float Prisms

The Linear Scheduling Method (LSM) is used to schedule linear projects in this study. For this purpose, the Space-Time float is considered in this study to take into account the movement constraints of the resources in scheduling linear activities. Space-Time float is an envelope for all possible movement patterns that an activity or its associated resources can take considering the time and space constraints of that activity (Roofigari-Esfahan et al., 2014). Movement of resources can be classified as actual and potential. Actual movement is represented by a space-time path, that is, the set of space-time coordinates where a resource entity is actually taken. Potential movement is represented by a Space-Time float prism, which consists of the set of space-time coordinates representing the activity-related constraints. Each spatially dispersed activity has association with spatial anchors, i.e. pre-determined locations at which an activity must take place. Such activities are not only associated with a duration, but also with locations, showing where they start and/or finish. These activities’ start and end locations are assumed as the anchor points of Space-Time float prisms (see Figure 2).

![Figure 2: Realization of a) 2D and b) 3D Space-Time Float Prism](image)

Traditionally, productivity has been defined as the ratio of input/output, e.g. the ratio of the input of an associated resource (usually, but not necessarily, expressed in person per hours (p-hrs)) to its real output (in creating economic value). To restate this definition for use in the construction industry it can be said that labor productivity is the physical progress achieved per p-hrs (Dozzi & AbouRizk, 1993). Converting this definition to Space-Time float and path, the slope of the space-time paths in each time interval can be used as an indicator of crew productivity within that interval. Vertical paths accordingly demonstrate idle times in an activity when no productive work is actually executed. The optimum path can also be identified. This is the path for which the slopes of the line at each time interval are equal to the planned productivity for that activity at the corresponding time interval (see Figure 2(a))

In order to draw respective Space-Time float prisms for all possible productivity rates for each activity, prism boundaries are also needed in addition to its anchor points. These boundaries in the construction concept can be considered as maximum and minimum allowable productivity rates for resources. As can be seen in Figure 2(b), the minimum productivity rate can be zero, meaning that the activity can be stopped for some time. This, as known, is consistent with the definition of activity floats in construction scheduling. Subsequently, based on the maximum and minimum acceptable productivity rates for activities, the respective Space-Time float prism is constructed. The prism is an envelope which comprises all the possible productivity rates for an activity at each time interval (see Figure 2(b)). Further, scheduling the project through the generation of a Space-Time float for each activity also provides a better understanding and realization of Space-Time flexibilities that are available for each activity.

Identifying spatial conflicts between activities and their respective resources in construction sites provides a potential to minimize delays caused by such conflicts. Because deviation from planned production rates
in linear projects’ activities may result in spatial conflicts between their respective resources, the generation of Space-Time Float prisms is important to help detect such conflicts. Through the use of Space-Time float, the schedule can adapt to variable production rates at each time interval and subsequently the system can potentially identify and forecast potential space-time conflicts (i.e. congestion). It should be noted that identification, quantification, and optimization of space-time conflicts are not within the scope of this paper.

After scheduling the linear activities and visualizing this initial-non optimum schedule using Space-Time Float prisms, the method proceeds to the next module to optimize the generated schedule. The optimization method presented in this paper aims at generating optimized schedules for linear schedules, taking into account all logical and spatio-temporal constraints of linear activities as described in the next section.

3.2 Schedule Optimization Module using Constraint-based integer programming

The optimization phase of the proposed scheduling and control model is a Constraint Satisfaction -based integer optimization model. This module can automatically establish linear schedules with minimum achievable schedule duration. Optimal or near-optimal schedules can be obtained in a relatively short period of time using Constraint Programming (CP) techniques. It should be noted that Constraint Satisfaction Problems are defined by a set of variables, X1;X2; … ;Xn, and a set of constraints, C1;C2; … ;Cm. Each variable Xi has a non-empty domain Di of possible values. Each constraint Ci involves some subset of the variables and specifies the allowable combinations of values for that subset. A state of the problem is defined by an assignment of values to some or all of the variables. An assignment that does not violate any constraints is called a consistent assignment. A complete assignment is one in which every variable is mentioned, and a solution to a CSP is a complete assignment that satisfies all the constraints.

Constraint programming is a programming paradigm being used for solving Constraint Satisfaction Problems (CSPs) through using a combination of mathematics, artificial intelligence, and operations research techniques (Chan and Hu 2002; Liu and Wang 2012; Tang et al. 2014b). It has been successfully used to solve complex combinatorial problems in a wide variety of domains. Its Selection of appropriate variables and values through heuristics reduces the required computational effort and improves the search ability (Liu and Wang 2007; Russell and Norvig 2009).

Apart from being an effective tool in solving a variety of problems, CP has particular advantages in solving scheduling problems (Menesi et al. 2013; Chan and Hu 2002; Heipcke 1999) due to: (1) its efficient solution search mechanism, (2) flexibility to consider a variety of constraint types, and (3) convenience of model formulation. In other words, the highly constrained problems associated with project scheduling can be best modeled and optimized using CP because of its flexibility in description of constraints as well as its capacity to naturally incorporate constraints into the problem description (Chan and Hu 2002) and in processing complex and special constraints (Tang et al., 2014a). When solving an optimization problem in CP, the objective function in the problem is treated as a constraint and this additional constraint forces the new feasible schedule to have a better objective value than the current schedule. The upper or lower bounds of the constraint are replaced as soon as a better objective function value is found. The propagation mechanism narrows the domains of decision variables to reduce the size of the search space while recording the current best schedule. The search terminates when no more feasible schedule is found and the last feasible schedule is the optimal schedule (Pinedo 2008; Liu and Wang 2008).

For the proposed model in this study, the objective and variables were determined in the problem specification stage. In the research reported in this paper, the objective was considered as duration minimization, and the decision variables include the start date and productivity rates of linear activities. To facilitate the use of CP algorithms in scheduling problems, a powerful optimization package, termed ILOG CPLEX Optimization Studio (Beck et al. 2011), was developed incorporating a CP optimizer engine that offers features specially for solving scheduling problems. ILOG CPLEX Optimization Studio was used and the ILOG OPL language was adopted as the model formulation language.
To optimize the schedule with the objective of minimizing duration for the initial schedule, spatial and temporal availabilities to each activity are considered as constraints applied in the optimization process. To do so, all the productivity rates in the feasible productivity interval for each activity (i.e. within prism boundaries) are translated into integer feasible durations for that activity. The search engine then explore these options and finds the productivity rate for each activity that optimizes the overall project duration. The following variables, constraints, and objectives were adopted in the construction of the CSP-based model:

**Constants:**
- SLi  Start location of activity i;
- ELi  End location of activity i;
- \( P_{\text{mini}} \)  Minimum productivity rate of activity i;
- \( P_{\text{maxi}} \)  Maximum productivity rate of activity i;
- \( B_{ij} \)  Required time buffer between activity i and activity j;
- \( D \)  Project deadline

**Decision variables:**
- \( \text{OptPro}_i \)  Optimum resource production rate of activity i;
- \( \text{OptPro}_i \in [P_{\text{mini}}, P_{\text{maxi}}] \)
- \( \text{ST}_i \)  Start time of activity i;
- \( \text{ST}_i \in [0 , D] \)

**Decision expressions:**
- \( \text{ET}_i \)  End time of activity i;
- \( \text{ET}_i = \text{ST}_i + (\text{EL}_i - \text{SL}_i)/ \text{OptPro}_i \)

**Constraints:**

The precedence relationships between activities are considered as the main constraints applied to the optimization model. In this study, all kinds of precedence relations are taken into account, namely: Finish to Start (FT), Start to Finish (SF), Finish to Finish (FF) and Start to Start (SS). The required time buffers between activities are also considered when considering the precedence relationships between succeeding activities.

There are also fixed constraints applied to the model. These fixed constraints are as follows:

- \( \text{ST}_i \geq 0 \)
- \( \text{ET}_i \leq D \)
- \( \text{ET}(\text{fa(last activity)}) \leq D \)
- \( \text{ET}(\text{fa(first activity)}) = 0 \)  (or the start time assigned to the project)

The output of this Module is the best option of each activity i.e. optimum productivity rates for each activity which will minimize the project duration. These rates along with maximum and minimum productivity rates of each activity are then used to visualize the generated optimum schedule.

**4 CASE STUDY**

The method presented here was applied to a case study previously presented in the literature (Mattila and Abraham, 1998, Tang et al., 2014a). The minimum and maximum productivities are calculated from the minimum and maximum resources available in the original example. In the real-world examples also project management teams are requested to enter general information about the project and respective activities. The project network consists of 9 activities. The project included widening of a segment of U.S. Route 41, located in northern Michigan. Major activities consist of removal of existing concrete paving, ditch excavation, embankment, sub-base, gravel, and bituminous paving. This highway construction project was used for verifying the scheduling and optimization capabilities of the proposed model. The
finish date presented in the literature for this example is 38 days. The description of each activity as well as inputs and outputs of the optimization process are included in Table 1.

As it is shown in Table 1, the input data of the optimization process include Activity IDs, their start and end location, successors, and their minimum and maximum achievable productivity rates. It should be noted that these boundaries were calculated using minimum and maximum available resources used. The optimization engine used this information to search for the minimum duration for the project considering all logical and spatio-temporal (productivity) constraints for each activity. As shown in that Table, the project deadline, and project start day are other constraints inputted to the optimization process. If some activities are required to start or finish at a certain day, this information will also be included as constraints. The output of this process includes optimum productivity rate and the duration associated with this productivity rate, as well as start and end times of all the activities, considering precedence relationships. The optimum duration for each activity is also calculated from the optimum productivities attained in the optimization process. It should be noted that in case of non-repetitive activities, the start time is calculated based on the precedence relationships with their predecessors and successors.

Table 1: Input data to the optimization process

<table>
<thead>
<tr>
<th>NbTasks</th>
<th>Deadline</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Task</th>
<th>succsId</th>
<th>SL</th>
<th>EL</th>
<th>Pmin</th>
<th>Pmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ditch excavation</td>
<td>1</td>
<td>2,3</td>
<td>0</td>
<td>50</td>
<td>3.3</td>
<td>10</td>
</tr>
<tr>
<td>Culvert installation</td>
<td>2</td>
<td>0</td>
<td>50</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Concrete pavement removal</td>
<td>3</td>
<td>4,5</td>
<td>0</td>
<td>50</td>
<td>1.67</td>
<td>5.83</td>
</tr>
<tr>
<td>Peat excavation and swamp backfill</td>
<td>4</td>
<td>5</td>
<td>30</td>
<td>50</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Embankment</td>
<td>5</td>
<td>6</td>
<td>0</td>
<td>50</td>
<td>2.5</td>
<td>8.75</td>
</tr>
<tr>
<td>Utility work</td>
<td>6</td>
<td>7</td>
<td>30</td>
<td>50</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Sub-base</td>
<td>7</td>
<td>8</td>
<td>0</td>
<td>50</td>
<td>2.56</td>
<td>6.41</td>
</tr>
<tr>
<td>Gravel</td>
<td>8</td>
<td>9</td>
<td>0</td>
<td>50</td>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>Paving</td>
<td>9</td>
<td>0</td>
<td>50</td>
<td>8.33</td>
<td>20.83</td>
<td></td>
</tr>
</tbody>
</table>

The optimum duration for the project was calculated to be 36 days in the optimization module which is 2 days shorter than the other methods (Mattila and Abraham, 1998, Tang et al., 2014a) (see Table 3). The optimum productivity rates achieved in the optimization process, which creates the duration of 36 days, are listed in Table 2 for all activities. It should be noted that because integer approach has been used, the conversion errors persist to exist, causing some values to be located near the assigned interval. Table 2 also shows the comparison of the activity durations and optimum productivities of the initial schedule with the optimized schedule obtained through the optimization process.

Table 3 shows the durations achieved previously for this example versus the results of this study. By considering the whole range of possible productivity rates of each activity, the current method is able to relax some activities, causing less required resources per day. This consequently reduces the potential congestion in the job site while still not passing the project deadline. It should be noted that in relaxing of activities, daily fluctuation of the resource usage is also taken into account.

Furthermore, generating schedules with due consideration of the Space-Time floats for each activity instead of only the optimum path helps in better management and control of these projects. This simple example demonstrates the ability of the proposed method to derive alternative plans in order to meet project deadlines. The optimized generated schedule demonstrates that by considering flexibility of movement in addition to all activity constraints, the best duration for the project can be achieved that can be shorter than the estimated duration. Summary and concluding remarks
This study proposed a scheduling and control system for linear projects. The proposed method aims to address the limitation of the current scheduling and control methods for linear projects by taking into consideration the spatio-temporal as well as logical constraints of linear activities. For this purpose, the new concept of Space-Time float and constraint satisfaction problem approach were incorporated. As such, by having Space-Time floats for different activities’ resources and using such constraints, the schedule is optimized to get the minimum achievable duration for the total project. Furthermore, knowing the exact or near exact location of required resources for each activity (or set of activities) and visually integrating such information with the project schedule and space-time constraints, leads not only to an optimized and more practical, updated, and executable schedules, but also to more efficient project control. Consequently, management decisions and corrective actions can be made to prevent/treat the identified issues.

Table 2: Output of the optimization

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Duration</th>
<th>OptPro</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12</td>
<td>12</td>
<td>4.17</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>4</td>
<td>2.00</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>21</td>
<td>2.38</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>2</td>
<td>6.00</td>
</tr>
<tr>
<td>7</td>
<td>26</td>
<td>19</td>
<td>2.63</td>
</tr>
<tr>
<td>26</td>
<td>28</td>
<td>2</td>
<td>10.00</td>
</tr>
<tr>
<td>12</td>
<td>32</td>
<td>20</td>
<td>2.50</td>
</tr>
<tr>
<td>24</td>
<td>34</td>
<td>10</td>
<td>5.00</td>
</tr>
<tr>
<td>30</td>
<td>36</td>
<td>6</td>
<td>8.33</td>
</tr>
</tbody>
</table>

Table 3: Comparison of the results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total duration (days)</td>
<td>38</td>
<td>38</td>
<td>38</td>
<td>36</td>
</tr>
</tbody>
</table>

To demonstrate the use of the proposed method and to illustrate its capabilities, a numerical example was analyzed. This example shows the benefits of considering space-time flexibilities and constraints when optimizing schedules of linear projects. As the results of the numerical example illustrates, the optimized schedule saves 2 days in overall duration of the project. Also, despite other methods whose objective is to minimize the daily fluctuation in resource usage linear projects, considering number of resources as variable, here the productivity rate are considered which is a more meaningful factor showing progress of activities over time. Furthermore, the spatio-temporal constraints considered in the optimization process not only facilitate the search for the optimum solution by narrowing down the search space but also leads to having more practical schedules this way, the scheduling optimization method presented in this paper provides an efficient tool for scheduling of linear projects. The method can help the manager teams of liner projects to plan their activities in the most efficient way, while also decrease delays to their minimum, and accordingly prevent cost overruns.

5 SUMMARY AND CONCLUDING REMARKS

This study proposed a scheduling and control system for linear projects. The proposed method aims to address the limitation of the current scheduling and control methods for linear projects by taking into consideration the spatio-temporal as well as logical constraints of linear activities. For this purpose, the new concept of Space-Time float and constraint satisfaction problem approach was used. As such, by
having Space-Time floats for different activities’ resources and using such constraints, the schedule is optimized to get the minimum achievable duration for the total project. Furthermore, knowing the exact or near exact location of required resources for each activity (or set of activities) and visually integrating such information with the project schedule and space-time constraints, leads not only to optimized and more practical, updated, and executable schedules, but also to more efficient project control.

Consequently, management decisions and corrective actions can be made to prevent/treat the identified issues. To demonstrate the use of the proposed method and to illustrate its capabilities, a numerical example has been analyzed. This example shows the benefits of considering space-time flexibilities and constraints when optimizing schedules of linear projects. By bringing all the necessary elements of a successful control system, i.e. timely schedule, tacking all the spatio-temporal and logical constraints of activities in the optimization phase, the method provides an efficient tool in scheduling and control of linear projects. Such a control system can also decrease delays to their minimum, and accordingly prevent cost overruns.

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OPTIMIZING LINEAR SCHEDULES: CONGESTION-MINIMIZATION APPROACH

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Abstract: Space is a strictly limited resource on a construction site. For linear type of construction projects, the importance of effectively managing space is crucial as their schedules is generated with due consideration to both time and space. As a result, spatio-temporal congestions between activities of these projects could substantially hinder the performance of interfering activities and cause deviations from planned schedules. The existence of such congestions decreases work productivity, and causes accidents to occur. The current literature focuses on minimizing the workspace conflicts in order to perform efficient work and increase productivity. However, the other side of this problem, i.e. the changes in productivities which give rise to such spatio-temporal congestions is overlooked. To tackle this limitation, this paper proposes a constraint satisfaction approach to quantify and minimize potential space-time congestions in the schedules of linear projects using space-time floats. The method is able to detect not only potential conflicts between each activity with its immediate successors, but also any possible conflict between resources of any activity with all other project activities throughout the lifecycle of the project. In order to optimize the potentially congested schedules in the planning stage, either the range of productivities available to activities are narrowed down, or the overlapped activities are rescheduled to minimize the conflict. A numerical example is analyzed to demonstrate the added benefits of the proposed method.

1 INTRODUCTION

Workspaces associated with construction activities and materials continuously go through variations in space and time throughout the lifecycle of a project. Selecting construction methods, scheduling activities, and planning the use of site space over time have been known to be the key to constructing a construction project efficiently (Zouein and Tommelein, 2001). Construction planning, scheduling and control need to be studied and employed not only on temporally but also spatially.

Integrating spatial information of project resources and activities into project scheduling and control has long been studied. However, compared to the available methods for sequencing tasks, provided by critical path analysis and its derivatives, still relatively lower attention is paid to the allocation of tasks to spaces (Winch and North, 2006).

The space planning problem in construction has been studied in two different domains: the space scheduling problem, which focuses on planning of task execution spaces (e.g. (Thabet and Beliveau, 1997, Dawood and Mallasi, 2006, Koo et al., 2013, Choi et al., 2014)) and the site layout problem which
focuses on the location of temporary facilities of various kinds (e.g. (Zhou et al., 2009, Andayesh and Sadeghpour, 2014, Pradhananga and Teizer, 2014, Karan and Ardeshir, 2008)).

Acknowledging activity work space requirements and integrating this requirement as a constraint in the scheduling process provides a number of benefits such as: improved safety, decreased conflicts among workers, reduced crew waiting and idling, improved efficiency, increased productivity, better quality, and reduced project delays (Thabet and Beliveau, 1994, Su and Cai, 2013). Among all, the main purpose of such integration of spatial information into schedules is to prevent available and/or potential space-time conflicts and congestions in the construction site. Existence of congestions in construction site not only decreases resource productivity, but also impacts safety, and may lengthen project durations.

Linear projects such as highways, bridges, pipelines and railways not only aren’t exception to this rule, but also need more careful considerations in terms of spaces allocated to the movement of their resources. This is due to the fact that, this class of project is characterized by a series of repetitive activities; where construction crews are often required to repeat the same work in various locations and therefore, move from one location to another. This frequent movement of resources makes it important to continuously integrate the location and movement of resources into the schedules of these projects (Roofigari-Esfahan et al., 2015). As a result, the progress of these projects highly depends on the productivities achieved from their resources. In other words, activity production rates derive the development and accuracy of linear schedules (Duffy et al., 2011). The productivities achieved in these projects are dependent upon the space paved by resources allocated to activities over time. Congestion on construction sites often leads to lowered efficiency and productivity of resources (Watkins et al., 2009). Consequently, a reasonable and resource-leveled schedule that allows for adjustments for unforeseen circumstances and minimizes possible congestions during construction is critical for managing linear construction projects.

The spaces considered by some methods are the spaces associated with construction objects and not the ones required for the movement of resources. Also, the current linear scheduling methods still do not consider the whole range of possible production rates that are available to each activity at each point in time and space. Also, As a result, they disregard all other possible production rates that can be achieved without delaying activities. This is a limitation that can be tackled by using Space-Time float, as explained in authors’ previous work (Roofigari-Esfahan et al., 2015).

As a continuation of the previous work, this paper proposes a constraint satisfaction approach to quantify and minimize potential space-time congestions in the schedules of linear projects using space-time floats. The space-time congestion in this research specifically means the workspace interference when two activities have both spatial and temporal overlaps. The method is able to detect not only conflicts between each activity with its immediate successors, but also any possible conflict between resources of any activity with all other project activities, throughout the life cycle of the project.

2 RELEVANT LITERATURE

Early research studies in construction site planning have recognized the importance of space as a construction resource and have subsequently incorporated it as an integral part of planning constraints (Winch and North, 2006, Hildum and Smith, 2007). Watkins et al. (Watkins et al., 2009) proposed an agent-based modeling method to represent the construction site as a system of complex interactions and explore whether labor efficiency can be treated as an emergent property resulting from individual and crew interactions in space with positive results.

Zouein and Tommelein (Zouein and Tommelein, 2001) noted that construction sequences were often constrained by the sequential occupation of workspaces. The utilization of space associated with these sequences is then analyzed from a comparison of space supply and demand. Winch and North (Winch and North, 2006) further refined this idea by defining and analyzing the criticality of space in a manner analogous to critical-path method. Akinci et al. (Akinci et al., 2002) introduced a taxonomy of space conflicts which correctly defines conflict as a high-level knowledge construct, encompassing various forms
including congestion, unavailability of access, safety hazards, damage of finished products, and design conflict.

Guo (Guo, 2002) analyzed spatial conflict and temporal conflict separately, introducing two independent interference indicators called the interference space percentage and the interference duration percentage. Additionally, the spatial requirements of movement paths (space for moving workers, equipment, and materials on-site) have not been adequately modeled. Other research used graphical methods to explain potential congestions in collided areas and detection of interferences among trades (e.g. (Chua et al., 2010, Koo et al., 2013). Riley and Sanvido (1995) argued that abstracting workspaces in “solid” CAD models was not truly representative of on-site construction. Four-dimensional 4D computer-aided design CAD overcomes this difficulty by incorporating the temporal element in three-dimensional 3D models. Many construction practitioners and researchers have developed four-dimensional (4D) models by linking the three-dimensional (3D) components of buildings with the network activities of a project schedule (Wang et al., 2014, Mallasi, 2006, Moon et al., 2014). However, these methods mainly model the space required for objects in the construction site. They do not consider the space that is occupied throughout execution of the project only as a result of movement of its resources. This way, the space floats that are available to each resource at each point during activity execution is not taken into account while dealing with unforeseen events.

As mentioned in the introduction section, due consideration to space requirements becomes more important when it comes to scheduling linear type of construction projects. This is because the dynamic resources on sites of linear projects are more likely to interact with each other in a complex spatial-temporal manner. Currently available network techniques and linear scheduling methods mainly consider technological constraints and resource requirements in the generation of schedules. Such techniques and methods overlook the requirements of activities for the requisite work space for material storage and movement of manpower and equipment.

There are methods that attempted to visualize linear schedules, using 4D CAD (Staub-French et al., 2008) and MS-Excel (Lluch, 2009) as well as methods that consider variable productivity rates for linear activities; e.g. (Lucko, 2008, Duffy et al., 2011). Yamin (2001) developed an approach to analyze the cumulative effect of productivity rate variability (CEPRV) on linear activities in highway projects. The focus of the research was to advance the risk analysis capabilities of linear scheduling to allow managers to forecast the probability of project delay. Duffy, et al.’s method (2011) divided linear schedules to areas of time and location for which unique production variables, called working windows can be assigned. Working windows display when and where production variables may change along the linear project. Similarly, (Lucko et al., 2014) models linear schedules using singularity functions to model changes in productivity along the execution time of each activity.

However, none of these methods considers the space available to the activities’ resources throughout their execution. As such, the potential space-time conflicts that can happen as a result of variation in planned productivity rates cannot be detected. This is a limitation that can be tackled by using Space-Time float, as introduced in authors’ previous work (Rofigari-Esfahan et al., 2015). As a continuation of the previous work, this paper proposes a constraint satisfaction approach to quantify and minimize potential space-time congestions in the schedules of linear projects using space-time floats. The space-time congestion in this research specifically means the workspace interference when two activities have both spatial and temporal overlaps. The method is able to detect not only conflicts between each activity with its immediate successors, but also any possible conflict between resources of any activity with all other project activities, throughout the life cycle of the project. The details of the method are presented in next section.

3 RESEARCH METHOD

The optimization method presented in this paper aims at generating minimized-congestion schedules for linear schedules. The method utilizes the output of the duration optimization method presented by the authors (Rofigari-Esfahan and razavi 2015) to identify and quantify the potential congestions and and re-
optimizes the schedule by minimizing them. This is done in two different inter-related phases as described in following sections and shown in Figure 1.

3.1 Congestion Detection and Quantification

As stated earlier, the optimized schedule generated from (Roofigari-Esfahan and Razavi 2015) is used as the input to the congestion minimization framework presented here. In this schedule, optimum project duration and optimum productivity rates for each activity are defined. However, there exist potential congestions in the generated schedule that are to be minimized to ensure successful implementation of the planned schedule. The focus of this study is to detect and quantify potential congestions in the generated schedule. These potential congestion areas are those that might be happening as a result of changes in planned productivities. It should be noted that congestion in this paper is defined as areas in space and time where the possibility of interaction between resources of subsequent activities exists. Such congestions will actually happen if the progress rate of activities deviates from what planned for them, which is a common case in execution of linear activities. This way, the congestions can also be predicted even before the execution phase starts. Such changes in productivity will, therefore, be identified before they cause project delays as shown in Figure 2. The locations and times where such congestion would potentially happen are also identified (Figure 2). The figure also shows the comparison of the generic linear schedule generated versus the schedule generated with due consideration to space time constraints of different activities; through use of Space-Time Float Prisms.

![Congestion Minimization Framework](image)

Such potential congestion areas cannot be detected using the traditional linear models which present only optimum productivities. Considering a range of possible productivity rates, i.e. through consideration of space-time prisms/polygons for each activity, helps in identification of Space-Time floats simultaneously. This consequently helps in detection and prevention of potential congestions between succeeding activities. It should be noted that simultaneous consideration of space and time floats makes it possible to trade-off one for the other which consequently allows planning for potential delays before the actual execution commences (Roofigari-Esfahan and Razavi 2015).

This phase is modeled in MATLAB environment. In order to transfer the data generated in the previous study, a spreadsheet interface is used between the two environments. The data transferred include number of project activities, activity id’s and the information required to generate space-time polygons for each activity. This information includes start and end locations and times of the activity, minimum and
maximum achievable resource productivity rates (polygon boundaries) and activity’s optimum productivity rate.

As it can be seen in Figure 2, the intersection between polygons, i.e. potential congestion between activities, are automatically detected. Subsequently, a matrix is generated in which the exact areas of the congestions are calculated. In that matrix, if the element $a_{ij}$ is filled with a number, it means there would exist potential congestion between activities $i$ and $j$. Essentially, the element $a_{ij}$ will be equal to zero if no potential congestion exist between the two activities $i$ and $j$. It is important to note that in the generation of congestion matrix, these congestions are considered for any two activities within project network. This helps detect not only potential congestions between each activity with its immediate successors, but also will detect any potential congestion in the construction job site. The schedule is then revised in the next phase to minimize the detected congestions. Further, as shown in that figure, the time and space that these congestions would potentially happen are also identified.

Figure 2: a) Generated Linear Schedule b) Realization of Potential Space-Time Congestions with Due Consideration to Space-Time Float prisms

3.2 Congestion Minimization

The optimization framework proposed here is a Constraint Satisfaction Problems CSP-based optimization model. Constraint programming (CP) is a programming paradigm being used for solving Constraint Satisfaction Problems (CSPs) through using a combination of mathematics, artificial intelligence, and operations research techniques (Chan and Hu 2002; Liu and Wang 2012 (Tang et al., 2014b). It has been successfully used to solve complex combinatorial problems in a wide variety of domains. To improve the computational efficiency of solving problems, CP provides users with different consistency techniques such as node, arc, and path consistency for variable domain reduction. Constraint programming provides different search strategies such as generate and test (GT), backtracking (BT), and forward checking (Liu and Wang 2008; Marriott and Stucky 1998). Its Selection of appropriate variables and values through heuristics reduces the computational effort required and improves the search ability (Liu and Wang 2007; Russell and Norvig 2009).

Apart from being applicable to solve a variety of problems, it has particular advantages in solving scheduling problems due to: (1) its efficient solution search mechanism, (2) flexibility to consider a variety of constraint types, and (3) convenience of model formulation (Menesi et al., 2013). In other words, the highly constrained problems associated with project scheduling can be best modeled and optimized using CP because of its characteristics (constraints are naturally incorporated into the problem description); (Chan and Hu 2002), as well as its flexibility in description of constraints, and its capability in processing complex and special constraints (Tang et al., 2014a). When solving an optimization problem, the objective function in the problem is treated as a constraint and this additional constraint forces the new feasible schedule to have a better objective value than the current schedule. The upper or lower bounds of the constraint are replaced as soon as a better objective function value is found. The propagation
mechanism narrows the domains of decision variables to reduce the size of the search space while recording the current best schedule. The search terminates when no feasible schedule is found and the last feasible schedule is the optimal schedule (Liu and Wang 2008).

CP is suitable for modeling and solution finding of the project scheduling optimization of linear projects and accordingly applied to schedule optimization phase based on LSM. This is because for LSM-based scheduling problems, prioritization of activities in linear scheduling problems becomes clear owing to the logical and sequential constraints in CP (Liu and Wang 2007). Also, the procedure for the solution of a problem does not require complex mathematical models and formula derivation, eliminating unavoidable simplification and ignorance, truthfully reflecting the original appearance of the problems and ensuring the quality of the solution. To facilitate the use of CP algorithms in scheduling problems, a powerful optimization package, termed ILOG CPLEX Optimization Studio (Beck et al. 2011), was developed incorporating a CP optimizer engine that offers features specially adapted to solving scheduling problems. ILOG CPLEX Optimization Studio was used and the ILOG OPL language was adopted as the model formulation language.

For the proposed model, the objective and variables were determined in the problem specification stage. In the research reported in this paper, the objective was considered as minimizing the total congestion area between prisms of different activities, and the decision variables include the start date, minimum and maximum productivity rates of linear activities. For this purpose, the optimum productivity rates of activities and their respective time interval (including start and times) are used as known information. In this optimization phase, different decision variables are taken into account in the optimization process. These variables include prism boundaries, i.e. min and max productivity rates of activities, as well as start time of activities. In other words, in order to minimize the congestion (intersection) areas between activities, the float prism for the either of the intersecting activities (or both) becomes narrower on the congested side; or the start time of the activities in moved to reduce the intersection area.

Changing the boundaries of the float prism on the congested side only, provides the advantage of not reducing the floats available to activities where it is not necessary (Figure 4). In other words, the floats are only compensated where their existence leads to occurrence of congestion between activities. This way, the generated schedule gives the planners a better sense of spaces and times that are practically available to activities. This capability enables the planners to make more practical decisions in using floats of activities when delays happen during execution of activities.

It should be noted that, the deadline constraint and precedence relationships between activities are considered as strict constraints which cannot be changed. The optimization data are listed in detail below:

**Constants:**

- \( SL_i \): Start location of activity \( i \);
- \( EL_i \): End location of activity \( i \);
- \( OptPro_i \): Optimum resource production rate of activity \( i \);
- \( P_{min_i} \): Minimum productivity rate of activity \( i \);
- \( P_{max_i} \): Maximum productivity rate of activity \( i \);
- \( D \): Project deadline

**Decision variables:**

- \( P_{1min_i} \): Minimum productivity rate of activity \( i \) which minimizes congestions;
- \( P_{1max_i} \): Maximum productivity rate of activity \( i \) which minimizes congestions;

\[
P_{1min_i} \in [P_{min_i}, OptPro_i]
\]

\[
P_{1max_i} \in [OptPro_i, P_{max_i}]
\]

- \( ST_i \): Start time of activity \( i \);
- \( ST_i \): Start time of activity \( i \) \( \in [0, D] \)

**Decision expressions:**

- \( ET_i \): End time of activity \( i \);
Where $A_{cong_{ij}}$ is the area of the intersection between space-time prisms of activities $i$ and $j$ respectively, $A_{cong}$ is the total congestion area available in the construction site, $x_1$ is the $x$ coordinate of vertex 1 and $y_n$ is the $y$ coordinates of the $n$th vertex.

For minimizing the potential congestion areas between construction activities, first, such areas need to be calculated taking into account the decision variables. To formulate this area, a mathematical formula for finding the area of polygons with known coordinates of vertices is used as presented in the Equation 1.

This area represents the possible interactions between successive prisms.

In order to use this equation, the coordinates of the intersection polygons between each two activities need to be formulated in terms of the decision variable; i.e. start times of the two activities and their prism boundaries. The intersection points are identified by getting the information from the second phase which includes the intersecting lines of the two polygons and the coordinate of the intersection points. Having identified the intersected lines, the system of line equations is set to find the intersection points in terms of decision variables.

After solving the parametric system the intersection points are found in terms of start time (ST) and minimum and maximum productivity rates ($P1_{min}$ and $P1_{max}$) of the intersecting polygons. The coordinates of the intersection points are feed into the area equation. Subsequently, the objective function of the optimization process is formed by summing up all the intersection areas in the project network schedule. The optimization process then optimizes the schedule by minimizing the total congestion in the project network. This is done through narrowing down the space–time float prism of one or both of the intersected prisms by changing their boundary slopes and/or changing start time of succeeding activities.

4 NUMERICAL EXAMPLE

The method presented here was applied to a case study to demonstrated and validated. The minimum and maximum productivities are assumed here, while in the real-world examples, project management teams are requested to enter general information about the project and respective activities. The project
includes construction of a 4-kilometer altering access road. Four activities (A, C, D and F) are assumed to be linear activities while the other two (B and E) were considered to be non-repetitive for this specific example. Accordingly, maximum, minimum were estimated (the inputs to the optimization module) for repetitive activities. The project was initially estimated to finish in 17 days. The description of each activity as well as inputs and outputs of the optimization process are included in Table 1 and Table 2, respectively.

As it is shown in Table 1, the input data of the congestion minimization process include Activity IDs, their start and end location, successors, their minimum and maximum achievable productivity rates, as well as their planned (optimum) productivity rates and its associated duration. The developed optimization engine uses this information to search for the optimum duration for the project for which the least potential congestion in the project is achieved, considering all logical and spatio-temporal (productivity) constraints to each activity. As shown in Table 1, the project deadline (17 days in this case) is another constraint which is inputted to the optimization process. The output of this process includes optimum minimum and maximum productivity rates for all repetitive activities (that also is representative of floats available to the resources at each point in time and space) as well as start and end times of all the activities, considering precedence relationships. The optimum duration for each activity and its associated duration are kept the same. The optimum duration achieved in this process might be longer than the previously duration for the project, but still satisfies the deadline constraint.

![Figure 4: Initial Schedule versus the Optimum Congestion-less Schedule](image)

**Table 1: Input of the Optimization Process**

| NbTasks | 6 |
| Deadline | 17 |

<table>
<thead>
<tr>
<th>Task</th>
<th>SL</th>
<th>EL</th>
<th>Pmin</th>
<th>Pmax</th>
<th>Succsl</th>
<th>Duration</th>
<th>productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>4</td>
<td>0.3</td>
<td>0.9</td>
<td>[2,3]</td>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>4</td>
<td>Non</td>
<td>Non</td>
<td>[4]</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>4</td>
<td>0.3</td>
<td>0.8</td>
<td>[4,5]</td>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>4</td>
<td>0.2</td>
<td>0.7</td>
<td>[6]</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>4</td>
<td>Non</td>
<td>Non</td>
<td>[6]</td>
<td>Non</td>
<td>Non</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>4</td>
<td>0.5</td>
<td>1</td>
<td>-</td>
<td>6</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Figure 4 shows the initially generated schedule for this project along with the optimum schedule. As it can be seen in that figure, in the generated schedule the intersection between space-time float polygons for succeeding activities are detected and marked. These potential congestions are totally eliminated in the optimum schedule. The potential congestion area between intersecting activities as well as the total congestion inherent to the project schedule is calculated. As it can be seen in the Figure 4a, potential congestion in location/time exists between activities C and D, as well as between activities D and F. The project schedule’s total potential congestion is calculated to be 4.418 (km.day). Table 2 shows the results of the schedule after the proposed optimization process. It can be inferred from the table 2 that the scheme of the schedule generated using proposed model is significantly different from that of the initial schedule in which congestion was not considered. The schedule finishes at 16 days which still satisfies the 17 day deadline constraint. Although the achieved duration is 1 days longer than the original minimum duration, the potential congestions are reduced to zero in the optimized schedule. For this purpose, as can be seen in Table 2 and Figure 4b, activities D and F are moved by one day, i.e. from day 5 to 6 and 9 to 10, respectively. Also, the available productivity interval for activity D (its minimum and maximum productivity rates) is reduced from [0.2, 0.7] to [0.3, 0.5], which accordingly means less float will be available to the resources of this activity. The result attained through this example ensures the applicability of the method. This way, the approach presented here helps in providing realistic plans for linear projects both in terms of time and space, while satisfying all there logical constraints.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pmin(opt)</th>
<th>Pmax(opt)</th>
<th>ST</th>
<th>ET</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>0.9</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>0.3</td>
<td>0.8</td>
<td>4</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>0.3</td>
<td>0.5</td>
<td>6</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>F</td>
<td>0.5</td>
<td>1.0</td>
<td>10</td>
<td>16</td>
<td>6</td>
</tr>
</tbody>
</table>

5 CONCLUDING REMARKS

In order to avoid or eliminate space-time conflicts in construction job sites, the subcontractors may frequently change their schedules. This occasionally cause a change in the materials delivery dates and/or the operation productivity or production rates. Such changes can be eliminated through detecting the potential space-time congestions in the planning phase and minimizing them before they happen. In this paper a method of detection, quantification and minimization of potential space time congestions of linear projects is presented. The method minimizes the potential space time congestions in the schedules of linear projects with due consideration to all their logical and precedence constraints. This is done by first, identifying the space time floats available to the resources of each activity, and then using this flexibility in predicting and accordingly minimizing the potential congestions. The method for time-space scheduling was subsequently validated through a numerical example. The results obtained promise applicability of the proposed method in managing linear construction projects. Running the optimization framework presented here for different number of resources will help project managers and decision makers to identify the potential spatial conflict that can affect the output of their projects.

References


AN INTEGRATED FRAMEWORK TO PREVENT UNSAFE PROXIMITY HAZARDS IN CONSTRUCTION BY OPTIMIZING SPATIO-TEMPORAL CONSTRAINTS

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Abstract: Hazardous proximity of construction resources, such as construction equipment, materials, and workers-on-foot has been identified as a distinct safety issue on construction jobsites. Spatial and temporal limits are practical constraints that coexist in movement of construction resources. Space and time conflicts could substantially hinder the productivity of ongoing activities as well as causing safety issues. Therefore, the spatial and temporal constraints and the state of construction resources need to be considered to prevent space-time conflicts and unsafe proximities. The state of a moving construction resource includes its position, moving direction/heading, speed, orientation, and other safety-related information. The area around each resource is divided into alert and warning areas which are quantified for them according to their corresponding spatial or proximity constraints. By integrating the states of resources, their warning/alert areas, and proximity constraints, as well as by visualizing them in time-integrated 2D space, a more precise understanding of potential hazardous situations can be achieved and therefore prevented. This paper presents a visual support tool aiming to reduce safety hazards in project planning stage by optimizing spatio-temporal proximities of resources. For this purpose, the developed method first optimizes potential movements of the resources by minimizing intersection of their warning areas and avoiding overlap of their alert areas. Thereafter, it visualizes the optimized locations of resources in time-integrated 2D space throughout the duration of their corresponding activities. In this way, the integrated visualization framework enables managers to make more judicious decisions and take corrective actions pertinent to safety hazards prevention. A numerical example with different scenarios and proximity measures is analyzed to test and validate the proposed framework.

Key Words: Construction Safety; Spatio-Temporal Constraints; Optimization; Alert and Warning Areas; Visualization

1 INTRODUCTION

Construction sites are generally comprised of multiple resources such as personnel, equipment, and materials moving in pre-defined spaces. These resources are involved in dynamic work tasks which require moving through space at different times on the job site. Because of their frequent unstructured and almost random motion, these resources can come in close proximity to each other. If not coordinated
and organized properly through optimized work planning (schedule and resource leveling), spatial interference can lead to incidents between two or more resources (personnel, equipment, material). These incidents can be characterized as contact collisions that can threaten the safety and health of construction personnel (Teizer et al., 2010).

Mustafa and Al-Bahar (Mustafa and Al-Bahar, 1991a) have identified risks sources central to construction activities to be physical, environmental, design and logistics based risks. Also the most frequent causes of accidental death and injuries were found to be falls, falling materials and collapses, as well as mobile resources’ accidents. Such risks can be reduced if the use of vehicles and mobile resources are properly managed. As a result, proper routing of resources can affect the cost and the time during construction projects by reducing safety risks. In addition, major productivity gains in terms of the reduction in wastage and working time can be achieved by planning the site from a logistics perspective (Mahdjoubi and Yang, 2001). Accordingly, during a construction project, site planners need to select paths for site operatives and vehicles. Such path planning in construction site spaces is a complex and multi-disciplinary task as it involves accounting for a wide range of scenarios and conditions. In other words, provision of safe paths could be used to control high-risk situations on the site and helps in having safe and efficient working conditions (Soltani et al., 2002).

Consequently, path/trajectory planning aids to improve safety and productivity margins by providing time-optimal and collision-free paths for navigating through the construction site that seek to prevent hazardous contacts between construction elements. To identify the potential of unsafe contacts between construction elements, it is essential to understand the potential regions of intensive activities not only during execution, but also in the planning phase. This definitely helps in having a more efficient activity resource planning which also increases safety on the job site. However, despite its importance, path/trajectory planning is not efficiently taken into account in the planning stage of construction projects. Further, although there are methods tending to optimize motion paths of resources or robots for special site operations (e.g. (Bernold, 1993, Olearczyk et al., 2010, Lee and Adams, 2004), still the time factor is very much neglected in both analysis and visualization. These methods mainly use shortest path algorithms such as Dijkstra to find 2D trajectories for construction resources. A common problem of current studies is that the distance between entities is the only factor taken into consideration and the direction of the entities’s movements (headings) are neglected. In some cases, the distance between two entities could be flagged and alarmed as an unsafe proximity while in reality, the entities are moving apart from each other.

To fill the gap in the literature, this paper aims at optimizing trajectories of construction resources in time-integrated 2D space in planning phase of the project. For this purpose, this study proposes and develops an unsafe proximity avoidance model focused on decreasing resources interactions throughout the planned activities’ duration. The model uses the attributes of distance and moving direction to define state of different resources and predict and optimize their motion through space and time. Subsequently, this paper discusses the key factors that should be considered in quantitatively defining the distance thresholds between resources. Current research either has not fully considered these factors, or has not described the relationship between the distance threshold and these essential factors (IHSA 2013; Marks and Teizer 2013). The thorough description of the proposed method is presented in following sections.

2 RELEVANT LITERATURE

Unsafe proximity of workers-on-foot to construction equipment or equipment-to-equipment has been identified as one of the distinct safety issues on construction jobsites (Pradhananga and Teizer 2012). Struck-by hazards are the second leading cause of construction fatalities, in which approximately 58% fatalities are resulted from struck-by-equipment (Wu et al. 2013). Thus, entities on construction jobsite have to interact and co-ordinate effectively with each other to maintain a safe environment. Even though such issue has been extensively studied in previous research efforts, the published casualty statistics indicate that contact collisions remain a major problem in construction industry. Hence, the trajectories of construction resources should be properly planned and monitored so that the potential collisions can be prevented in a timely manner. The trajectory of a construction entity includes the information regarding its
movement in space and time, taking into account its position, moving direction/heading, speed, orientation, and other safety-related information.

Optimizing trajectories of resources and operations is a common practice in different industries. Specially, trajectory optimization methods are widely used for planning optimal trajectories of robotic systems and machineries (Posa et al., 2014, Ahmad et al., 2013, Betts, 1998). With the growing use of robots and automated systems in construction industry, the problem of trajectory planning of these systems has been raised. Previous work on trajectory and path planning analysis in construction focused on three principal categories: (1) navigation of multiple vehicles, (2) efficient jobsite geometric modeling, and (3) real-time motion planning and control of equipment (Cheng et al., 2012). These methods are either focused on the trajectory planning of robotic workers, or equipment used in special construction processes. The early works in this regard included simulated work studies focused on large vehicle routing around an industrial construction site (Varghese and O'Connor 1995), motion planning for automated construction excavation (Bemold, 1993), heavy lift planning (Lin and Haas 1996), interactive path planning for vehicle operations (Wi Sung. et al. 2000), and visualization of construction simulation (Kamat and Martinez, 2001).

In order to execute the construction activities in a safe and efficient manner, construction site spaces needs to be properly planned. The risky sources of construction activities were identified to be physical, environmental, design, logistics, financial, legal, political, and operational risks (Mustafa and Al-Bahar, 2011b)). As a result, the paths of construction resources need to be planned in a way to be associated with less risks and would not cause congestion on the construction site. In addition, routing of resources affects the cost and the time during construction projects, and major productivity gains in terms of the reduction in working time can be achieved. Soltani et al. (Soltani et al., 2002, Soltani and Fernando, 2004) presented the application of path planning on construction sites according to multiple objectives. In their method, they evaluated the performance of three optimisation algorithms namely: Dijkstra, A*, and Genetic algorithms. The optimised path in this approach was defined as the shortest path, the safest path, the most visible path or a path that reflected a combination of short distance, low risk and high visibility. Chi et al. (2008) examined crash avoidance algorithms for providing routes that prevent collisions with other movable objects on a construction site. While the calculated path avoided crashes, it was not necessarily the most efficient. Other methods used the highly parallel unconstrained Dijkstra approach in order to develop a new optimal algorithm in which paths were subjected to turning constraints such that the final solved path contained no turns greater than 45°((Solka et al., 1995, Hassoun, 1990). In this regard, Pei et al. (2009) also generated a basis for vehicle movement trajectory reconstruction in two-dimension collision accidents and accidents disposal. Recently, some methods also focused on providing potential optimized paths for special construction equipment or operations, e.g. (Filla, 2013, Lin et al., 2014, Wi Sung et al., 2012). Lin et al. (2014) performed motion planning for mobile construction machinery to generate collision-free path for multiple construction machines, including wheel-type, track-type and chain-type machines, moving simultaneously on a construction site, based on the true movement of construction machinery. (Wi Sung et al., 2012) also introduced a Genetic Algorithm-based Repetitive Tasks Simulation (GARTS) model for planning steel erection in high-rise building construction. This model produced an optimized movement path of a bolting robot for fabricating steel structures, proposed a collaboration plan between a robot and a worker, and quantified the uncertainty of the duration of steel erection.

Visual representation of the stated resource paths is the next step towards efficient planning of construction sites. In other words, visualizing simulated construction operations can provide valuable insight into the subtleties of construction operations that are otherwise non-quantifiable and presentable. This is because planners must comply with many considerations, such as increasing construction productivity, decreasing site congestion and providing a safe work environment during the process of site space planning which is more achievable when properly visualized (Zhou et al., 2009). (Kamat and Martinez, 2001) presented the Dynamic Construction Visualizer, which enabled spatially and chronologically accurate 3D visualization of modeled construction operations and the resulting products. William et al. (2007) also developed a dynamic path planning system to improve mobile robot navigation in a dynamic building construction site by integrating a set of sensor-equipped robots into a real-time indoor positioning system, using the ultra wide band (UWB) position system. The method then displayed the mobile robot movements and paths in a 3D CAD drawing in a real-time manner.
As stated, when dealing with heavy machinery and vehicles, following a safe and efficient path reduces the risk of worker injury and fatality, reduces collateral damage to equipment, and improves overall work efficiency. However, limited research in path finding on construction site has been conducted. In addition, although the 2D or 3D visualization of these paths has many potential uses toward the monitoring and maintenance of an automated construction site, still all the few available visual methods disregard the time aspect of the possible congestions when planning and visualizing the paths of actual resources. Up to now, such trajectories in construction industry are only available recently for unmanned Aerial Vehicles (UAVs) (Alejo et al., 2014) or for workers-on-foot (Dagan and Isaac, 2015). Their innovative method presented a new system for assembly and structure construction with multiple Unmanned Aerial Vehicles (UAVs) which automatically identifies conflicts among them. After detecting conflicts between UAVs, the system resolved them cooperatively using a collision-free 4D trajectory planning algorithm based on a simple one-at-a-time strategy to quickly compute a feasible but non-optimal initial solution. Further, the available methods still do not take into account the results of the interaction between two individual workers with different characteristics, which might create safety risks and their daily interactions with other site equipment and obstacles. As a result, the method presented in this paper tends to fill the gap in the current literature by proposing a time integrated framework for trajectory optimization of construction resources, aiming at preventing the proximity hazards in the construction job sites. The detailed description of the optimization method follows.

3 TRAJECTORY OPTIMIZATION-VISUALIZATION FRAMEWORK

As stated in previous sections, visualizing simulated construction operations in time-integrated 2D space can provide valuable insight into the subtleties of construction operations that are otherwise non-quantifiable and presentable. The optimization method presented in this paper aims at generating minimized-congestion trajectories for construction resources. This is done in two essential inter-related phases, namely trajectory optimization and visualization phases, as shown in Figure 1. This framework consequently enables spatially and chronologically accurate visualization of modeled construction operations and the resulting optimum planned trajectories for activity resources. This section describes the steps of the time-integrated 2D trajectory optimization-visualization framework.

![Diagram](image)

Figure 1: Trajectory optimization-visualization framework

The optimization method presented in this paper uses the unsafe proximity detection process presented by (Wang and Razavi, 2015). In this method, the authors divided the area around equipment into alert and warning areas. Further, the distance threshold used for unsafe proximity identification is differently considered when the piece of equipment is moving as opposed to staying stationary. The key factors that should be considered in quantitatively defining such distance thresholds are then described. This approach will prevent congestions between activity resources in the planning phase, which will subsequently lead to achieving more safety and higher productivity rates from the resources.
3.1 Quantification of Alert and Warning Distances

In this study, alert area is defined as the hazardous area around the equipment, and warning area is the area that has the potential to become hazardous under certain conditions. A hazard refers to a situation that an entity is within the alert area. For the proof of concept, circles are adopted as an approximation of the alert and warning areas for equipment and workers-on-foot (Figure 2). It should be noted that different equipment exhibits different alert distance (R1) and warning distance (R2). Accurately quantifying R1 and R2 can assist in effectively performing proximity detection methods and also contributes to enhancing mobility and productivity on the job site.

![Figure 2: Intersection between warning areas of a) two pieces of equipment and b) equipment-worker](image)

For one piece of specific equipment, alert distance R1 is the same under general condition, regardless of its static or moving state. This study uses forklift as sample equipment to explain the process of defining R1 and R2. It is expected that no intersection of alert areas occurs when the forklift comes to a complete stop. This study adopts 2 meters as the alert distance for the forklift with 2.5 tonne capacity. The determined 2 meters includes the length of the fork attached to the forklift. In order to take into account all conditions, including both congested and non-congested time periods, this paper proposes adjusting warning distances for the same equipment over time. The warning distance for equipment is adjusted by considering equipment reaction distance and equipment braking distance. Equipment reaction distance is the distance that equipment travels after the operator's realization of a hazard and before a determined response (e.g. brake) exactly comes into work. Equipment braking distance is defined as the distance the equipment will travel from the point when its brakes are fully applied to the point when it comes to a complete stop. As thus, R2 needs to be increased when the equipment is moving with a higher speed. Likewise, for the equipment with a lower speed, this distance is decreased in order to have efficient space allocation on the job site.

For workers-on-foot, an alert area with an average 1 meter diameter is adopted which is the area a worker demands for safety operation of different construction activities (Dagan and Isaac, 2015). An average 1.5 meters is adopted as the warning distance. The difference between the warning distance and the alert distance is 1 meter which is the distance a worker needs to achieve a complete stop upon realizing a hazard occurrence. It is obtained by multiplying the mean of actual comfortable gait speed of men at 30s and 40s (Bohannon, 1997) and the average reaction time of a normal people (Technology Associates, 2014).

3.2 Trajectory Optimization

This paper proposes a step-by-step optimization algorithm to find the safest trajectory for activity resources in the planning phase, based on the information available in this phase of the project. For this purpose, first, a set of check time intervals is defined based on the nature of the project. These check time intervals are then used to attain the optimum average location of each activity resource as shown in Table 1. It should be noted that, the step-by-step nature of the algorithm enables it to be applicable to planning as well as monitoring and tracking phases; i.e. when exact location and progress at one time is known, and the planned trajectory needs to be re-optimized to plan for following movements in space and time. The developed safety planning method was applied in MATLAB. Its application is carried out in the following steps.
3.2.1 Identification of resource locations and their safety areas

For construction equipment and workers-on-foot, safety area refers to their warning area and alert area. For temporary or permanent site facilities and obstacles, safety area refers to the area around them that other construction resources (static or dynamic) are not allowed to be inside except by authorizations. To start the optimization process, the approximate coordinates of the expected location of each resource is determined based on the nature and the schedule of activities they will be involved in. The alert distance (R1) and warning distance (R2) are also to be defined at each time. Subsequently, the step-by-step optimization is initiated. The process of defining R1 and R2 starts at the first check-time, which is generally the start of the project or the date on which a certain part of the project starts for which a safe trajectory needs to be planned. In each check-time, the alert and warning areas are created around the approximate planned location as shown in Figure 2. The location optimization will only take place in predefined check-time intervals. Therefore, whenever equipment is added or removed, its starting point will be added and then its optimization will start from the first nearest check time and then the whole trajectory will be demonstrated through space and time in the visualization phase.

3.2.2 Location optimization

The purpose of this phase is to minimize the potential hazardous contacts between resources that co-exist in each check-time. First, the distance between each two different resources (D) and the intersection of their safety areas need to be calculated. It should be noted that, the method is able to take into account not only hazardous contacts between resources, but also the possible contacts between these resources and any temporary or permanent site facilities and obstacles. Distance D is then defined as the center-to-center distance of the warning areas of two resources or a resource and an obstacle that is calculated using Equation 1; where (x₁, y₁) and (x₂, y₂) are the approximate coordinates of resource i and j, respectively, at check time t.

\[ D = \sqrt{[x_i(t) - x_j(t)]^2 + [y_i(t) - y_j(t)]^2} \]

When calculating the intersection between safety areas of each two resources, three possible situations might exist:

1. Distance D is greater than the summation of the waring areas of the two resources, in which no intersection area (IA) between safety areas would exist.

\[ D \geq R^2_i + R^2_j \rightarrow IA = 0 \]

2. Distance D is less than the subtraction of the waring areas of the two resources, in which intersection area is the area of the smaller warning area of the two.

\[ D \leq R^2_i - R^2_j , \ R^2_j \leq R^2_i \rightarrow IA = \pi R^2_j \]

3. Distance D is greater than the subtraction of the waring areas of the two resources, and less than their summation. This means the areas are partially overlapped. In such case intersection area is calculated as follows:

\[ R^2_i - R^2_j \leq D \leq R^2_i + R^2_j , \rightarrow \]

\[ IA = R^2_j \cos^{-1} \left( \frac{D^2 + R^2_j - R^2_i}{2DR^2_j} \right) + R^2_i \cos^{-1} \left( \frac{D^2 + R^2_i - R^2_j}{2DR^2_i} \right) - \frac{1}{2} \sqrt{(-D + R^2_j + R^2_i)[(D + R^2_j - R^2_i)(D - R^2_j + R^2_i)](D - R^2_j + R^2_i)(D + R^2_j + R^2_i)} \]

This paper focuses on the third case in which a partial overlap between safety areas occurs. Therefore, the objective is to minimize the total intersection areas of all resources that co-exist in each check time.
In this optimization process, the coordinates of each resource at time $t$ is set as decision variables. As a result, the optimization process seeks for the optimum coordinates for each resource that will minimize the total intersection areas considering the rules and constraints of the project. It should be noted that no overlap can be existed between two resources’ alert areas. In other words, no entity would be allowed to enter the alert area of the other entity. This condition is employed as a constraint to the optimization process as shown in Equation 7.

$$\text{min } [f(x,y)_t = \sum_{k=1}^{m} (IA_{i,j})_t]$$

$$m = \binom{n_t}{2} = \frac{n_t!}{2 \times (n_t - 2)!}, \ n = \text{number of resources at time } t$$

The optimization process is performed for all check-times. Consequently, vectors of the optimum trajectories for all the resources in time-integrated 2D space are created. The achieved optimum trajectories as well as the prisms are then realized in the visualization phase to give the planners a better sense of the safety hazards and the optimum trajectories. Based on the obtained plan, in the project implementation phase, the rates at which planned activities are expected to be carried out, and the rate achieved from the optimum trajectory can be compared to ensure optimality of the assessed productivities. Therefore, this method represents resources’ movements, and also verifies that they adhere to the planned productivities at all times.

### 3.3 Space-time trajectory visualization

In the presented study, time–space diagrams were developed to represent the actual movements of resources along different paths on the construction site. The time–integrated 2D space diagrams, whose $(x,y)$ axis represent the changing locations of resources on site and the vertical axis represents time, were developed as prisms representing the locations of resources as well as potential safe spaces available to them on the site at different time (Figure 3). The time-integrated 2D space diagrams are used to visualize the movements of resources and to ensure their safety through planning the safest distance between their prisms. Each optimum trajectory is simultaneously represented as a number of polylines in the diagram, connecting the optimum locations at each time interval to the next. Space distance between resources, introduced in time order to reduce safety risks, is represented as distances between the polylines.

![Figure 3: Realization of prism for one activity a) without and b) with site obstacles](image-url)
As stated earlier, in addition to the representations of the movements of equipment and workers on the site, certain static objects (i.e. temporary or permanent site facilities and obstacles) and areas on the site that may expose resources to hazards are also represented in the space-time diagram. For example, some of the workers may need to work at a certain distance from a crane, or from a storage area with flammable material. Such elements are represented as cylinders in the diagram. The footprint of the shape represents the portion of the site occupied by the object, and its height represents the duration for which the object remains on the site as shown in figure 3b. Figure 3a demonstrates the prism for equipment as well as the optimum trajectory throughout its execution period. Figure 3b illustrates the result of the optimization process when one piece of equipment is to perform, and one temporary and one permanent obstacle exist on the job site. Figure 4 demonstrates the intersection between resources with site obstacles as well as between two activities with different start and finish times in time-integrated 2D space. Table 1 and Figure 5 respectively represent the initial data inputs and visualization of a small sub project including three resources (equipment 1, 2 and 3). As shown in table 1 and figure 5, check time intervals of 7 days are considered in this example. However, for equipment 3 that starts at day 5 from start of the sub-project, its optimization starts on day 7, i.e. at the nearest pre-defined check time interval.

Figure 4: Realization of 2D intersections between a) activity and site obstacles and b) two activities

Table 1: Data inputs of three resources

<table>
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<tr>
<th>Resource</th>
<th>Time</th>
<th>X coordinate</th>
<th>Y coordinate</th>
<th>Warning distance</th>
<th>Alert distance</th>
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</table>

- Once the resources’ movements on site have been analyzed, the construction managers can implement controlling actions and approve of a safe construction plan. In cases in which the planned or actual distance between resources is not acceptable as a result of a special site condition, or the planned productivities deviate from the planned, the following actions can be taken:
Adjustment of the planned schedule, in order to move the resource space-time prisms in time by changing the timing of the activities they are to be carried out, or stopping it for some time in between and re-continuing when the space issue is resolved.

Adjustment of the way in which a planned activity will be carried out (for example, by allocating different equipment to a worker), in order to reduce the risks identified in the first stage of the application of the model, and consequently the safety distance that needs to be kept between the resources can be maintained.

Figure 5: Realization of the optimum space-time prisms for a) two and b) three activities

4 CONCLUSION

A methodology has been developed for analyzing and if necessary adjusting the planned locations of construction resources on sites, in order to prevent the hazards that occur due to an excessive proximity between different resources. Such hazards may occur due to the impact that the resources of an activity have on the safety of other resources carrying out other activities in adjacent locations on the site. This research focuses on the minimizing the intersection between safety areas considered for each resource, in a way to both prevent site congestions and unnecessary space allocations, since this problem has not been sufficiently studied so far.

The proposed methodology includes a step-by-step optimization method for the assessment of distances between resources, and the use of prisms to analyze the existing construction plan. These tools allow managers to take into account the dynamic activities of the resources on sites, as well as the different characteristics of different resource types which may reinforce or counteract risk factors. The proposed method can be particularly useful for projects in which activities are repetitive, reducing the complexity of resources' movements and increasing their predictability. By utilizing other shapes to represent the safety areas around equipment and site elements, such as using a rectangle for a permanent building on the job site, to further improve the effectiveness of the model is the future step of this study.

References


EXPLORING THE RELATIONSHIP BETWEEN PROJECT INTEGRATION AND SAFETY PERFORMANCE

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Abstract: While recent studies suggest that there is a relationship between indicators of project integration—such as early involvement of constructors—and the quality of project health and safety outcomes, there is no study that empirically investigates this relationship. To address this limitation in the current body of knowledge, the purpose of this paper is to explore the relationship between several characteristics of the integrated projects and construction safety performance. To achieve this objective, the following activities were conducted. First, to collect detailed information regarding recently completed building projects, a survey questionnaire was developed in which, safety performance metrics—such as the number of accidents—were considered as dependent variables, and project organization, team integration, and using emerging processes and technologies were included in the questionnaire as independent variables. Second, the questionnaire was distributed to reach a diverse set of respondents, and a database of 204 building projects was created. The collected data was validated by conducting follow-up phone interviews with respondents. Finally, the database was analyzed using various statistical techniques to investigate the relationship between project integration indicators and safety performance. The results of this study provide preliminary evidence that early decisions of owners and contractors to move towards more integrated projects can impact the safety performance of projects.

1 INTRODUCTION

Using more integrated project delivery systems are gaining traction in the construction industry. The integrated projects are usually characterized with usage of alternative delivery methods such as integrated project delivery method (IPD), team integration techniques such as partnering and colocation, and emerging processes and technologies such as building information modeling (BIM), prefabrication, and lean tools. There is an interest among both owners and contractors to understand the relationships among these new variables and typical definitions of project success such as cost, time, and safety outcomes (El-Asmar et al. 2013).

Considering its importance, several studies attempted to find empirical relationships between safety performance and other project related factors. Most significant studies conducted by researchers focused on using empirical evidence provided in accident reports in national databases such as the Occupational Safety and Health Administration (OSHA) Integrated Management Information System (IMIS) (Hinze et al. 1998, Huang and Hinze 2003, Goh and Chua 2013, and Esmaeili et al. 2015a, Esmaeili et al. 2015b).
Although these studies provide significant contribution to educate project managers regarding factors that contribute to accident occurrence, they provide limited knowledge about the impact of project integration on safety performance. In fact, national databases provide a little information about the type of delivery method used, time of involvement of a contractor in the design process, existence of a partnering statement, or using building information modeling in a project.

To address this growing knowledge gap, the objective of this study is to determine the role of project integration in terms of project organization, team integration, and application of emerging processes and technologies on safety performance. To achieve this objective, a comprehensive questionnaire was developed and distributed into the U.S. construction industry to create a large empirical database of building projects. Then, the database was analyzed using various statistical analysis. This study departs from the current body of knowledge by empirically measuring the impact of project integration—such as project organization, team integration, and using emerging processes and technologies—on the safety performance of building projects. It is expected that the results of this study will provide a guideline for both owners and contractors to understand the impact of their early decisions on safety performance.

2 BACKGROUND

In this section, the research team aimed to identify a dependent variable that measures safety performance and to identify several independent variables that explain project integration. The notable results of the literature review and discussion of dependent and independent variables are provided below.

2.1 Dependent variables

The dependent variables are safety outcomes that reflect the measured safety performance or number of accidents in the project. However, as worker-hours increase, the possibility that workers will get exposed to hazards and get injured will also increase. Rather than collect the number of worker-hours, which is a difficult undertaking, to consider the impact of project size and worker-hours, the number of recordable incidents were divided by the area of the building. Thus, the safety performance was calculated using the following equation:

$$\text{Safety Performance} = \frac{\text{Number of Recordable Incidents}}{\text{Area (ft}^2\text{)}} \times 100,000$$

2.2 Independent Variables

The independent variables are those factors that can impact performance outcomes. A comprehensive literature review was conducted to identify independent variables that define project integration. Four variables were selected to be included in the questionnaire for further analysis: (1) project complexity; (2) project organization; (3) team integration; and (4) using emerging processes and technologies. These variables are explained in more details in the following sections.

2.2.1 Project Complexity

One of the project characteristics that can influence project performance is complexity. Previous studies investigated the impact of complexity in design (Glavan and Tucker 1991) and scheduling (Nasser and Hegab 2006) of projects. In one of the recent studies, Puddicombe (2011) investigated the cost and schedule performance of 1,300 projects and found that complexity is an important characteristic of a project that has a crucial impact on project performance. However, there is no previous study that has empirically investigated the impact of project complexity on safety performance.
2.2.2 Project Organization

The construction industry is highly fragmented mainly due to the lack of communication among designers and contractors. The traditional delivery practices such as design-bid-build also exacerbate separation of design and construction process. Separation between different parties negatively impacts the potential for innovation as this division makes knowledge exchange more difficult. There are several empirical studies that investigated the impact of project organization on project performance (Konchar and Sanvido 1998, Molenaar and Songer 1998, Ibbs et al. 2003, Hale et al. 2009). Most of these studies had consensus that as one moves towards more integrated delivery methods, the possibility of cost and schedule growth decrease (Konchar and Sanvido 1998, Molenaar et al. 1999, Gransberg et al. 1999, El-Asmar et al. 2013). While the contribution of these studies is significant, none of them has considered the impact of different delivery method on safety performance of a project.

In addition to project delivery types, the project organization determines the time of involvement for different stakeholders. Song et al. (2009) studied the early involvement of contractors in design and its impact on construction schedule performance. They found that constructability input provided by contractor can improve drawing quality, material supply, information flow, and can indirectly impact construction schedule performance. One of the major limitations of previous studies in this domain is that they did not consider the impact of early involvement of project stakeholders on safety performance.

2.2.3 Team Integration

Three major characteristics of team integration that are investigated in this study are: partnering, co-location, and collaborative goal setting. The complexity, uncertainty, and time pressure existed in construction industry has increased the need for cooperation, flexibility, integration (Eriksson and Pesamaa 2007). One of the concept that can affect project performance through improving team behavior of project participants is partnering. Partnering facilitates knowledge and resource sharing, and improves collaborative relationships that are necessary for successful project completion (Cacamis and El-Asmar 2014). Some studies measured the impact of partnering on project performance. In one of the seminal studies, Gransberg et al. (1999) found that partnering could help to control cost and time growth on projects greater than five million dollar. Nevertheless, there are limited number of studies looked at the relationship between project’s safety performances and partnering.

One of the most notable differences between integrated and less integrated delivery methods is co-location in an environment, which encourages informal collaboration and face-to-face communication among stakeholders (Raisbeck et al. 2010). Within an open floorplan office, known as the “Big Room,” a team of the contractors, architects, and owners work in a collaborative environment during the design and construction of a project. According to Hall et al. (2014), co-location facilitates collaborative decision making, innovation, and transparency. In this study, the research team decided to assess impact of using co-location on safety performance of a project.

The third characteristics of team integration that was investigated by the research team was collaborative goal setting. According to the OSHA act, the employers or contractors are responsible for the safety of their employees, and the standard form of contracts in the construction industry—such as AIA A201 and EJCDC E-500—explicitly transfers responsibility of safety to general contractors. However, if the contractor or builder is participating in goal settings, he or she can inform owners and designers regarding the impact of various decisions on safety performance. In other words, as far as the contractor is concerned regarding safety of his or her employees, the contractor can convince other project stakeholders to consider safety as one of the objectives. A minimal number of studies have investigated the impact of team integration on safety performance.

2.2.4 Using Emerging Processes and Technologies

Three emerging processes and technologies that seem to have a significant impact on enhancing safety performance are offsite prefabrication, using lean construction tools, and using building information modeling (BIM). As prefabrication provides several benefits to the project in terms of cost, time, and
productivity, its usage has been steadily increased in past decades (CII 2002, Eastman and Sacks 2008). Previous studies claimed that prefabrication has the potential to enhance safety performance by reducing the hazard levels of a task (Gambatese et al. 1997, Toole and Gambatese 2008). For example, to reduce risk of fall accidents, work can be shifted from a high elevation to the ground; to avoid the risk of cave-in, work can be shifted from inside an excavation to grade; or to reduce the risk of suffocation, work can be moved from inside a confined space to an open space (Toole and Gambatese 2008). In addition, when work is shifted from the field to the factory, work can be conducted in an environment where the majority of risks are under control and equipment is in better condition.

Toole and Gambatese (2008) highlighted the importance of prefabrication in facilitating hazard prevention through design practices. They found that one of the main pathways that hazard prevention through design will progress in the future is in using prefabricated elements. Using prefabrication elements in design help designers to improve construction safety without fear of liability. In another study, Tanabe and Miyake (2010) proposed a safety design approach for an onshore modularization liquefied natural gas liquefaction plant. Their innovative design showed the feasibility of considering prefabrication elements in the design phase to enhance safety in downstream operations. While there is a common perception that prefabrication can enhance safety, there is no study that empirically supports this hypothesis.

Another independent variables that was identified from the literature is using lean construction tools. Lean production originated in the manufacturing and automotive industries, and after its successful contribution to the manufacturing industry, it has been used in the construction industry (Salem et al. 2006). Previous studies in the construction industry indicated that using lean tools has a positive impact of safety performance (Ohno 1988, Thomassen et al. 2003, Salem et al. 2006, Nahmens and Ikuma 2009, Wong et al. 2009, Womack et al. 2009). The research team decided to consider the impact of using lean construction tools beside other independent variables on safety performance.

Previous studies indicated that using building information modeling (BIM) has a great potential to improve safety performance in a project. Some of the potential applications are: (1) hazard identification; (2) design for safety; (3) site safety planning; and (4) training and education. First, BIM can be used to effectively enhance hazard identification by creating a 3D model of a project. Park and Kim (2013) developed a framework to integrate BIM, augmented reality, location tracking, and game engine technologies into a comprehensive site safety planning process. According to the framework, safety risk factors can be identified in the planning stage by visualizing 3D design and the required site safety facilities for project activities. Second, BIM enables designers to modify designs by considering safety constraints in early stages of a project (Rajendran and Clarke2011). To provide proof of concept, Qi et al. (2013) developed prevention through design (PtD) tools to provide feedback to designers about the hazards created by different design alternatives. Third, BIM-based site planning can improve safety performance by providing detailed spatial information of construction environments as wells as dynamic planning and 4D model (Sulankivi et al. 2009). For example, the visualization of a crane’s reach was carried out to examine the risk of load fall or the objects the crane’s rib could hit (Sulankivi et al. 2009). Finally, Rajendran and Clarke (2011) stated that 3D model of a building can be used in orientation sessions to enhance situational awareness of workers new to the working environment. Although previous studies stated that BIM can help to solve some of the safety issues on the site, a limited number of studies have empirically investigated the relationship between using BIM and safety performance.

3 RESEARCH METHODOLOGY

The purpose of this study was to explore the impact project integration measures—such as delivery method, team selection, and other behavioral and technological factors—have on project safety performance. The objective of the study was achieved by conducting the following activities: (1) questionnaire development; (2) data collection; (3) data compilation and validation; and (4) data analysis. First, a survey questionnaire was developed to collect the required data from owners and contractors with an industry advisory board (Esmaeili et al. 2013, Franz et al. 2014). Recordable accidents per square foot of a project were collected as a dependent variable to measure safety performance, and several independent variables were collected including: project complexity; project delivery method (i.e., design-
bid-build, construction manager at risk, design-build, integrated project delivery method; time of involvement of different parties; co-location; collaborative goal setting; and using offsite prefabrication, lean construction tools, and building information modeling.

Second, the survey was distributed by e-mail and postal mail to professional organizations in the U.S. construction industry. During the data collection process, more than 8500 project managers were contacted in the two years. A cover letter, set of instructions, and glossary of terms were attached to the survey in order to illustrate the project objectives and to explain the key terms. The diverse group of respondents was asked to answer the survey according to the most recent project that their organization completed (Franz 2014).

Third, the data collected via e-mail and postal mail were compiled and validated by conducting follow-up phone interviews. In total, 331 surveys were received and reviewed and compiled into a single database in Microsoft Access® with unique identification codes. The reviewing procedure included: verifying the project information to check for possible missing data, scrutinizing the consistency in given values, excluding out-of-scope projects, eliminating unverified projects, and resolving multiple response discrepancies. The reviewing procedure resulted in a database of 204 building projects (Franz 2014).

Forth, the descriptive statistics were examined for each variable and each distribution was checked for normality in the screening procedure. Then, correlations between variables were analyzed. Because all variables were non-normally distributed, correlations between them were analyzed using Spearman's rank-based correlation coefficient (Schumacker 2015). Correlation between recordable accidents were measured against other project performance measures such as cost, schedule, and delivery speed.

Kruskal-Wallis test was used for the group comparisons for recordable accidents per square foot area, because each of the response variables was significantly non-normal and the group sizes within could be relatively small for some categories. The Kruskal-Wallis test is a common nonparametric test that compares the overall population distribution for any number of groups. Since there are lots of "ties" in the data (observations with the same number of incidents) and in some cases quite a few groups, a chi-square approximation was used to calculate the p-value (Schumacker 2015). Post-hoc analyses were also conducted on significant groupings using pairwise Wilcoxon-Mann-Whitney tests with a Bonferroni adjustment. Since there were multiple comparisons in this data set, the Bonferroni adjustment kept the Type 1 error probability controlled. All analyses were done using R, which is an open-source statistical program (R Development Core Team 2011).

4 RESULTS AND DISCUSSION

From 204 projects, 124 projects provided information about recordable accidents with a range of 62 and median of 1. Fifty-two percent of projects had at least one recordable accidents. These results indicate that, on average, safety performance of projects in the database was higher than the industry average. As mentioned earlier, in the questionnaire, several questions were asked related to independent variables such as project organization, team integration, and using emerging processes and technologies. The recordable incidents per square foot of a building for each of these independent variables are calculated and summarized in Table 1.

The results of the correlation analysis are summarized in Table 2. As is shown, only unit cost, project delivery speed, and construction delivery speed are significantly correlated with safety performance measures. This can be justified by considering that safety performance was calculated by dividing the number of accidents by area of the building; unit cost, project delivery speed, and construction delivery speed are also related to the total area of the building. Another project performance metric that is marginally correlated to the safety performance is construction cost growth.
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</tr>
<tr>
<td>Bidding</td>
<td>0.594</td>
<td>1.329</td>
<td>23</td>
</tr>
<tr>
<td><strong>Time of Mechanical, Electrical, and Plumbing (MEP) Contractor Involvement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-design</td>
<td>0.738</td>
<td>0.942</td>
<td>12</td>
</tr>
<tr>
<td>Conceptual</td>
<td>2.007</td>
<td>2.339</td>
<td>11</td>
</tr>
<tr>
<td>Schematic</td>
<td>1.859</td>
<td>1.827</td>
<td>15</td>
</tr>
<tr>
<td>Development</td>
<td>1.732</td>
<td>2.109</td>
<td>12</td>
</tr>
<tr>
<td>Documents</td>
<td>1.220</td>
<td>1.259</td>
<td>18</td>
</tr>
<tr>
<td>Bidding</td>
<td>0.944</td>
<td>1.778</td>
<td>48</td>
</tr>
<tr>
<td><strong>Time of Structural Contractor Involvement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-design</td>
<td>0.496</td>
<td>0.653</td>
<td>12</td>
</tr>
<tr>
<td>Conceptual</td>
<td>1.093</td>
<td>1.757</td>
<td>11</td>
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<tr>
<td>Schematic</td>
<td>1.596</td>
<td>1.598</td>
<td>9</td>
</tr>
<tr>
<td>Development</td>
<td>1.943</td>
<td>1.919</td>
<td>14</td>
</tr>
<tr>
<td>Documents</td>
<td>1.547</td>
<td>1.603</td>
<td>16</td>
</tr>
<tr>
<td>Bidding</td>
<td>1.158</td>
<td>1.937</td>
<td>54</td>
</tr>
<tr>
<td><strong>Using Partnering</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1.244</td>
<td>1.732</td>
<td>32</td>
</tr>
<tr>
<td>No</td>
<td>1.224</td>
<td>1.800</td>
<td>92</td>
</tr>
<tr>
<td><strong>Builder Participated in Co-Location</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1.588</td>
<td>1.771</td>
<td>19</td>
</tr>
<tr>
<td>No</td>
<td>1.083</td>
<td>1.766</td>
<td>61</td>
</tr>
<tr>
<td><strong>MEP Contractor Participated in Co-Location</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1.920</td>
<td>1.842</td>
<td>9</td>
</tr>
<tr>
<td>No</td>
<td>1.064</td>
<td>1.728</td>
<td>71</td>
</tr>
<tr>
<td><strong>Structural Contractor Participated in Co-Location</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1.916</td>
<td>1.875</td>
<td>6</td>
</tr>
<tr>
<td>No</td>
<td>1.081</td>
<td>1.727</td>
<td>74</td>
</tr>
<tr>
<td><strong>Builder Participated in Goal Setting</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1.447</td>
<td>1.895</td>
<td>92</td>
</tr>
<tr>
<td>No</td>
<td>0.629</td>
<td>1.243</td>
<td>28</td>
</tr>
<tr>
<td><strong>Using BIM in a Project</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>1.516</td>
<td>1.874</td>
<td>90</td>
</tr>
<tr>
<td>No</td>
<td>0.472</td>
<td>1.209</td>
<td>34</td>
</tr>
<tr>
<td><strong>Using Prefabrication in a Project</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>1.037</td>
<td>1.747</td>
<td>62</td>
</tr>
<tr>
<td>High</td>
<td>1.441</td>
<td>1.817</td>
<td>59</td>
</tr>
<tr>
<td><strong>Using Lean Scheduling Tools in a Project</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>2.078</td>
<td>2.100</td>
<td>20</td>
</tr>
<tr>
<td>No</td>
<td>1.137</td>
<td>1.669</td>
<td>104</td>
</tr>
</tbody>
</table>
Table 2: Correlation between recordable accidents per square foot of area and other success measures

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Cost Growth (%)</td>
<td>-0.055</td>
<td>0.557</td>
</tr>
<tr>
<td>Project Schedule Growth (%)</td>
<td>-0.044</td>
<td>0.627</td>
</tr>
<tr>
<td>Construction Cost Growth (%)</td>
<td>0.180</td>
<td>0.064</td>
</tr>
<tr>
<td>Construction Schedule Growth (%)</td>
<td>-0.004</td>
<td>0.973</td>
</tr>
<tr>
<td>Unit Cost (log)</td>
<td>0.314</td>
<td>0.001</td>
</tr>
<tr>
<td>Project Delivery Speed</td>
<td>0.298</td>
<td>0.008</td>
</tr>
<tr>
<td>(sf/month of project duration; log)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Delivery Speed</td>
<td>0.259</td>
<td>0.004</td>
</tr>
<tr>
<td>(sf/month of construction duration; log)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the results, the project complexity has a statistically significant impact on safety performance. This is understandable since in more complex projects, contractors might have to use unfamiliar means and methods that expose workers to unknown hazards. The post hoc analysis revealed that very complex projects (Likert value=6) have lower safety performance than projects with medium (Likert value=5, p-value=0.005) and low complexity (Likert value=1~4, p-value=0.037).

Table 3: Group comparison between independent variables using Kruskal-Wallis test

<table>
<thead>
<tr>
<th>Grouping variable</th>
<th>Test stat (chi-square)</th>
<th>p-value</th>
<th>DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Complexity</td>
<td>15.56</td>
<td>0.001</td>
<td>3</td>
</tr>
<tr>
<td>Delivery Methods</td>
<td>9.75</td>
<td>0.021</td>
<td>3</td>
</tr>
<tr>
<td>Time of Builder Involvement</td>
<td>12.95</td>
<td>0.024</td>
<td>5</td>
</tr>
<tr>
<td>MEP Contractor Participated in Co-Location</td>
<td>6.84</td>
<td>0.009</td>
<td>1</td>
</tr>
<tr>
<td>Struct. Contractor Participated in Co-Location</td>
<td>5.49</td>
<td>0.019</td>
<td>1</td>
</tr>
<tr>
<td>Using BIM in a Project</td>
<td>13.58</td>
<td>0.000</td>
<td>1</td>
</tr>
<tr>
<td>Using Lean Scheduling Tools in Project</td>
<td>5.12</td>
<td>0.024</td>
<td>1</td>
</tr>
</tbody>
</table>

As far as project organization is concerned, the type of delivery method and time of builder involvement in a project design had significant impacts on safety performance. The post hoc analysis showed that projects delivered by design-bid-build method had a better safety performance than projects delivered by construction manager-at-risk (p-value=0.032). This is a surprise finding as it is a common belief that constructability input provided by a CMR agent in design phase can have a positive impact on safety performance. To understand the underlying reasons for such a difference, one needs to conduct follow up interviews with project personnel. Conducting post hoc analysis for the time of builder involvement showed marginally significant difference between the safety performances of projects that the builder involved in design development phase versus projects that the builder involved in bidding phase (p-value=0.096). Because the number of projects in which the builders were involved in design development phase was only five and the results of Wilcox-Mann-Whitney test was marginally significant, the research team believes that the time of builder involvement should not be considered as a significant factor.

Although previous studies indicated that BIM can help to improve safety performance, the results of the study show that projects that did not use BIM had better safety performance. There are several other confounding factors that might have contributed to this finding. Empirical evidence provided in this study encourages further analysis to objectively measure impact of using various BIM functions on safety performance. Previous studies also claimed that using lean tools has a positive impact on safety performance; however, the findings of the current study imply that projects that used lean scheduling tools had more accident per square foot of a building (2.078) than projects that did not use any lean tools.
Further analysis of database revealed that projects that use lean tools, on average, had larger square foot area (335,431 SF) than the ones that did not use lean tools (151,457 SF). As discussed earlier, square foot area of a building plays a significant role in determining number of accidents.

The results of the study indicated that co-location of MEP and structural subcontractors have a significant impact on safety performance of projects; however, the post hoc analysis did not show any significant difference. The statistical analysis of results also could not find any significant relationship between safety performance and following independent variables: time of involvement of MEP and structural subcontractors; using partnering; builder participated in co-location; builder participated in goal setting; and using prefabrication in a project.

5 CONCLUSION

This study assessed the factors contributing to safety performance by looking at project integration measures. The safety performance was defined as the recordable incidents per square foot of a building and several independent variables were considered related to project organization, team integration, and using emerging processes and technologies. The study has practical implications for both academia and practice. The large database of 204 building projects created in this study can be used to answer numerous questions defined by academia and the results of the study can also provide empirical evidence for both owners and contractors to understand the impact of their early decisions regarding project integration on safety performance.

While this study is unique in its kind and provides significant contributions to the body of knowledge, there are several limitations that need to be addressed in future studies. First, one of the limitations of the current study is to use lagging indicators (e.g., number of accidents) as safety performance metrics. One should note that recordable and lost time work incidents are rare events in projects and do not capture unsafe behaviors that do not lead to an incident. Further studies should be conducted to explore the impact of project delivery decisions on leading indicators such as near-misses. Second, we could not collect the number of worker-hours in projects, which inhibited us from calculating some of the standard safety measures such as total recordable incidence rate (TRIR) and days away, restricted or transferred (DART). Future studies should be conducted to address this limitation. Third, most of the independent variables in this study were simplified so we could measure them using a Likert scale. For example, complexity has several definitions in the construction industry and future studies should be conducted to investigate the relationship between complexity in design and construction activities and safety performance. Finally, as safety performance depends on people, more qualitative studies should be conducted to understand the drivers of unsafe behavior in worksites. Nevertheless, the research reported in this paper is a pioneer study in establishing the relationship between safety performance and independent variables that define integrated projects.

Acknowledgements

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References


A STRATEGIC SAFETY-RISK MANAGEMENT PLAN FOR RECOVERY AFTER DISASTER OPERATIONS

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2 Civil Engineering Department, University of Nebraska–Lincoln
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Abstract: One of the early activities in any post-disaster management plan is to remove debris, clean the area, and reconstruct the damaged properties. However, a major focus of workers involved in cleaning operations after a disaster are concerned about construction safety because there are several unknown hazards that differ from hazards in a typical construction project. The risk can be compounded by the fact that construction activities after a disaster are usually conducted by small companies or even property owners with limited knowledge of safety. Therefore, the objective of this study was to develop a safety-risk management plan for recovery after disasters. The objective was achieved in two distinct phases. The first phase of the study focused on risk identification. An extensive literature review was conducted to identify hazards in post-disasters operations. The primary list of hazards was identified and classified into seven major groups: (1) physical; (2) chemical; (3) biological; (4) weather and temperature; (5) ergonomic (6) psychological; and (7) other (e.g., natural hazards and noise). During the second phase of the study, risk assessment was conducted to quantify the safety risk of the hazards identified in the previous phase. Fourteen safety professionals with an average 18 years of experience participated in the risk assessment. It was found that being caught-in/between a trench, getting electrocuted while using cranes or boomed vehicles near energized power lines, and getting electrocuted while using conductive tools, ladders, or scaffolds near energized power line are the hazards that cause the most severe injuries. Concurrently, working in cold or windy weather is the most frequent and risky hazard in post-disaster recovery operations. A risk matrix was developed for post-disaster operations by determining the likelihood and consequence of potential accidents using a 5-point Likert scale. It is expected that the results of this study will transform the current safety practices in post disaster recovery operations by providing an easy-to-use safety-risk management tool.

1 INTRODUCTION

On average, natural and man-made disasters cause approximately $24 USD billion worth of damage and affect the lives of 60 million people around the world (United Nations Human Settlements Programs, 2001). In the United States alone (1980-1999), thirteen hurricanes caused $68 billion in damages and more than 400 deaths (National Oceanic and Atmospheric Administration, 2000). Recently, in January 2010, the Haiti earthquake ruined around 250,000 houses (Arumala, 2012). To cope with such a huge loss, a large number of studies have been conducted to develop emergency response plans (Perry and Lindell, 2003; Sheu, 2007), revise land-use regulations (Burby and Dalton, 1994), improve building retrofitting programs (Erdik and Durukal, 2008; Rey, 2004), or design more effective early warning systems (Hooke, 2000; Zschau and Küppers, 2003).
Natural disasters, such as hurricanes and floods, cause severe damage and demand infrastructural recovery, operations that typically involve construction workers. The number of workers who are involved in post-disaster recovery and reconstruction depends on the scale of the catastrophe; however, this number can reach up to 18,000 workers (Rotimi et al., 2006). Workers involved in cleaning and reconstruction operations after a disaster face greater danger than traditional workers because they are exposed to chemical-biological materials, contaminated floodwater, downed energized power lines, confined space entry, potential structural collapse, or other high-risk situations. For this reason, careful attention should be paid to identifying and assessing potential safety risks for these workers. Unfortunately, there are currently a limited number of studies that investigate the potential hazards for workers involved in post-disaster operations.

To address this limitation in the body of knowledge, the overarching goal of the broader project is to enhance the safety of workers in post-disaster recovery and reconstruction operations. Within this large-scale project, our objectives are to: (1) identify common hazards in post-disaster recovery and reconstruction operations; and (2) quantify the safety risk of common hazards in post-disaster recovery and reconstruction. The results of the study will help practitioners to create more effective training programs for workers involved in post-disaster recovery operations.

## 2 LITERATURE REVIEW

In one of the seminal studies, Esworthy et al. (2005) published a report through the Congressional Research Service (CRS) Reports about the environmental considerations for cleanup activities after hurricane Katrina. This report includes a comprehensive review of activities that were carried out during the cleanup process. These activities included—but were not limited to—debris assessment and management, oil and other hazardous materials’ evaluation; the evaluation of previous contaminated sites; dewatering; cleaning up water; recycling, reusing or disposing of the debris; and monitoring. This report provides a unique insight into the difference between the common hazards in ordinary construction projects and cleanup response in recovery after a disaster.

According to Esworthy et al. (2005), one of the major differences between a post-disaster recovery operations and ordinary construction projects is that a natural or man-made disaster can cause large amount of debris. For example, the amount of debris created by Hurricane Katrina was estimated at 55 million cubic yards (Esworthy et al., 2005). The debris consisted of construction materials, damaged or destroyed building fragments, sediments, green waste (trees, limbs, leaves, and shrubs), white goods (utensils), asphalt, oil, chemicals, and other substances. To conduct an efficient debris management program, one needs to accumulate all debris and separate the hazardous materials from other substances. During these operations, construction workers are exposed to hazardous materials, such as pesticides, drain cleaners, cleaning supplies, paint, asbestos, and surfaces coated in lead-based paint.

Another early recovery after disaster activity is to remove the trapped water. For example, after Hurricane Katrina, 114 million gallons water had to be pumped out from the city of New Orleans (Esworthy et al., 2005). The difficulties of such an operation can be compounded by the fact that the water was contaminated with animal and human sewage, decaying bodies, oil, gas, and other chemicals. If water contains bacteria and poisonous metals (e.g., arsenic), then the area can be exposed to epidemic and contagious diseases. Even after draining the water, some pollutants can remain in the sediments, and the mixed water evaporation or the released chemical substances can affect the air quality of the disaster area. In addition, in such an unfavorable situation, the presence of rodents, insects, and the growth of fungi and molds (e.g., humid conditions) can also contaminate the area.

In another study, Reissman et al. (2008) studied emergency responders’ safety and health after a disaster by focusing on the situation of people involved in the September 11th World Trade Center disaster. The authors analyzed the emergency responders’ time of arrival and the duration of exposure to dust. The authors found that due to the combustion, people in the area inhaled a lot of toxic fumes, and many people got injured by rubble when the buildings collapsed. It was concluded that disaster
preparation activities should provide training regarding hazard identification, quick and effective scene control, personal tracking, and safety enforcement.

According to the literature, another common hazard in recovery after a disaster includes psychological disorders. These kinds of hazards are different from the ones in ordinary construction activities. In one of the studies, Kowalski et al. (2001) conducted research to enhance occupational health and safety of workers involved in emergency response. The authors found that work related stress can increase risk of injuries or psychological disorders. Various kind of stress, such as physical (bio-organic) and emotional (psycho-social) can cause fatigue, emotional withdrawal, and depersonalization. The authors stated that by obtaining knowledge of social science, safety managers might decrease the risk of work stress among workers. In another study, Reissman et al. (2008) found that disasters can increase the chance of psychological disease such as depression, panic disorder, and anxiety among workers. Working in high-stress environments in conjunction with viewing distressing scenes—i.e., those that include injuries and dead bodies—are factors for stress and other adverse psychological impacts (Benedek et al., 2007). Thus, to protect workers, this type of hazards should be taken into consideration as well.

Some researchers stated that assessment of a situation after a disaster using various data collection techniques can be helpful for reducing the risk of injuries. For example, to help first responders and civil engineers, Peña-Mora et al. (2012) developed a mobile workstation chariot (MWC) to conduct damage evaluation and hazard identification after a disaster. The workstation has a platform that provides mobility for people engaged in a disaster response and helps them collect, analyze, and distribute information to facilitate decision making. In another study, Gong (2013) suggested the use of mobile LiDAR to collect and analyze data for post-disaster recovery operations. The authors used this technique after Hurricane Sandy in the east coast and found that mobile LiDAR can outperform airborne remote sensing and typical ground survey data collection. While these innovative approaches can be used to enhance the situational awareness of workers involved in recovery after disaster operations, the current adoption rate of these innovations in actual construction operations is minimal. Therefore, there is a need to develop a practical way to identify hazards and assess their risk in post-disaster construction activities.

3 RESEARCH METHODS

The objective of the study was achieved by conducting two distinct tasks: (a) cataloging the common hazards in recovery after disaster operations; and (b) assessing the risks of the identified hazards. Prior to risk assessment, it was necessary to create a list of potential hazards in recovery after disasters for construction workers. Therefore, the first activity involved conducting a literature review to identify hazardous scenarios that lead to injuries in post-disaster recovery. Search engines such as the American Society of Civil Engineering (ASCE), Google Scholar, and Science Direct were used to find articles on these scenarios. A large number of studies have been conducted on post-disaster operations; however, studies on the safety risk of workers are limited. Therefore, to provide a comprehensive list of hazards, we also searched national databases such as those for the Occupational Safety and Health Administration (OSHA), Federal Emergency Management Agency (FEMA), and National Institute for Occupational Safety and Health (Niosh). These activities led to a list of common hazardous scenarios in post-disaster recovery and reconstruction operations.

The second activity served to quantify the safety risks associated with the common hazards identified in the previous task. We followed the traditional paradigm in risk quantification used in previous studies (Brauer, 1994; Hallowell et al., 2011; and Esmaeili and Hallowell, 2013) to obtain ratings of frequency and severity from industry experts. Since there is not enough archival data to make statistically significant inferences (Shapira and Lyachin, 2009; Rozenfeld et al., 2010) and since empirical data cannot be obtained in a realistic timeframe, to accomplish this activity, subjective risk-assessment techniques were employed. Accordingly, to quantify the safety risk of common hazards in post-disaster recovery and reconstruction projects, experts were asked to provide frequencies and severity of injury for each hazardous situation using five-point Likert scale. In this non-comparative scale, respondents were supposed to select a numeral value describes frequency and severity of each hazardous situation (Allen and Seaman, 2007; Jamieson, 2004).
To collect data, the questionnaire was distributed among safety professionals in the Midwest. Local contractors located in Lincoln and Omaha (Nebraska) were the main point of contacts. Other organizations such as the Nebraska Department of Roads (NDOR), the Midwest chapters of the Associated Builders and Contractors (ABC) and the Associated General Contractors of America (AGC) were also contacted. A copy of the questionnaire was sent to the safety managers of these organizations and encouraged them to distribute the questionnaire among people who might be able to fill it out. The research team also used their personal contacts with safety professionals to further increase the number of participants.

4 RESULTS AND ANALYSIS

As mentioned earlier, the first objective of the study was to identify common hazards in post-disaster recovery and reconstruction operations. This objective was achieved by conducting a comprehensive literature review on the current body of knowledge. In total, 45 hazards were identified and categorized into seven major groups (Table 1): (1) physical; (2) chemical; (3) biological; (4) weather and temperature; (5) ergonomic; (6) psychological; and (7) other (e.g., natural hazards and noise). The second phase of the study involved assessing safety risks associated with post-disaster recovery hazards. To accomplish this objective, we contacted 87 professionals and in total, 14 safety professionals returned the filled-out questionnaire. The people who returned the questionnaire were very well-qualified and had an average of 18 years of safety experience. Participants were mainly from the Midwest: 12 from the State of Nebraska, one from the state of Iowa, and one from the State of Illinois. The frequency and severity values for each hazard were independently quantified on a Likert scale and the results are shown in Table 1. To measure the internal reliability of data collected, Cronbach alpha was calculated for the frequency (0.984) and severity (0.992) scores reported in Table 1 that indicate excellent internal reliability.

Table 1: Median of frequency, severity, and risk factors obtained from safety managers

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median) *</th>
<th>Severity (Median) **</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Falling from a ladder</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>2 Falling from an unprotected edge, opening, or skylight</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3 Falling from a scaffold</td>
<td>2</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>4 Falling from a structural frame (tower, steel frame, ...)</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>5 Falling from an aerial platform</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>6 Struck-by a boomed vehicle</td>
<td>1</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>7 Struck-by construction equipment</td>
<td>1.5</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>8 Struck-by nail gun</td>
<td>1</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>9 Struck-by personal vehicle</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>10 Struck-by flying debris/objects</td>
<td>2.5</td>
<td>3</td>
<td>7.5</td>
</tr>
<tr>
<td>11 Struck-by falling objects</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>12 Caught-in/between a trench</td>
<td>1</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>13 Electrocuted while using cranes or boomed vehicles near energized power line</td>
<td>1</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>14 Electrocuted while using conductive materials, ladder, or scaffold, near energized power line</td>
<td>1</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>15 Electrocuted while working on/near live wiring or energized circuit</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>16 Electrocuted while working with electrical device, tool</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>17 Electrocuted after contact with underground, buried power lines</td>
<td>1.5</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median)</th>
<th>Severity (Median)</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Entering a confined place that has the probability of toxic gas emission</td>
<td>1</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>19 Touching paints and plastics materials that can cause Asthma</td>
<td>1.5</td>
<td>3</td>
<td>4.5</td>
</tr>
<tr>
<td>20 Demolition, plumbing, or painting that exposes workers to lead</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>21 Exposure to metal materials coating and metal clearing</td>
<td>1.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>22 Exposure to rust-preventing on steel</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>23 Inhaling fumes during welding and cutting (galvanized metal, alloy, and brass)</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>24 Demolition, dry wall installation, enhancing fire-proofing, and insulation activities that expose workers to asbestos</td>
<td>1</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>25 Stone dressing, masons quarry, and stone cutting</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>26 Inhaling cement particles while making concrete, which can cause lung cancer, chest pain, and difficulty in breathing</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>27 Working with MDF in demolition and sawing, which can cause coughing, wheezing, or stomach pain</td>
<td>1.5</td>
<td>2.5</td>
<td>3.75</td>
</tr>
</tbody>
</table>

**Biological**

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median)</th>
<th>Severity (Median)</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Exposure to fungi, mildews, yeasts, and mold</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>29 Encountering corpses of people and animals during rescue operations</td>
<td>2</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>30 Touching poisonous plants or inhaling the fumes that result from burning such poisonous plants</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>31 Exposure to disease, such as Hepatitis, Tuberculosis, Tetanus, Legionella and Rabies</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>32 Exposed to sludge and debris</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

**Weather**

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median)</th>
<th>Severity (Median)</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33 Working in a hot and humid outdoor condition for a long time</td>
<td>4</td>
<td>3.5</td>
<td>14</td>
</tr>
<tr>
<td>34 Working in a hot indoor room without suitable ventilation</td>
<td>2</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>35 Working in cold or windy weather</td>
<td>4.5</td>
<td>4</td>
<td>18</td>
</tr>
</tbody>
</table>

**Ergonomic**

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median)</th>
<th>Severity (Median)</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 Lifting heavy weight in adverse positions</td>
<td>3</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>37 Using excessive force (over-exertion)</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>38 Using unsuitable devises for a specific job</td>
<td>2</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>39 Gripping a part of the body during the task</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>40 Performing an activity frequently</td>
<td>4</td>
<td>3</td>
<td>12</td>
</tr>
</tbody>
</table>

**Psychological**

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median)</th>
<th>Severity (Median)</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41 Substantial distress responses (e.g., sleep disturbance, fear, and worry-altered connections)</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>42 Mental health and illness (e.g., post-traumatic stress disorder (PTSD), acute stress disorder (ASD), and depression)</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>43 Behavioral changes in high-stress environment (e.g., smoking, evacuation, alcohol, and over-dedication)</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

**Other**

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Frequency (Median)</th>
<th>Severity (Median)</th>
<th>Risk (S×F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 Encountering natural hazards (exposure to snakes, wasps &amp; bees, spiders, scorpions, and mosquitoes)</td>
<td>3.5</td>
<td>3</td>
<td>10.5</td>
</tr>
<tr>
<td>45 Exposure to disturbing noises</td>
<td>3.5</td>
<td>3</td>
<td>10.5</td>
</tr>
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4.1 Physical Hazards

Physical hazards include falls, struck-by, caught in/between, and electrocution hazards. These hazards are usually referred to as “the big four” because they are responsible for almost 60% of all injuries in the construction industry (OSHA Training Institute, 2011). In total, 17 different physical hazards were identified and included in the survey (Table 1). One of the interesting findings of the study is that, based on the safety managers’ judgment, in recovery after disasters operations physical hazards do not occur as frequent as ordinary construction activities. The highest frequency belongs to the “struck-by flying debris/objects.” On the other hand, physical risk have some of the most sever hazards.

According to the ratings provided by experts, struck-by flying objects is considered to be the most critical hazard in this category. Both the severity and frequency of this hazard were rated as 3. In addition, falling from structural frames, electrocution after contact with underground power lines, and struck-by personal vehicle were placed as the second and third most risky hazards. Furthermore, caught in/between a trench and electrocution from various sources were highlighted to have the worst consequences.

4.2 Chemical

Hazardous chemical substances are one of the potential safety risks that construction workers face when involved in debris-removal after a disaster. Although, we expected to see chemical materials as a frequent hazard in recovery after disaster operations, the experts who participated in the study rated this hazard with frequency ratings of one or two (Table 1). Inhaling welding fumes is found to be the most perilous hazard in this category and the highest severity belongs to entering confined places. Wearing suitable respiratory protection, work and rubber gloves, steel toe boots, outer clothing, and other PPE are the most common suggested approaches that can reduce the severity of chemical hazards (Grosskopf, 2010; OSHA 29 CFR, 1926; Health Hazards Workbook, 2012).

4.3 Biological

During rescue operations, unwatering, and cleaning up debris activities, workers are prone to various biological hazards. Allergies, dermatitis, asthma, and lung disease are the most common outcomes of exposure to biological hazards (Esworthy, 2006; Grosskopf, 2010). The results of the survey indicated that the range of risks for most biological hazards is between 4 and 6, and the safety managers do not consider them as fatal risks during recovery operations. Wearing protective clothing, respiratory devices, and proper gloves in conjunction with immunization (vaccination), carrying both insect repellant and first aid devices are the most recommended mitigation plans against this type of hazard (Grosskopf, 2010; Health Hazards Workbook, 2012).

4.4 Weather

Working under extreme weather conditions can be hazardous for the workers. For example, if workers are exposed to extreme sun, their skin might suffer from sunburn. In extreme conditions, exposure to sun can even cause skin cancer (melanoma). Experts identify this type of hazard to be the most frequent and severe hazard of all the selected conditions (Table 1). Temperature and weather effects are some of the most risky hazards identified in this study. Working for a prolonged time in adverse weather might cause problems such as frostbite, hypothermia, heat cramps, heat exhaustion, heat rashes, and heat stroke for the workers (Health Hazards Workbook, 2012). Some mitigation strategies are suggested below.

When the weather is extremely hot, several actions should be taken to protect workers: workers should eat small portions; they should not drink caffeinates beverages or alcohol; cool liquids should be provided for workers; frequent breaks should be allowed; and workers should be encouraged to wear cotton and proper clothes (Health Hazards Workbook, 2012). Working in an extreme cold weather (below - 32°C) can also be hazardous for workers. This condition can be exacerbated when the weather is wet and windy (Health Hazards Workbook, 2012). Wearing proper clothing and carrying relevant PPE are proper actions against cold weather. In addition, workers should put on dry clothes, drink a lot of warm beverages, take a break at regular intervals, and report any weird symptoms to the supervisor (Centers for Disease Control and Prevention, 2015).
4.5 Ergonomic hazards

Ergonomic hazards are defined as the possible incidents that might happen due to a poor relationship between work features and the mental and physical abilities of the employees (Faridah et al., 2008). Some of the most common ergonomic hazards are strains and sprains, fatigue, carpal tunnel syndrome (vibration), low back pain, and tendonitis (OSHA Publication 3125, 2000). Both the risk and consequence of performing an activity frequently (fatigue) is at the top of the ergonomic category (Table 1). The results of the study indicate that fatigue plays a significant role in potential injuries after a disaster. Removing debris from an exposed area requires extensive material handling and physical activity. Following measures can help the workers to reduce the ergonomic hazards (Ramsey et al., 2014): reducing the distance between the load and the body; avoiding excessive twisting; traversing with the load for fewer than 10 feet or using a conveyer; using proper personal protective equipment; having enough training (e.g., lifting techniques); taking breaks; wearing robust resistance gloves; and using pneumatic and power tools.

4.6 Psychological

The construction workers are one of the first people who will arrive in an area that has been hit by a disaster and will be exposed to numerous psychological hazards. Working in high-stress environments, such as recovery after disasters, can lead to post-traumatic stress disorder (PTSD) among workers. The symptoms of PTSD can be initiated by observing unpleasant experiences, such as seeing others’ injuries, suffering personal injuries, losing loved ones, or encountering dead bodies. Headaches, loss of asleep, nervousness, and nightmares are some the symptoms of people impacted by PTSD (Benedek et al., 2007).

The results of the survey demonstrated that psychological hazards threat workers approximately as often as chemical and biological hazards in post-disaster recovery and reconstruction (Table 1). Thus, these hazards should be taken more seriously. The risks of post-traumatic stress disorder, behavioral changes, and substantial distress in a recovery after a disaster operation have been designated as a 6 for all. Previous studies stated that improving social science can mitigate the consequences of psychological disorders (Benedek et al., 2007). To control for psychological hazards, periodic medical treatment, counselling service, training programs (e.g., relaxation, medication and biofeedback), and providing recreation activates can be helpful (World Health Organization, 2001).

4.7 Other hazards

Noise and natural hazards were viewed as moderate risks (Table 1). Every year many construction workers suffer from noise in construction sites. Due to the chaos conditions in post disaster environments, workers might suffer from noise hazards as well. Therefore, using hearing protection devices, performing supervisor’s controls in conjunction with restricting workers’ proximity to the damaging noise hazards areas can be enumerated as the most effective approaches used to reduce noise hazards (Health Hazards Workbook, 2012; Bergström and Strom, 1986; Franks et al., 1996).

After a disaster, due to the moist conditions, deficient hygiene, and prevalence of animal corpses; a large number of rodents might surge into exposed areas. Increasing rables aside, the presence of rodents make their hunters (snakes, scorpions, and spiders) follow them into the regions. Therefore, a careful attention should be paid to natural hazards. Finally, wearing proper pants, boots, gloves, and outer clothing will help workers to keep themselves safe during operations (Health Hazards Workbook, 2012).

To provide a visual representation, the findings are summarized in a risk matrix (Figure 1). As it is clear that weather-related hazards are the most critical safety risk-factors in post-disaster recovery operations. Several mitigation practices are suggested in this paper to help practitioners reduce the risk of injuries for workers involved in recovery after disaster operations.
5 CONCLUSION

After a disaster, workers who are involved in recovery and maintenance activities are exposed to a large number of hazards that are not similar to hazards related to typical construction activities (Faridah et al., 2008). Protecting workers from hazards during recovery after disasters is gaining attention in both academia and practice (Esmaeili et al., 2014). To address this emergent need, this study sought to identify common hazards in post-disaster recovery operations and to assess their safety risk in terms of frequency and severity. Practitioners can use findings of the study to identify high risk situations in post-disasters recovery operations and implement mitigation plans to reduce potential of injuries.

In future stages of this research project, we aim to develop a safety guideline for workers involved in recovery after disaster operations. The guideline will summarize best mitigation practices for dealing with safety risks in construction operations after a disaster. Furthermore, to disseminate the results of the study and reach a larger audience, a mobile application will be developed. Nevertheless, the findings reported in this paper will advance the subsequent tasks of our overall project in the years to come.

There are some limitations related to this research that need to be addressed in future studies. First, the frequency and severity rating were obtained from safety managers mainly located in Nebraska. This situation will limit the external validity of the study. Future studies should be conducted to collect data from larger and more diverse groups of experts. Second, assessing the frequency and severity of hazards using a Likert scale does not provide an accurate estimate of actual risk in sites. Further studies should be conducted to measure the safety risk of identified hazards more accurately. Despite these limitations, the study provides a significant contribution to the practice by helping safety managers to identify and strategically manage safety risks in post-disaster recovery operations.

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COMMUNICATION ISSUES IN DESIGN-BUILD PROJECT DELIVERY METHOD

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² daniel.tran@ku.edu

Abstract: Design-Build (D-B) is a project delivery method in which the owner procures both design and construction services in the same contract from a single legal entity referred to as the design-builder. Having both design and construction in the hands of one contractual entity allows for a single point of responsibility and, in turn, provides improved project performance. There is a limited study on how communication among all parties involved influences the success of D-B projects. This paper investigates the modern-day communication issues that affect the D-B delivery method. A questionnaire was developed to collect data from professionals across the nation with an average of 22 years of experience related to D-B in commercial construction projects. The authors conducted five structured interviews to verify and validate the results from the survey questionnaire. The findings of this study indicate that the primary communication issues that have an effect on D-B are: (1) establishing the clear points of contact throughout the D-B communication process, (2) providing clear and understandable information among stakeholders during the D-B process and (3) the timely sharing of information to all stakeholders. It is recommended that further improvement strategies be implemented which include coordinating, clarifying, documenting and decision-making in order to better achieve project success. Understanding these communication issues will help professionals not only mitigate risk and uncertainty, but also enhance the likelihood of the success in D-B contracts.

1 INTRODUCTION

The design-build (D-B) project delivery method continues to grow as a viable delivery method in the construction industry. The Design-Build Institute of America (DBIA) reported that more than half of projects above $10 million are being completed using D-B project delivery (DBIA 2014). D-B has been used throughout the world for approximately 40 years (Lam et al. 2008) and its popularity has increased substantially over the last two decades.

A number of studies have investigated several topics related to D-B project delivery method in both building and transportation sectors. For example, studies have documented topics such as D-B performance (Konchar and Sanvido 1998), D-B evolution (Molenaar et al. 1999), D-B success factors (Chan et al. 2010), design-builder selection issues (Palaneeswaran and Kumaraswamy 2000), and impact of risk on D-B selection (Tran and Molenaar 2014) to name only a few. However, there is a limited study that focuses on the influence of communication issues on the D-B process. The objective of this study is to investigate the modern-day communication issues that affect the D-B delivery method in the building sector. This study defines communication in the D-B process as a two-way process of reaching mutual understanding in which participants impart or exchange information and ideas.
2 LITERATURE REVIEW

D-B is a project delivery method in which the owner contracts with a single entity to perform both design and construction. The single entity may be represented by a D-B firm with in-house design and construction teams or a joint-venture designer and contractor. Contractually, D-B offers the owners a single point of responsibility for design and construction service such as an overall project planning and scheduling (Konchar and Sanvido 1998).

The literature shows that D-B delivery method can bring about many benefits to a project. For example, in the building sector, the Construction Industry Institute (CII) has supported several studies that compare project delivery performance. Konchar and Sanvido (1998) defined a set of criteria for a performance comparison of different delivery methods, including D-B, a traditional design-bid-build (D-B-B), and Construction manager at Risk (CMR). They used a survey to collect post-project performance data from owners and contractors on 351 completed projects. The sample data consisted of a variety of project types and sizes (i.e., six different project types, project size varying from 500 to 200,000 m2). This study concluded that D-B performs better than D-B-B in terms of cost and schedule, and D-B performs better than both CMR and D-B-B in terms of quality. Another CII related study was conducted by Ibbs et al. (2003). This study compared cost growth, schedule growth and productivity between D-B and D-B-B based on 67 global projects from the CII database. The study concluded that D-B outperformed D-B-B in terms of schedule. However, D-B did not perform better than D-B-B in terms of cost growth and productivity in this sample.

Researchers showed that many factors impact the success of D-B projects. Chang et al. (2010) identified six project success factors for D-B delivery method, including project team commitment, contractor’s competencies, risk and liability assessment, client’s competencies, end-users’ needs, and constraints imposed by end-users. Lam et al. (2008) indicated that a clearly defined scope is vital for the success of a D-B project. Under D-B project delivery, the amount of information and the level of detail also play an important role in D-B contracts. Xia et al. (2012) showed that a sufficient amount of owner-provided design information should be provided in order to describe the owner’s requirements without compromising the potential for innovation.

The understanding and interpretation of the owners’ requirements along with communication between owners and design-builders was essential to the success of D-B projects. Adnan et al. (2012) pointed out that it is the responsibility of the design-builder team to provide care and attention to understanding the owners’ requirements. In addition, researchers claimed that communication is sometimes a problem in D-B contract due to the lack of contractual relationship between the owner and designers. Owners and design-builders need to have a proper and comprehensive checking and communication system to ensure the design is coordinated and construction complies with the design documents (Ling and Poh, 2008). One of the problems in D-B contract involved coordination issues arising from design and construction concurrence. Chang et al. (2010) concluded that further investigation into the coordination and communication issues resulting from the concurrence of design and construction is recommended.

A review of the literature indicated that although a number of studies have investigated the benefits of D-B projects, the overall D-B process, and D-B success factors, limited studies have explored the impact of communication on the D-B process. To fill this knowledge gap, this paper investigates the modern-day communication among all project participants involved corresponding to each of the typical phases in D-B delivery method.

3 RESEARCH METHODOLOGY

This study employed a survey questionnaire and interview methodology to examine the impact of communication on major phases of D-B projects. An online questionnaire survey was developed and distributed to 282 members of the DBIA Mid America region. The web-based software allowed for an anonymous link to be used and sent to potential participants. The use of this anonymous link was a requirement of the DBIA, because it allowed the responses of the participants to remain confidential.
participants were divided into five different groups based on their roles in the D-B delivery method and the type of services their organization provided:

- **Owner Agency**: A private or public organization that advertises awards and supervises the design and construction of the project.
- **General Contractor**: The general construction contractor who physically completes the construction with its own forces and/or who holds the construction subcontracts.
- **Design-Build Firm**: An organization that has the internal capability to complete both the design and construction of a project.
- **Engineering/Design Firm**: An organization that completes the design portion of the D-B project prior to and during construction. This includes both architects and engineers.
- **Other**: This group includes specialty firms, consultants and educators that have experience with D-B.

The survey questionnaire included thirty-one questions that were either multiple choice or open-ended questions. The questionnaire consisted of three parts. In the first part, the participants were asked to read a series of definitions related to communication and the D-B delivery method. These definitions were necessary to establish uniformity in the participant’s interpretations and to avoid misunderstandings. The second part of the survey consisted of collecting the participant’s background information. The respondents were asked to describe which type of group or organization they worked for. They were also asked to provide their job title and their years of experience in the building industry. Finally, respondents were asked to provide their email information if they were willing to be available for additional follow-up questions. The third part involved D-B communication issues, which was divided into six different sections corresponding to the key phases in the D-B process as follows:

1. Request for Qualifications (RFQ)/Qualifications Statements;
2. Request for Proposal (RFP);
3. Design-Builder Evaluation and Selection;
4. Design Development Phase; and
5. Construction Phase.

In addition to the survey questions, the authors conducted five structured interviews to verify and supplement the findings from the survey. These five interviews, including three with owners and two with design-builder firms were selected based on the responses from the survey questionnaire and their relevant D-B experience. During these interviews, the authors focused on the collection of empirical data by asking project-based questions.

### 4 RESULTS AND ANALYSIS

Out of the 282 professionals invited for the survey questionnaire, the authors received 59 completed questions. The response rate is 21%. On average, the respondents have more than 23 years of relevant experience. Figure 1 shows the percentage of survey responses associated with the different aforementioned groups. Figure 2 shows the participant experience on D-B project delivery method. The following sections briefly present communication issues associated with the five key phases in the D-B process resulted from the survey and interviews.
4.1 Request for Qualification and Qualification Statements

The owner's requirements for offerors are defined and articulated in a RFQ either by in-house staff or by outside consultants (Beard et al. 2001). After the project is advertised and the RFQ has been issued, the potential design-builder teams submit their qualification statements. The qualification statement is a description of the design-build team's composition and organization. To examine the communication issues regarding this phase, the questionnaire asked participants regarding what types of communication and clarification factors can affect their decision to pursue a D-B project. The survey results indicated that the content and presentation of RFQ is essential for D-B projects. Specifically, 38 out of 40 respondents (95%) agreed that the presentation of RFQ affected their decision to pursue the project. It is noted that 14 owner participants did not respond to this question. The completeness of RFQ documentation and how it is written to request the right information was a critical factor for design-build firms to submit their quantification statements. In addition, a number of respondents indicated that the
willingness of an owner to meet and discuss the project has a significant impact on their decision to pursue the project. Overall, almost all respondents indicated that they would like to receive more clear and understandable information, timely responses to their questions, and discuss the project with the owner or owner's representative directly. The results from the structured interview confirmed this finding. One of the interviewees, who works for a General Contractor firm, stated that "sometimes the owner doesn't provide any information on the project itself that significantly hinders their decision on submitting the qualification statement."

The owner participants were asked what types of communication and clarification factors influence their decision to select or "short-list" a design-builder for a project. Out of 14 owner participants, nine (64%) stated that clarity, readability and technical approach of the qualifications statement was the primary selection factors. The owner representative in the interview process confirmed that "they selected the shortlisted design-builder based on their ability and clarity in their statements of qualification that demonstrate the understanding of a given D-B project requirement."

### 4.2 Request for Proposal

Design and cost proposals are solicited from the shortlisted design-builders in an RFP. Among the items found in a typical RFP are project design criteria, program requirements, performance specifications, site information, contract requirements, selection procedures, and proposal requirements or deliverables. The survey questions were developed to investigate the impact of communication between the owner and proposer on the D-B solicitation process.

Almost all respondents (81%) agreed that developing a clear, comprehensive and well-defined RFP is a critical success factor for D-B projects. However, six respondents (10%) slightly disagreed and five respondents (8%) disagreed that they received RFPs that clearly and comprehensively describe and the owner's needs and requirements. The survey results also indicated that it is important to enhance communication between the owner and proposers during the solicitation process. In addition, the participants were asked how communication and coordination issues can be improved during the solicitation process. The main responses (66%) involved documenting questions and answers/clarifications and provided them in a timely manner. One contractor in the interview stated that understanding the selection criteria and how the project would be awarded was the essential for his firm to compete for the project. This participant also emphasized that his firm sometimes received RFPs that were not clear in the scope and they need to make assumptions and interpretations. His concern is that each proposer may interpret the RFP differently and the final comparisons would not be fair and transparent. Another contractor in the interview pointed out that "the timeliness of responses, lack of response, clarity of the responses and the time allowed for asking and answering questions were their primary concerns" during the solicitation process. Another interviewee, who works for a public owner, believed that there is some confusion regarding the final decision makers among the owner's representatives. He stated that sometimes this causes issues because the design-builder does not know who to speak with or get decisions from.

### 4.3 Design-Builder Evaluation and Selection

Once received, proposals are evaluated on the basis of quantity, quality, functional efficiency, aesthetics, price and other factors (Beard et al., 2001). Compared to Design-Bid-Build (D-B-B) projects, it is more difficult to evaluate D-B tenders because of the need to evaluate both price and design (Ling and Poh, 2008). Effective communication is an integral part of the D-B evaluation and selection process.

Out of 59 respondents, 51 (86%) agreed that a well-established evaluation system along with a guideline for how to use it would be critical for selecting a design-builder. However, eight respondents slightly disagreed that they always received the guidelines for the evaluation process. The participants were also asked whether or not the level of communication between the owner and the proposer during the selection process was insufficient in need of improvement. Twenty eight respondents (47%) believed that the level of communication in their projects were sufficient while 31 respondents (53%) indicated that the level of communication between the owner and proposers need to improve. These 31 respondents suggested several approaches to improve communication between all parties involved in the selection process.
The main theme involves increasing the number of meetings to resolve confusion, especially face-to-face meetings, and specifying the right point of contact during the selection process. With the prolific use of online communication, many respondents would like more face-to-face meetings during the selection process as they believe this would help with communication during the process.

In the structured interview, a participant from a design-build firm stated that “email is a distribution device and not a communication device and the face-to-face meetings are very important in the design-builder evaluation and selection process.” This interview also mentioned that all project information needs to be clear and in writing, especially meeting minutes. Documenting and understanding which information is available to share during the evaluation process is very important. The interviewee stated that “many of the design-builders and general contractors felt that during the evaluation process, there should be clear instructions on what will or will not be shared with competitors.”

4.4 Design Development Phase

After a design-builder is awarded the contract, a notice to proceed with the design work is issued by the owner. In accordance with the design-builder’s proposal and the owner’s comments, the team proceeds to develop more detailed architectural and engineering documents, often in close coordination with representatives of the owner and local building code officials (Beard et al. 2001). Communication is sometimes a problem because once the D-B contract is awarded, owners may be out of the loop if all design and construction decisions and tradeoffs are internal to the design-build team and do not involve the owners (Ling and Poh 2008).

In this phase, the participants were asked to explain the impact of communication on solving conflicts in design between the owner and design-builder. The survey results indicated that 25 respondents (42%) agreed that there was insufficient communication between the design-builder and owner to solve design issues occurred during the design development phase. The common theme of these responses is that the majority of projects only have one meeting between the owner and design-builder during design. This finding is consistent with the literature. The researchers showed that there is insufficient communication between the owner and the design-builder team because of the absence of a contractual relationship between owners and the design-builders’ design consultants, subcontractors and suppliers. In fact, owners may be concerned that exclusion from the D-B team discussions may compromise project quality (Ling and Poh 2008).

The respondents also agreed that enhancing communication between the owner and design-builder and timelines for approvals were important to solve any potential design conflicts. Forty five respondents (76%) showed that they preferred to have a weekly meeting between the owner and design-builder during the design development phase. Figure 3 illustrates the different methods of communication. One can observe from Figure 3 that email, face-to-face meeting, and phone conversation are common communication methods in the design development process.
The respondents also indicated that allowing direct communication and using multiple methods of communication would be helpful in solving design issues. One of the interviewees agrees that the single-contract basis of D-B almost always limits any communication too strictly between the owner and design-builder entity. This fact makes the communications process extremely linear in both directions and limits the flow of project information.

The participant was also asked for the challenges of coordination and communication during the design phase in a D-B project, and some of the strategies to overcome such challenges. The major challenges included (1) timely and understandable decisions by the owner's group; (2) meeting owner design expectations; (3) timely and successful sharing of information. The main strategy to overcome these challenges involved establishing a centralized information storage and sharing system to ensure effective communication between the owner and design-builder.

4.5 Construction Phase

For D-B projects, construction can begin prior to design completion. When the owner approves the construction documents for all elements or for specific parts of the work, construction can start (Beard et al. 2001). During construction the owner's representative will monitor the work for quality and degree of completion. After the completion of construction, the owner's representative will examine the facility for compliance with the initial program and performance requirements, as well as with the design-builder's proposal and its construction documents (Lam et al. 2008). Similar to the design development phase, 43 respondents (73%) showed that they preferred to have one meeting per week between the owner and design-builder during the construction phase. Additionally, communication methods such as email, face-to-face meeting, and phone conversation are common in the construction phase. Figure 4 shows the different communication methods resulted from the survey.
To investigate further the impact of communication on the construction phase, all participants were asked to identify the challenges of coordination and communication during the construction phase in a D-B project, and the strategies to overcome such challenges. The typical challenge involved timely and successful sharing of information among all project participants in the construction phase. One contractor in the interview process stated that when questions are not asked, assumptions are made which can result in incorrect information being assumed. When answers are not given in a timely manner, the lack of response can affect the proposal, design and/or construction. The contract discussed that “more and more D-B projects are being done because they save time. Response time should be fast. Owners understand the need for responsiveness, but don’t always behave the way that would be best.”

The typical strategy to overcome such challenge is to enhance communication between the owner and design-builder. The survey results showed that 45 responses (76%) agreed that one meeting between the owner and design-builder per week appears to be the standard during the construction phase. In addition, the design and construction teams need to communicate clearly and understandably to one another though they are one team during construction.

5 CONCLUSION

This paper examines the communication issues during each typical phase of D-B projects. The survey questionnaire and follow-up interviews were employed to collect data in the building sector. The results suggested that the primary communication issues that have an effect on D-B include: (1) establishing and meeting with the clear points of contact and decision makers throughout the D-B process, (2) providing clear and understandable information among project participants involved, and (3) and the timely and successful sharing of information. In addition, the results suggested that coordination, clarification, documentation of relevant information in each phase of the D-B process is essential to the success for D-B projects. These findings furnish stakeholders with an understanding of the communication issues that are occurring in D-B. These findings also deepen the current body of knowledge and serve to enlighten professionals regarding D-B communication issues.

There are several limitations to this study. First, the survey questionnaire was only sent to the members of the DBIA Mid America region. It is expected that the accuracy and validity of the finding will increase if
the survey was nationwide distributed. Second, while the response rate of the survey questionnaire was adequate to determine the major communication issues, an increased response would enhance the verification and validation process. Finally, the follow-up interviews included only five participants. Additional interviews can provide more data and input to augment the findings for this study. It is recommended that future studies should seek additional industry input as well as conduct case studies in order to better document how the communication issues affect the D-B delivery method.

References


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STATISTICAL MODELING OF PUBLIC ATTITUDES TOWARDS WATER INFRASTRUCTURE RETOOLING ALTERNATIVES IN SHRINKING CITIES

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Abstract: Many US cities, such as Gary, Indiana and Detroit, Michigan, have and continue to experience substantial population decline. The footprint of the built infrastructure in these cities does not contract with urban decline, but remains relatively unchanged, consequentially resulting in underfunded and underutilized infrastructure. Right sizing the physical footprint for the current and projected population needs has the potential to stabilize or reduce the rising per capita cost of services. While unilateral infrastructure decisions may save time and money, they pose risks, such as inefficient or unsuccessful implementation or unsustainable infrastructure projects, due to public opposition. The objective of this paper is to assess the public attitude concerning water infrastructure management alternatives. In November 2013, a voluntary survey was deployed to residents of 21 medium or large US shrinking cities. Binary probit models were estimated to determine the demographic and geographic variables influencing the support (or opposition) of five water infrastructure management alternatives. The statistical models indicated that different alternatives have different probabilities of support (or opposition) in varied geographic locations. Demographic variables, such as age, employment status, and income, have a propensity towards (or against) select management alternatives. This study demonstrates a method for understanding and incorporating public opinion into the pre-planning process for potentially reducing public opposition. Potential opposition regarding infrastructure management decisions may be alleviated through participatory processes and targeting identified demographic groups for involvement in new infrastructure projects and decisions.

1 INTRODUCTION

Many US cities, such as, Cleveland, Ohio, and Buffalo, New York, have and continue to experience substantial population decline (Pallagst 2008). As the populations decline, these cities, termed shrinking cities, face a multitude of infrastructure-related challenges, including a decreasing tax base, a reduced number of customers demanding infrastructure services, and a built infrastructure footprint that remains relatively unchanged in spite of the shrinking populations. These challenges result in an excess of underutilized and underfunded infrastructure. Approximately, 75 to 80 percent of water infrastructure costs to provide service are fixed costs (Herz 2006; Hummel and Lux 2007; Schlör et al. 2009). These fixed costs must still be recovered in the presence of the urban decline and a reduced number of customers, potentially resulting in infrastructure services becoming prohibitively more expensive per capita (Rybczynski and Linneman 1999; Herz 2006; Butts and Gasteyer 2011; Beazley et al. 2011). Further straining this financial situation with regard to water service is the financial capital necessary to meet the increasingly stringent regulations set by the state and federal government (Roberson 2011).
Prior literature regarding water infrastructure in shrinking cities has: (1) qualitatively discussed water infrastructure management alternatives to reduce the physical footprint for the current and projected population, such as decommissioning/razing or repurposing underutilized infrastructure components (Hoornbeek and Schwarz 2009; USEPA 2014), and (2) examined the relationship between urban decline and rising per capita water/wastewater service costs (Herz 2006; Hummel and Lux 2007; Schlor et al. 2009; Butts and Gastayer 2011). To the authors’ knowledge, the literature has not addressed the attitudes towards possible water infrastructure retooling alternatives in shrinking cities. Water infrastructure retooling alternatives are changes to the systems, whether physical, operational, or managerial, that may have the potential to reduce or stabilize the cost or increase the level of service of the systems. Prior work regarding public views has evaluated the perceived quality of life in areas of urban decline and perceptions towards abandonment and vacancies (Greenberg and Schneider 1996; Bright 2000; Hollander 2010; Hollander 2011). Understanding the public attitude and ensuring adequate public support may increase the success of an infrastructure project by mitigating the possibility of inefficient or unsuccessful implementation, or unsustainable alternatives arising from public opposition (Susskind and Cruikshank 1987, Global Water Partnership Technical Advisory Committee 2000, Gerasidi et al. 2009, Nancarrow et al. 2010, Faust et al. 2013). Sustainability, in the context of this paper, refers to managing and maintaining the water infrastructure system’s ability to provide adequate service to the current and projected populations.

This study aims to evaluate the attitude of residents in shrinking cities towards select water infrastructure retooling alternatives. A survey was deployed to residents of shrinking cities to evaluate the public attitudes towards five water infrastructure retooling alternatives using statistical modeling: (1) investing in more infrastructure, (2) razing or decommissioning infrastructure components, (3) repurposing the existing infrastructure, (4) investing in the maintenance of the current infrastructure, and (5) doing nothing (make no changes) to the current infrastructure. Of interest to this study are the outcomes of the statistical models, which provide insight into the geographical and demographic characteristics of the public that increase the likelihood of supporting or opposing the implementation of different water infrastructure retooling alternatives. Understanding the attitudes of the public in shrinking cities (that is, which locational and demographic characteristic have an initial propensity towards certain alternatives) may help facilitate the analysis of implementable alternatives within these communities (Faust et al. 2013) that have minimal public opposition.

2 METHODOLOGY

A survey was deployed in November 2013 to the general public to capture the perceptions, attitudes, awareness, and knowledge regarding specific retooling alternatives and water sector infrastructure challenges. The attitude questions were posed as a binary question, agree/support or disagree/oppose, to avoid decision paralysis and force a stance that is often missed when questions are posed on a multi-point scale with a neutral or an I do not know option (Tversky and Shafir 1992). These attitude questions directly asked what the respondent thinks should be done in his or her city, and thus, may capture factors such as, the NIMBY theory (“not in my backyard”). It should be noted that the attitudes expressed in this paper represent the public views at a snapshot in time. Attitudes are dynamic, changing with external factors such as, additional information, experience, education, and outreach.

Qualtrics, a web-based survey software, was used to format and deploy the voluntary survey to residents over the age of 18 in 21 US shrinking cities (Table 1). The survey was validated via content review by 11 subject matter experts with expertise in issues inherent to shrinking cities, water sector infrastructure management, or survey analyses. Following content validation, the survey underwent IRB review at Purdue University and was pre-deployed to 25 people with limited knowledge of water sector infrastructure issues to confirm that residents could easily respond to, and understand the posed survey questions. The responses from the pre-deployment were not included in the final sample pool used for the statistical modeling.

The respondent pool consisted of residents from shrinking cities that had peak populations greater than approximately 100,000, and have experienced a decline of at least 30% of their population since the peak
population (Table 1). As of the 2010 census, the combined population of the targeted cities was approximately 4.6 million (US Census Bureau 2011). A confidence level of 95% with a confidence interval of 5% was obtained with a sample size of 455 complete surveys from these 21 the shrinking cities. A minimum of 10 responses was gathered from each targeted city. Responses were sought from cities spanning multiple states to reduce the potential that responses reflect local policies, and to allow the comparison of the attitudes of residents across cities/states.

Table 1: Targeted cities comprising survey response pool

<table>
<thead>
<tr>
<th>City</th>
<th>Percent decline from peak population</th>
<th>Peak Population (Year)</th>
<th>2010 Population (US Census Bureau 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akron, Ohio</td>
<td>34.5%</td>
<td>290,351 (1960)</td>
<td>199,110</td>
</tr>
<tr>
<td>Baltimore, Maryland</td>
<td>34.6%</td>
<td>949,708 (1950)</td>
<td>620,961</td>
</tr>
<tr>
<td>Birmingham, Alabama</td>
<td>37.7%</td>
<td>340,887 (1950)</td>
<td>212,237</td>
</tr>
<tr>
<td>Buffalo, New York</td>
<td>53.4%</td>
<td>580,132 (1950)</td>
<td>270,240</td>
</tr>
<tr>
<td>Camden, New Jersey</td>
<td>37.9%</td>
<td>124,555 (1950)</td>
<td>77,344</td>
</tr>
<tr>
<td>Canton, Ohio</td>
<td>37.6%</td>
<td>116,912 (1950)</td>
<td>73,007</td>
</tr>
<tr>
<td>Cincinnati, Ohio</td>
<td>41.1%</td>
<td>503,998 (1950)</td>
<td>296,943</td>
</tr>
<tr>
<td>Cleveland, Ohio</td>
<td>56.6%</td>
<td>914,808 (1950)</td>
<td>396,815</td>
</tr>
<tr>
<td>Dayton, Ohio</td>
<td>46.1%</td>
<td>262,332 (1960)</td>
<td>141,527</td>
</tr>
<tr>
<td>Detroit, Michigan</td>
<td>61.4%</td>
<td>1,849,568 (1950)</td>
<td>713,777</td>
</tr>
<tr>
<td>Flint, Michigan</td>
<td>43.4%</td>
<td>196,940 (1960)</td>
<td>84,465</td>
</tr>
<tr>
<td>Gary, Indiana</td>
<td>55.0%</td>
<td>178,320 (1960)</td>
<td>98,026</td>
</tr>
<tr>
<td>Niagara Falls, New York</td>
<td>51.0%</td>
<td>102,394 (1960)</td>
<td>52,200</td>
</tr>
<tr>
<td>Pittsburgh, Pennsylvania</td>
<td>54.8%</td>
<td>676,806 (1950)</td>
<td>371,102</td>
</tr>
<tr>
<td>Rochester, New York</td>
<td>36.7%</td>
<td>332,488 (1960)</td>
<td>121,923</td>
</tr>
<tr>
<td>Saginaw, Michigan</td>
<td>47.5%</td>
<td>98,265 (1960)</td>
<td>51,508</td>
</tr>
<tr>
<td>Scranton, Pennsylvania</td>
<td>46.9%</td>
<td>143,333 (1990)</td>
<td>67,244</td>
</tr>
<tr>
<td>St. Louis, Missouri</td>
<td>62.7%</td>
<td>856,796 (1950)</td>
<td>537,502</td>
</tr>
<tr>
<td>Syracuse, New York</td>
<td>34.2%</td>
<td>220,583 (1950)</td>
<td>75,413</td>
</tr>
<tr>
<td>Trenton, New Jersey</td>
<td>33.7%</td>
<td>128,009 (1950)</td>
<td>43,096</td>
</tr>
<tr>
<td>Youngstown, Ohio</td>
<td>60.6%</td>
<td>170,002 (1930)</td>
<td>103,020</td>
</tr>
</tbody>
</table>

To determine the demographic and location parameters that influenced the attitudes of the respondents towards the five infrastructure retooling alternatives, different statistical models were assessed to identify the best-fit models. Ultimately, binary probit models were used to identify the parameters influencing public attitude. The binary probit models were estimated with the standard maximum likelihood method and assumed normally distributed error terms (ε) with a mean of zero. The binary probit model:

\[
P_i(YES) = \Phi \left( \frac{\beta_{YES} X_{YES}}{\sigma} \right)
\]

estimates the probability of outcome 1 for observation \(i\). \(\Phi\) is the standardized cumulative normal distribution, \(\beta_1\) are the estimable parameters for outcome \(i\), and \(X_{ij}\) are the vectors of the observable characteristics (e.g., demographic characteristics, cities) that determine if “1” is the suggested outcome of observation \(i\) (Washington et al. 2011).

Marginal effects, which are the average changes in probability resulting from a one-unit change in the independent variables (or a change for zero to one for indicator variables), are used to interpret the impact of each parameter (Washington et al. 2011). The reported marginal effects presented in the tables below for each significant parameter is the average of the individual marginal effect for all observations. For model selection, the Akaike information criterion (\(AIC\)) and the Bayesian information criterion (\(BIC\)) were used. Both criterion incorporate the same goodness-of-fit term and, with \(k\) equal to the number of
parameters in the model and log-likelihood function $f(y \mid \beta)$, where $AIC = -2 \ln f(y \mid \beta_0) + 2k$ and $BIC = -2 \ln f(y \mid \beta_k) + k \ln n$ (Cavanaugh 2012). $AIC$ is asymptotically efficient, selecting the model that minimizes the mean square error, and thus, is appropriate as a predictive criterion (identifying, via a pairwise comparison, which model most efficiently predicts the outcomes). $BIC$ is consistent, identifying the model with the factors that are the most influential, and thus, is appropriate as a descriptive criterion (Cavanaugh 2012). When selecting models, the smallest $AIC$ and $BIC$ are indicative of the best fitted models (Schneider and Schneider 2009).

3 RESULTS

Of the survey’s respondents, approximately 60% were male and approximately 50% were over the age of 50 years old. A majority of respondents had an individual annual income of less than $35,000. Descriptive statistics of the significant demographic variable in the statistical models are shown in Table 2.

Table 2: Survey sample pool demographics

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>MIN/ MAX</th>
<th>AVE.</th>
<th>ST. DEV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual Characteristic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender (1 if male, otherwise 0)</td>
<td>0/1</td>
<td>0.61</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>Marital Status</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single (1 if single, otherwise 0)</td>
<td>0/1</td>
<td>0.36</td>
<td>0.48</td>
</tr>
<tr>
<td>Divorced (1 if divorced, otherwise 0)</td>
<td>0/1</td>
<td>0.12</td>
<td>0.33</td>
</tr>
<tr>
<td>Separated (1 if separated, otherwise 0)</td>
<td>0/1</td>
<td>0.02</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18-25 years old (1 if 18-25 years old, otherwise 0)</td>
<td>0/1</td>
<td>0.09</td>
<td>0.28</td>
</tr>
<tr>
<td>26-35 years old (1 if 26-35 years old, otherwise 0)</td>
<td>0/1</td>
<td>0.20</td>
<td>0.40</td>
</tr>
<tr>
<td>Over 50 years old (1 if over 50 years old, otherwise 0)</td>
<td>0/1</td>
<td>0.47</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Respondent Approximate Income</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Income (1 if respondent has no income, otherwise 0)</td>
<td>0/1</td>
<td>0.08</td>
<td>0.27</td>
</tr>
<tr>
<td>Under $19,999 (1 if respondent’s income is less than $19,999, otherwise 0)</td>
<td>0/1</td>
<td>0.26</td>
<td>0.44</td>
</tr>
<tr>
<td>$20,000-$34,999 (1 if respondent’s income is $20,000-$34,999, otherwise 0)</td>
<td>0/1</td>
<td>0.24</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Employment Status</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Out of work and looking for work (1 if out of work and looking for work, otherwise 0)</td>
<td>0/1</td>
<td>0.05</td>
<td>0.22</td>
</tr>
<tr>
<td>Retired (1 if a retired, otherwise 0)</td>
<td>0/1</td>
<td>0.21</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>Primary Source of News</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newspaper (1 if primary source of news is the newspaper, otherwise 0)</td>
<td>0/1</td>
<td>0.36</td>
<td>0.48</td>
</tr>
<tr>
<td>Internet (1 if primary source of news is the Internet, otherwise 0)</td>
<td>0/1</td>
<td>0.66</td>
<td>0.47</td>
</tr>
<tr>
<td>Television (1 if primary source of news is the television, otherwise 0)</td>
<td>0/1</td>
<td>0.75</td>
<td>0.43</td>
</tr>
<tr>
<td>Social media (1 if primary source of news social media, otherwise 0)</td>
<td>0/1</td>
<td>0.15</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grew-up in city (if grew-up in the city currently residing in, otherwise 0)</td>
<td>0/1</td>
<td>0.60</td>
<td>0.49</td>
</tr>
<tr>
<td>Responsible for water bill (1 if respondent responsible for water bill, otherwise 0)</td>
<td>0/1</td>
<td>0.71</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Household Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ownership of Household</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mortgage or loan (1 if household is owned via a mortgage or a loan, otherwise 0)</td>
<td>0/1</td>
<td>0.47</td>
<td>0.50</td>
</tr>
<tr>
<td>Rented (1 if household is rented, otherwise 0)</td>
<td>0/1</td>
<td>0.31</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of cars in household (cars)</td>
<td>0/8</td>
<td>1.49</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The final survey sample’s raw data indicated that only 18% of respondents had no interest in being actively involved in the decision-making process for water infrastructure needs. Approximately 20% of the respondents stated that they did not trust their water provider to make appropriate decisions, denoting potential for opposition or unstable relationships with the public in the absence of participatory
involvement. By understanding the public attitudes towards the different retooling alternatives and accounting for the public views in decision-making, some of the indicated distrust between the public and utility providers may possibly be alleviated, allowing for the transition towards more sustainable infrastructure systems.

The results in Tables 3-7 show the quantification of the significant parameters that increase the propensity towards agreeing/supporting (disagreeing/opposing) with the implementation of specific retooling alternatives. A positive (negative) parameter indicates an increased likelihood of agreeing/supporting (disagreeing/opposing) with the respective alternative, with the marginal effects of each parameter shown in the adjacent column.

Table 3: Significant parameters and marginal effects for survey responses to the statement “I think my city should invest in more infrastructure”

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Parameter (t-statistic)</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-0.855 (-8.644)</td>
<td></td>
</tr>
<tr>
<td>Income indicator (1 if less than $35,000, otherwise 0)</td>
<td>0.239 (1.704)</td>
<td>0.080</td>
</tr>
<tr>
<td>Ownership of household (1 if someone in the household rents the household, otherwise 0)</td>
<td>-0.370 (-2.372)</td>
<td>-0.115</td>
</tr>
<tr>
<td>Primary news source (1 if social media, otherwise 0)</td>
<td>0.453 (2.599)</td>
<td>0.160</td>
</tr>
<tr>
<td>Cleveland, Ohio indicator (1 if residing in Cleveland, otherwise 0)</td>
<td>0.454 (2.419)</td>
<td>0.162</td>
</tr>
<tr>
<td>Gary, Indiana indicator (1 if residing in Gary, otherwise 0)</td>
<td>0.702 (1.693)</td>
<td>0.263</td>
</tr>
<tr>
<td>Trenton, New Jersey indicator (1 if residing in Trenton, otherwise 0)</td>
<td>0.824 (2.047)</td>
<td>0.311</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AIC = 517.70355
BIC = 550.34525

Log Likelihood = -250.691

Table 4. Significant parameters and marginal effects for survey responses to the statement “I think my city should raze or decommission infrastructure”

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Parameter (t-statistic)</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-1.652 (-8.701)</td>
<td></td>
</tr>
<tr>
<td>Cars in the household (1 if household has more than two cars, otherwise 0)</td>
<td>0.490 (1.917)</td>
<td>0.083</td>
</tr>
<tr>
<td>Primary news source (1 if internet, otherwise 0)</td>
<td>0.357 (1.713)</td>
<td>0.041</td>
</tr>
<tr>
<td>Flint, Michigan indicator (1 if residing in Flint, otherwise 0)</td>
<td>0.601 (1.713)</td>
<td>0.112</td>
</tr>
<tr>
<td>Ohio State indicator (1 if residing in Ohio, otherwise 0)</td>
<td>-0.510 (-2.265)</td>
<td>-0.058</td>
</tr>
<tr>
<td>Log Likelihood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Log Likelihood = -114.9553

AIC = 240.04435
BIC = 260.51025
Table 5: Significant parameters and marginal effects for survey responses to the statement “I think my city should repurpose infrastructure”

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Parameter (t-statistic)</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-1.766 (-6.186)</td>
<td></td>
</tr>
<tr>
<td>Gender (1 if male, otherwise 0)</td>
<td>0.284 (1.918)</td>
<td>0.074</td>
</tr>
<tr>
<td>Age (1 if over 50, otherwise 0)</td>
<td>-0.047 (-3.252)</td>
<td>-0.126</td>
</tr>
<tr>
<td>Relationship Status (1 if single, divorced, or separated, otherwise 0)</td>
<td>0.282 (2.016)</td>
<td>0.075</td>
</tr>
<tr>
<td>Primary news source (1 if internet, otherwise 0)</td>
<td>0.359 (2.261)</td>
<td>0.091</td>
</tr>
<tr>
<td>Primary news source (1 if television, otherwise 0)</td>
<td>0.311 (1.802)</td>
<td>0.077</td>
</tr>
<tr>
<td>Frequency of following the news (1 if daily, otherwise 0)</td>
<td>0.377 (1.913)</td>
<td>0.090</td>
</tr>
</tbody>
</table>

Log Likelihood: -213.1905

AIC: 440.6311

BIC: 469.2233

Table 6: Significant parameters and marginal effects for survey responses to the statement “I think my city should invest in the maintenance of the current infrastructure”

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Parameter (t-statistic)</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-0.908 (-3.090)</td>
<td></td>
</tr>
<tr>
<td>Age (1 if less than 35, otherwise 0)</td>
<td>0.458 (2.029)</td>
<td>0.170</td>
</tr>
<tr>
<td>Employment status (1 if out of work and looking for work, otherwise 0)</td>
<td>0.564 (2.043)</td>
<td>0.221</td>
</tr>
<tr>
<td>Cars in the household indicator (1 if household has cars, otherwise 0)</td>
<td>0.375 (1.800)</td>
<td>0.142</td>
</tr>
<tr>
<td>Primary news source (1 if newspaper, otherwise 0)</td>
<td>0.276 (2.176)</td>
<td>0.109</td>
</tr>
<tr>
<td>Pennsylvania State indicator (1 if residing in Pennsylvania, otherwise 0)</td>
<td>-0.402 (-1.984)</td>
<td>-0.151</td>
</tr>
<tr>
<td>Trenton, New Jersey indicator (1 if residing in Trenton, otherwise 0)</td>
<td>-1.318 (-2.355)</td>
<td>-0.372</td>
</tr>
</tbody>
</table>

Log Likelihood: -296.415

AIC: 609.154

BIC: 641.79115

Table 7: Significant parameters and marginal effects for survey responses to the statement “I think my city should do nothing to the current infrastructure”

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Parameter (t-statistic)</th>
<th>Marginal Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.751 (2.231)</td>
<td></td>
</tr>
<tr>
<td>Age (1 if less than 35, otherwise 0)</td>
<td>-0.456 (-1.893)</td>
<td>-0.153</td>
</tr>
<tr>
<td>Income indicator (1 if less than $35,000, otherwise 0)</td>
<td>-0.284 (-1.825)</td>
<td>-0.082</td>
</tr>
<tr>
<td>Employment status (1 if retired, otherwise 0)</td>
<td>-0.328 (-1.819)</td>
<td>-0.090</td>
</tr>
<tr>
<td>Ownership of household (1 if someone in the household owns the house with a loan or mortgage, otherwise 0)</td>
<td>0.332 (2.285)</td>
<td>0.099</td>
</tr>
<tr>
<td>Number of cars in the household (cars)</td>
<td>-0.247 (-2.820)</td>
<td>-0.073</td>
</tr>
<tr>
<td>Indicator that city currently residing in is the same as grew up in (1 if grew up in the city currently residing in, otherwise 0)</td>
<td>-0.331 (-2.444)</td>
<td>-0.100</td>
</tr>
<tr>
<td>Responsible for water bill indicator (1 if responsible, otherwise 0)</td>
<td>-0.422 (-2.708)</td>
<td>-0.133</td>
</tr>
<tr>
<td>Primary news source (1 if internet, otherwise 0)</td>
<td>-0.355 (-2.462)</td>
<td>-0.110</td>
</tr>
<tr>
<td>Scranton, Pennsylvania indicator (1 if residing in Scranton, otherwise 0)</td>
<td>0.679 (1.763)</td>
<td>0.241</td>
</tr>
</tbody>
</table>

Log Likelihood: -231.8582

AIC: 484.211

BIC: 524.91985
4 DISCUSSIONS

When exploring viable infrastructure retooling alternatives, decision-makers may use the estimated models to identify the demographic and locational parameters of individuals having an increased likelihood of opposition (i.e., disagreeing with an alternative). Educational outreach or incorporating participatory processes involving these groups of residents may mitigate potential public resistance towards the alternative(s). In the statistical analyses, locational parameters were recurring, significant parameters for indicating an initial propensity to agree or disagree with the implementation of the different infrastructure retooling alternatives. Specific locations in which residents had an increased propensity to agree with the implementation of an alternative included:

- **Cleveland, Ohio.** Cleveland residents have a 0.162 increase in the probability of agreeing with measures to invest in more physical water infrastructure.
- **Flint, Michigan.** Flint residents have a 0.112 increase in the probability of agreeing with decommissioning or razing water infrastructure.
- **Gary, Indiana.** Gary residents have a 0.263 increase in the probability of agreeing with investing in more physical water infrastructure.
- **Scranton, Pennsylvania.** Scranton residents indicated a 0.241 increase in agreeing that the probability that the utility providers should maintain the status quo (i.e. do nothing).
- **Trenton, New Jersey.** Trenton residents have a 0.311 increase in the probability of agreeing with measures to invest in more physical water infrastructure.

The locations in which residents disagreed with select retooling alternatives were:

- **Shrinking cities in Ohio.** Residents of shrinking cities in Ohio have a 0.058 decrease in the probability of agreeing with decommissioning or razing water infrastructure.
- **Shrinking cities in Pennsylvania.** Residents of shrinking cities in Pennsylvania have a 0.151 decrease in the probability of agreeing with increasing the financial investment of maintaining the current water infrastructure.
- **Trenton, New Jersey.** Trenton residents have a 0.372 decrease in the probability of agreeing with measures that increase the financial investment of maintaining the current water infrastructure.

Location parameters are important to consider for decision-makers when considering viable, sustainable retooling alternatives to explore further for potential implementation. The initial propensity to agree/support or disagree/oppose with different infrastructure retooling alternatives may be due to a communication gap or lack of awareness regarding infrastructure issues typical to shrinking cities. For instance, albeit being residents in shrinking cities, the residents of Cleveland, Gary, and Trenton are more likely to support investing in more infrastructure, indicating a lack of knowledge regarding the relationship between the fixed grid infrastructure system and the declining population. This location specific information may be a conversation starter between the public and utility providers on how to move forward towards a sustainable infrastructure system, to dispel incorrect information regarding utilities in the context of urban decline, or to discuss the viability of infrastructure alternatives to promote increased likelihood of support of the implemented infrastructure retooling alternative.

The five models also revealed many demographic characteristics to be significant in influencing the attitude towards retooling alternatives. Age was a signification demographic variable, with individuals younger than 35 years old being more likely to disagree with the status quo/do nothing alternative and more likely to support maintaining existing infrastructure. Conversely, individuals over the age of 50 were more likely to oppose repurposing infrastructure. These findings may be capturing a resistance to change as openness for progressive change has been shown to decline as individuals age (Westerhoff 2008).

Men are more likely to agree with repurposing infrastructure, possibly reflecting the importance that males can play in household incomes and decision-making (Wang et al. 2013). Additionally, individuals who are single, divorced, or separated, are more likely to agree with repurposing infrastructure further supporting that retooling alternatives may be viewed as a viable method to stabilize costs when living expenses are not shared amongst partners.
Individuals with incomes less than $35,000 are more likely to agree with increasing the investment in more infrastructure and less likely to agree with doing nothing. However, those individuals who are out of work are more likely to agree with investing in maintaining the current infrastructure, likely recognizing this alternative to be seemingly less financially burdensome on the customers/rate-payers.

Ownership of cars increased the likelihood of disagreeing with the ‘do nothing’ alternative. Consistent with this finding is that individuals with more than two cars were more likely to support decommissioning or razing infrastructure, and households with at least one car were more likely to agree with maintaining existing infrastructure. This finding may be capturing some measure of wealth and mobility that would make individuals in these groups less likely to be impacted by increasing investments for maintenance, or may simply reflect the economics involved in owning additional cars which results in less disposable income. This measure of wealth associated with less disposable income may be a motivation to find a way (decommissioning or razing infrastructure or maintain infrastructure) to stabilize future utility rates.

Ownership of homes was a significant parameter. Renters were more likely to disagree with investing in more infrastructure, possibly capturing a disinterest in investing in an area that the renter is not permanently tied to or the economics involved in renting a household and having less disposable income (as discussed with car ownership). If the home is owned via a loan, the individual is more likely to agree with doing nothing to the water infrastructure. This home-ownership parameter seemingly captures the decrease in disposable income due to loan payments, and the view that doing nothing in the near future will not require increasing the water rates that further strain the low incomes rampant in these cities.

Those individuals who are responsible for their water bill were found to be less likely to agree with the doing nothing for water infrastructure retooling alternative. Additionally, individuals who were raised in the city, or individuals who have retired from regular employment are less likely to agree with doing nothing for water infrastructure. As the average income in shrinking cities is typically below the average income for the state (US Census Bureau 2011), these individuals may see these alternatives as viable methods to stabilize or reduce water service costs, one of many living expenses.

The primary source of news of the respondents was a significant parameter in many models. The significance of this parameter may be due to the different age groups using the medium as the primary source of news. For instance, radio is often the primary source of news for older generations (Kohut et al. 2010). Another reason for the significance of this parameter may be due to the stories that are highlighted via the medium and the flexibility to search for own stories of interest. The Internet provides for flexibility to choose from a wide range of news, whereas the radio provides the listener with limited flexibility.

5 SUMMARY AND CONCLUSIONS

As cities experiencing urban decline explore water infrastructure retooling alternatives, understanding the sources of opposition/disagreement and which alternatives are likely to be supported/opposed by the community may possibly mitigate opposition towards the implemented alternative(s). In this study, less than 20% of the survey respondents expressed no desire to participate in the decision-making processes regarding water infrastructure. This low percentage indicates that communication avenues must be open between the utility providers and the public making decisions regarding water infrastructure. Incorporating some level of participatory decision-making may allow for sustainable outcomes and increased support with efforts for stabilizing or reducing the costs of services. This paper contributes to the body of knowledge by illustrating the viability of evaluating public attitudes towards underground infrastructure and potential infrastructure retooling alternatives using survey analyses and statistical modeling.

Underground infrastructures (e.g., water, wastewater, natural gas) are unseen, and the public generally lacks the same level of awareness of operations and conditions of these systems compared to those of above-ground infrastructure systems, such as roads and bridges. However, price elasticity studies (e.g., USEPA ND; Espey et al. 1997; Lipsey and Chrystal 1999; NRDC 2012) have shown that consumers are sensitive to price changes with water utility services, illustrating that consumer behavior is directly tied to the utility service provided. Infrastructure retooling alternatives have the potential to reduce or stabilize
the costs of service. However, depending on how the necessity of these alternatives is perceived, the public may not agree with a specific alternative. Understanding public attitude is critical for the successful implementation of retooling alternatives since decisions lacking adequate public support may lead to inefficient or unsuccessful implementation (Susskind and Cruikshank 1987; Global Water Partnership Technical Advisory Committee 2000, Gerasidi et al. 2009, Nancarrow et al. 2010, Faust et al. 2013).

The statistical analyses show that a wide variety of factors influence the attitudes of residents in shrinking cities pertaining to water retooling alternatives. Results from the five water infrastructure retooling model estimations show that many of the same socioeconomic and demographic variables influenced the attitudes spanning the five models. These socio-economic and demographic findings may be used to evaluate the population in specific shrinking cities to determine the initial viability of different retooling alternatives, and to tailor information campaigns for specific groups to mitigate potential opposition towards different infrastructure retooling alternatives. Specific socio-economic and demographic results that had an increased propensity towards agreeing or disagreeing with different retooling alternatives included age, gender, income, number of cars, employment status, and primary source of news. Understanding the sources of support/opposition among the populations, while considering these attitudes in the decision-making process may allow for shrinking cities to transition towards strategies for stabilizing or reducing the per capita costs of utility services.

Acknowledgements

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References


APPLICATION OF PROSPECT THEORY TO MANAGEMENT DECISIONS UNDER RISK ON CONSTRUCTION PROJECTS

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\textbf{Abstract:} Working on a construction project requires making important decisions quickly and frequently. Most of these decisions are made under risk in that the outcomes are not known, but their probabilities and impacts can be estimated, however imprecisely. Deciding to pave, given temperature predictions, is an example of such a decision. When the impacts are aggregated, they can represent a non-negligible amount compared to project budgets. Understanding project leaders’ behaviour when they make such decisions under risks may create opportunities to avoid future losses that result from suboptimal choices. As those decisions are numerous on a construction project, it might be difficult for the project leaders to always make the best choice. By using a questionnaire referring to potential construction project situations, this study shows how some behavioural tendencies can influence the choices of construction leaders. This paper mainly focuses on one aspect of the study, which is the impact of the certainty effect on projects leaders’ decision making. It demonstrates how project leaders are sensitive to the behavioural tendency associated with the certainty effect. This observation leads to the question of how to detect those problems and, how to correct them so as to avoid non-negligible loss of money for construction projects.

\section{INTRODUCTION}
Project leaders are required to quickly make many day-to-day decisions on their construction projects. When aggregated, those decisions can have a significant influence on cost and schedule performance. Many of those decisions are made under financial risk. An example is the decision whether to place concrete on a day for which the risk of rain has been estimated. Studies have investigated this question of decision under risk in terms of gambling and investments, and they have proven that people will illogically avoid and chase risk under different circumstances. This paper reports on an investigation of this phenomenon with respect to decisions made on construction sites.

It begins with a literature review of relevant behavioural economics principles and findings. Based on this review, a set of experiments were designed in the form of a questionnaire that would test basic hypotheses to determine sensitivity to risk and influence on judgment when day-to-day decisions are being made. Project leaders such as foremen, general foremen, superintendents, and managers were asked to answer the questionnaire.

The results of these experiments partially demonstrate the impact of risk on decisions made by project leaders. Results mostly follow the behavioural tendencies previously identified in Behavioural Economics research which indicate that risk influences judgment. For example, when the risk-option was more advantageous in terms of expected value, most people made the logically correct decision, but a
significant subset made the other choice, and this represents a loss of money for companies. Also, different parameters of the project, such as the cost performance, may have influence on decisions. Respondents were less risk averse when the project was described as under budget, but many also chased risk when the project was over budget. These are expected behaviours based on behavioural economics theory. Demonstrating and understanding how some decisions made under risk can lead to a predictable non-negligible loss of money is a first step in this research. The ultimate goal is to help project leaders avoid making illogical decisions when sufficient information is available to avoid such decisions.

2 DEVELOPMENT OF BEHAVIOURAL ECONOMICS AND APPLICATION TO THE CONSTRUCTION SECTOR

2.1 Emergence of Behavioural Economics

Economics studies conducted in the second half of the last century have shown that making decisions under risk is not as easy as people might think. When people are making decisions, they are not using expected utility theory; other parameters influence their choices. This specific field in economics is called “Behavioural Economics”. It deals with the subfield of psychology which describes what guides people when they are making a decision.

The research field of behavioural economics can be classified in two categories: the process of judgment and the process of choice. Judgment deals with how people estimate probabilities, and choice is about how people select an action among others. The goal of this field is to understand how people are making their decisions, when they are facing risk.

But, some economists have also found that there are some effects which can generate problems during the phase of decision-making under risk. For example, people prefer earning an amount disproportionately more than their aversion to losing the same amount (Kahneman and Tversky 1979). Similarly, people generally give more value to what they already have compared to or referenced than to what they can have in a deal in objective and absolute terms. This effect is called reference-dependence (Knetsch 1992).

Psychologists also define different mechanisms which violate some principles of basic economics, like expected values. Such mechanisms, as “certainty effect” or “loss aversion” affect the process of choices when people are making a decision under risk. It is hypothesized that those mechanisms can also influence construction leaders when they are facing a risk and have to make a decision.

2.2 Factors influencing construction decisions

The decisions of construction project leaders are influenced by factors external or internal to the construction project. For instance, the experience of the decision-maker has an influence on his future choice: events that actually occurred are easier to imagine compared to ones that have not yet occurred in their experience (Kahneman and Frederick 2002).

Some factors can also influence the process of judgment such as the environment and the context. For example, if the same problem is presented or seen in two different ways, then it can lead to different answers from the decision maker. People will not react the same way if the problems are presented in terms of gains, or in terms of losses. This is called the “framing effect” (Tversky and Kahneman 1981).

Lists of parameters influencing the success of a construction project have been made numerous times in the literature (Sanvido et al. 1992, Chan et al. 2004). They can be human related, management related or process related. One objective of this study is to identify key factors and link them to a behavioural tendency to explore if the behavioural tendency will have an impact on a category of decisions made for the construction project.
2.3 Application of Behavioural Economics to the Construction Sector

Behavioural Economics knowledge has been applied to different sectors and to construction project management. An important area of construction project management to which it has been applied is the bidding process. As this step of the project can deal with large amounts of money, applying behavioural economics to understand how construction leaders make bidding decisions makes sense (Han et al. 2005, Chen et al. 2015).

Behavioural economics has many applications in the construction sector. Another example would be the application of social norms on typical construction project problem such as absence behaviour to understand those (Ahn et al. 2014).

This paper focuses on the application of behavioural economics to small decisions that are made frequently on projects. Taken individually, those decisions may not seem important enough to matter compared to the size of projects, however aggregated together they can represent a non-negligible amount. This paper describes an experiment applying behavioural economics to those kinds of decisions.

3 DESCRIPTION OF THE EXPERIMENT AND OF THE QUALITY OF MATERIALS QUESTION

3.1 Description of the Global Experiment

3.1.1 Goal of the experiment

Creating a controlled experiment that places construction decision makers under financial risk and which observes their decision making behaviour under such conditions is, ironically, fraught with risk and not likely to receive research ethics review process approval. A reasonably close and ethically acceptable approximation of the preceding approach is to develop a research tool that implements an experiment in which decision makers are asked to make a choice as if the conditions described were real. Such a tool has been developed in the form of a questionnaire. This timed questionnaire is used to conduct the experiment.

The experiment has three goals. The first goal is to determine the sensitivity of construction project leaders to different typical risks during the decision making process. The second goal is to study the impact of key parameters on those decisions. The final goal is to estimate the financial impact that those decisions can have on a construction project when they are compared with the same decisions problem resolved following expected utility theory.

Specifically, the questionnaire contains close-ended questions, each with two possible options. The participants are asked a series of questions that describe typical construction project situations. The reasons for this choice are:

- Approximation of action based experiment: As explained above, this approach approximates adequately a controlled experiment with real consequences.
- Simplicity of analysis: Compared to an open-ended questionnaire, the answers, here called options, for this kind of questionnaire are easier to read because there are only two possible choices for each question. The question is reduced to a specific problem, and the data linked with that question can be directly interpreted.
- Simplicity for understanding and focus: All the questions built for this questionnaire are as simple as possible to maximize likelihood of understanding and to maximize consideration of externalities that might influence the respondents’ decisions.
- Simplicity for answering: The close-ended questionnaire allows people to answer faster.
- Correspondence with research goals: Previous successful studies that focused on behavioural tendencies almost invariably used close-ended questionnaires (Allais 1953, Kahneman and Tversky 1979). This form of questionnaire is useful for isolating behavioural tendencies, because it forces the participant either to choose or to avoid the risk, and it makes the result easier to analyze as well using conventional statistics.
3.1.2 Development of the questions – Behavioural tendencies

The first problem was to determine how many questions should be in the questionnaire, what kind of questions would be included and how they should be presented to the participant. For this experiment, it was decided to build the questions around behavioural tendencies such as “certainty effect” or “loss aversion”, by identifying situations on construction projects in which those behaviours might be exhibited. Thus, one of the most important parts of the development of the questionnaire was to build situations where a behavioural tendency might appear, and make it realistic for the participant. Based on this rationale, some construction situations were chosen and linked to a behavioural tendency in order to construct each question. The questions were in four groups:

- Choice between two techniques – testing for Perception of Change
- Choice between two kind of shingles (Quality of the materials) – testing for Certainty Effect
- Construction of a set of bored piles – testing for Non Compliance
- Decision to work with a risk of rain – testing for Loss Aversion

3.1.3 Development of the questions – External Influences

When project leaders are working on a construction project, they can be influenced by many external factors. Those factors can influence their choice in day-to-day decisions when they are facing risk. From the behavioural economics literature, it is clear that current financial position typically influences decisions made with respect to possible future gains and losses (Tversky and Kahneman 1986). Project cost performance is a good proxy for this factor as it reflects on the project leader’s perception of their own situation, performance, and related future rewards or penalties. Thus, each question is framed in terms of the following three project cost performance situations:

- on budget
- over budget
- under budget

3.1.4 Development of the questions – Expected Values

The expected value (EV) of an option corresponds to the sum of the expected values of the possible outcomes. Expected value is calculated using equation 1.

\[ EV = \sum_{i=1}^{n} p_i c_i \]  

For both options to each question the associated expected value is computed and then compared to the expected value of the other option. Two cases occur:

- The expected value of both options are equal
- One option has an advantage over the other one in terms of expected value

These two cases are used in the questionnaire for different objectives. The first case, when the expected values of both options are equal, is intended to highlight the presence of a behavioural tendency, if it exists. For the second case, the option that comprises a risk is advantaged compared to the other one. This time the goal is to qualify the subset of participants who are averse to risk.

3.1.5 Distribution of the questions

All the questions are built to test for one behavioural tendency and one external influence. The expected values of their options are either equal or different depending on the experimental hypothesis for each behaviour. The different questions prepared for this questionnaire are shown in Table 1. The questions were mixed randomly in the questionnaire, so that two similar questions did not appear in sequence.
Table 1: Distribution of the questions in the questionnaire

<table>
<thead>
<tr>
<th>Situations – Behavioural Tendencies</th>
<th>Expected Values</th>
<th>External Influence</th>
<th>Number of the question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception of Change</td>
<td>Expected Values</td>
<td>Under budget</td>
<td>Q4</td>
</tr>
<tr>
<td></td>
<td>different</td>
<td>On budget</td>
<td>Q10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over budget</td>
<td>Q18</td>
</tr>
<tr>
<td>Quality of the materials – Certainty Effect</td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q6</td>
</tr>
<tr>
<td></td>
<td>equal</td>
<td>On Budget</td>
<td>Q15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q20</td>
</tr>
<tr>
<td></td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q22</td>
</tr>
<tr>
<td></td>
<td>different</td>
<td>On Budget</td>
<td>Q2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q12</td>
</tr>
<tr>
<td>Bored Piles – Non Compliance</td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q11</td>
</tr>
<tr>
<td></td>
<td>equal</td>
<td>On Budget</td>
<td>Q8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q5</td>
</tr>
<tr>
<td></td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q17</td>
</tr>
<tr>
<td></td>
<td>different</td>
<td>On Budget</td>
<td>Q14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q23</td>
</tr>
<tr>
<td>Weather – Loss Aversion</td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q1</td>
</tr>
<tr>
<td></td>
<td>equal</td>
<td>On Budget</td>
<td>Q21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q16</td>
</tr>
<tr>
<td></td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q19</td>
</tr>
<tr>
<td></td>
<td>different (option A advantaged)</td>
<td>On Budget</td>
<td>Q13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q7</td>
</tr>
<tr>
<td></td>
<td>Expected Values</td>
<td>Under Budget</td>
<td>Q24</td>
</tr>
<tr>
<td></td>
<td>different (option B advantaged)</td>
<td>On Budget</td>
<td>Q3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Over Budget</td>
<td>Q9</td>
</tr>
</tbody>
</table>

3.2 Construction of the “Quality of materials” Question

3.2.1 Materials of the question

This conference paper, due to limitations, focuses on the “Quality of the materials” questions where the construction project is on budget (Q15 and Q2). However, the distribution and experimental design of the full set of questions are presented. The “Quality of the materials” question deals with the certainty effect.

The certainty effect is the psychological effect referring to the reduction of probability from certain to probable in the perception or utility function of the decision maker. Usually, reducing a probability of winning creates some effects, such as displeasure. This displeasure leads the individual to a reaction of risk-aversion because the small possibility of not winning is perceived as a loss. This risk-aversion reaction is bigger when the probability is reduced from certain to probable than from probable to less probable (Tversky and Kahneman 1986). Conversely, extremely small probabilities are invariably overvalued, leading to behaviours such as the purchase of lottery tickets.
The “Quality of materials” question plays with this behavioural tendency of certainty effect. The question offers one option with a complete assurance of the quality that is relatively expensive and a second option where the assurance of the quality is close to complete, but it is not, and this option is less expensive compared to the first one. Here, it is important that the probability of acceptable quality for each shingle for the second option is close to 100% or else other parameters would enter in the question such as the time of replacement, cost of disposal, and shipment. The intent was for the respondent not to factor in these other issues. An example of this question is shown in Figure 1. This question deals with the installation of shingles, but no qualifications are needed to answer this question, so every project leader or decision maker should be able to answer it.

![Question 15:](image)

### 3.2.2 Choice of the values – Decision Trees

The “Quality of materials” question where the construction project is on budget appears twice in the questionnaire: once when the expected values are equal (Q15) and a second time when the risk option (shingle A) is advantaged in terms of expected values (Q2). The decision trees of these questions are shown in Figure 2. Both questions offer a probability of cracking of 97% during the installation of which is close to 100% and so corresponds to the criterion defined before. The price of the shingles is around $200 for both questions. It makes sense because nothing about the shingle was specified in the question.

The expected value is computed for each option. Equation 1 is used for this computation. For option B, the expected value is easy to compute because the probability linked is 100%. However, computing the expected value for option A is more difficult, because the broken shingles have to be replaced by the same kind of shingle and the operation can last infinitely in theory. However, this calculation corresponds to the sum of a series. These expected values appear in the decision trees of Figure 2.

### 3.3 Progress and methodology of the experiment

The data collection process was established within the guidelines of the Office of Research Ethics of University of Waterloo. The participants were given an information letter about this study, and they had to fill a consent form so that their data can be used. Once this first step was done, the participants were allowed to fill the questionnaire. Filling the questionnaire took approximately half an hour. To finish, after
they gave back their questionnaire, they received a feedback letter, explaining the objectives of this experiment.

The data from the answers of the questionnaire was then analyzed, question by question, testing for the behavioural patterns explained before. It was also studied and analyzed in relation with external influences and characteristics from the participants such as their position or their age to observe how those parameters can influence their choices and their reactions facing those behavioural patterns.

In total, this study had 53 participants; they are all construction project leaders, mostly located in North America, and at different levels: foremen, project managers, executives and a few teachers and researchers. Those people were chosen randomly with respect to their age, their location and their position. The range of age is large, from the twenties to the sixties, so it results in participants with different levels of experience. Some have a whole career behind them, while others just started their job. This absence or not of experience may influence the way they make decisions under risk, so it is important to have a sample representative of the population of construction workers.

4 ANALYSIS OF THE RESULTS

4.1 Results of the “Quality of the Materials” Question

The percentages of participants who chose option A or option B for these two questions are shown in Table 2. As expected, the majority of participants chose to avoid the risk and took option B (no risk) for the question where the expected values are equal. This result shows the impact of the certainty effect on the participants’ choice. The significance of this value will be determined in the next section by computing the 95% confidence interval.

Concerning the second question where option A (risk taking) was advantageous, most of the participants made the best decision in terms of expected values. However, 28% of the participants chose to avoid the risk even if it was obviously more attractive in terms of expected values. This represents a significant number of participants, and consequently, potential non-negligible loss for companies. Computing the expected utilities linked to this question may explain this behaviour. This will be shown in the next section.

Table 2: Results of the “Quality of the materials” questions

<table>
<thead>
<tr>
<th>Options</th>
<th>Shingle A (Risk Taking)</th>
<th>Shingle B (No Risk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV equal (Q15)</td>
<td>36%</td>
<td>64%</td>
</tr>
<tr>
<td>EV different (Q2)</td>
<td>72%</td>
<td>28%</td>
</tr>
</tbody>
</table>
4.2 Interpretation of the Results

4.2.1 Computation of the confidence interval

For the question where the expected values are equal (Q15), Table 2 shows that 64% of the participants choose to take option B; this value corresponds to the mean of the participants' answers. To calculate the mean for the overall population of the construction project leaders' potential answers, an approach would be to compute a confidence interval using the binomial analysis. This confidence interval is shown in equation 2:

\[ \bar{x} - t \cdot \frac{\sqrt{\bar{x}(1 - \bar{x})}}{\sqrt{n}} ; \bar{x} + t \cdot \frac{\sqrt{\bar{x}(1 - \bar{x})}}{\sqrt{n}} \]

Where:

- \( n \) = Sample Size
- \( \bar{x} \) = Sample Mean
- \( t \) = Value linked with the confidence level

For this experiment, the t-value corresponding to a 95% confidence interval is equal to 1.96. So, the 95% confidence interval for this question (Q15) computed with equation 2 is 36 ±13% for option A and 64 ±13% for option B. This interval is too large to quantify the impact of this behavioural tendency but it is enough to show the pattern of certainty effect on construction leaders' choices as the confidence interval of the two options are not intersecting. It means that more than half of the population of construction project leaders makes the choice to avoid the risk when the expected values are equals, which proves the impact of the certainty effect on them when they are making a decision under risk.

Concerning the second question (Q2), the 95% confidence interval computed with equation 2 is 72 ±12% for option A and 28 ±12% for option B. This interval is also too large to quantify exactly the part of the population of construction leaders who are avoiding the risk and prefer option B. However, it is enough to prove that this non-negligible part of the population of construction leaders can engender losses, because they choose to avoid the risk taking option, even if it is more attractive in terms of expected value. Those potential losses are most likely generated by the certainty effect (Tversky and Kahneman 1986). This behavioural tendency has an impact on daily decisions made by construction leaders, and it may lead to some losses for the construction project.

4.2.2 Computation of the expected utilities

Usually, when people are making a decision under risk, they are not computing expected values, but they are computing expected utilities. Following Prospect Theory (Kahneman and Tversky 1979), the expected utility represents the evaluation phase of the choice process. Following are the expression of the expected utility and the definitions of the scales used to compute it:

\[ U(x_1, p_1; \ldots ; x_n, p_n) = \pi(p_1)v(x_1) + \ldots + \pi(p_n)v(x_n) \]

- The first scale, \( \pi \) associates with each probability \( p \) a decision weight \( \pi(p) \), which reflects the impact of the probability.
- The second scale, \( v \) assigns to each outcome \( x \) a number \( v(x) \), which reflects the subjective value of that outcome.

For this question, only the first scale was considered to compute the expected utilities. The outcomes of the two options are close to each other, so the subjective values of the outcomes might still be close and so, might not create any difference in the computation of the expected utilities compared to the expected values.
Two expected utilities are computed for these questions: one adding 10% to the original probability of risk and a second one adding 20%. Inversely, the same amount is subtracted from the complementary probability. As everyone considers the risk from their own point of view, and there is no general expected utility true for everybody and for each problem, people see the risk from their own perspective. Some are adding 10% to the probability of risk, some add less, and some add more. This value of 10% corresponds to the mean found from previous studies made in behavioural economics to understand the choices under risk (Tversky and Kahneman 1992).

This study is looking for trends in decision making, so using approximates values like 10% or 20% is useful to understand the decision of the participants when they are making this decision under risk. The computation of the expected utilities for the question where the expected values are equal (Q15) is shown in Table 3. It explains the choice of the participants: for either of the expected utilities n°1 or n°2, option B is more attractive, explaining why a majority of participants chose option B. Participants who chose option A, may have considered the risk of option A as zero.

Table 3: Results of the “Quality of the materials” question – EV equal (Q15)

<table>
<thead>
<tr>
<th>Options</th>
<th>Shingle A (Risk Taking)</th>
<th>Shingle B (No Risk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Values</td>
<td>-$200</td>
<td>-$200</td>
</tr>
<tr>
<td>Expected Utilities n°1 (+10%)</td>
<td>-$223</td>
<td>-$200</td>
</tr>
<tr>
<td>Expected Utilities n°2 (+20%)</td>
<td>-$252</td>
<td>-$200</td>
</tr>
<tr>
<td>Percentage</td>
<td>36%</td>
<td>64%</td>
</tr>
</tbody>
</table>

For the question where the expected value of option A (risk taking) was more attractive compared to the expected value of option B (no risk), the expected utilities are presented in Table 4. These computations are helpful to understand the participants’ choices. The expected utilities n°2 are close to each other, which means that if someone overvalues the probability of the risk in option A by more than 20%, option B was selected instead. This happened for 28% of the participants. Conversely, if someone undervalues or overvalues the probability of risk in option A by less than 20%, option A was selected.

Table 4: Results of the “Quality of the materials” question – EV different (Q2)

<table>
<thead>
<tr>
<th>Options</th>
<th>Shingle A (Risk Taking)</th>
<th>Shingle B (No Risk)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Values</td>
<td>-$167</td>
<td>-$207</td>
</tr>
<tr>
<td>Expected Utilities n°1 (+10%)</td>
<td>-$186</td>
<td>-$207</td>
</tr>
<tr>
<td>Expected Utilities n°2 (+20%)</td>
<td>-$210</td>
<td>-$207</td>
</tr>
<tr>
<td>Percentage</td>
<td>72%</td>
<td>28%</td>
</tr>
</tbody>
</table>

These computations show how the certainty effect impacts the participants’ choices. The influence of the certainty effect differs between participants. Some are not affected by this behavioural pattern, however some are influenced by it, and they increased the probability of risk of the question linked with that pattern. By reacting like this when externalities are not considered, they are avoiding the best option in terms of expected values. An aggregation of all these types of decisions could represent non-negligible losses for construction projects.

5 CONCLUSION AND RECOMMENDATIONS

This experiment shows the impact of one behavioural pattern, the certainty effect, on construction project leaders when they have to make a decision under risk. When this pattern is present in the question, they are in the majority risk-avoiding. This can lead to some losses on the construction project. This happens when the risk-taking option is more attractive in terms of expected values. Some respondents avoided the
risk and took the safer option, which leads to small losses. Aggregated together, these small losses may represent significant losses for the construction project.

The “certainty effect” is not the only behavioural tendency which has been studied for its influence on decisions under risk. Other behavioural tendencies such as “loss aversion” may have an impact on construction project leaders’ decisions as well. What’s more, this impact may be more or less important depending of some critical factors for a construction project, such as the cost performance or the experience of the decision maker.

This application of behavioural economics, and more precisely of prospect theory, on common decisions made frequently and quickly by construction leaders helps to understand how these decisions are made for a construction project. Understanding them can lead to the prevention of the losses generated by illogical behavioural patterns. The final goal would be to quantify and prevent these losses by detecting those decisions and help the construction leaders when they have to deal with them.

Acknowledgements

The writers gratefully acknowledge all the participants of this experiment who made this study feasible and NSERC for supporting it.

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APPLYING THE CHRONOGRAPHICAL APPROACH FOR MODELLING TO DIFFERENT TYPES OF PROJECTS

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Abstract: Graphical modeling is considered to be a suitable approach for displaying project data because of its ability to effectively communicate information. To meet this objective, the Chronographic Approach analyses the layout of the user interface in the spatial dimension and discusses the suitable visual parameters and their associated values. The main goal is to communicate information clearly and effectively through a visual graphical representation of the schedule. This paper discusses the application of the Chronographical Approach to modeling different types of projects, such as buildings and infrastructure. The graphical approach describes how the schedule information can be communicated using tabular and graphical interfaces, in order to manage specialties, locations, means, processes and constraints on different strata and show them either separately or combined using layering, sheeting, juxtaposition, alterations and permutations while allowing for groupings, hierarchies and the classification of project information. The result is the presentation of the same project schedule through different compatible approaches. The planner has the ability to switch from one approach to another by changing the graphical parameters. In this way, graphic representation becomes a living, transformable image, thus assisting planners in solving problems of a variable nature, and simplifying site management while simultaneously utilizing the visual space as efficiently as possible.

1 BACKGROUND

1.1 Graphical modeling of projects’ schedules

Over time, graphic modeling has become an essential tool for project managers. Project schedules represent the graphical modeling of project performance that serves as decision support tool. In order to construct a model, we isolate a class of phenomena and try to report on them using a number of assumptions and rules. As a simplification of the world, every model has its limitations and its range of validity (Legay, 1997). Facing increasingly complex processes and procedures, and multidisciplinary infrastructures, a model with a clear visualization can facilitate the demonstration of the necessary information, and becomes a useful tool for decision making. Shen-Hsieh et al (2002) support the fact that each decision is a step based on the experience and intuition of the manager, and remains subjective. Graphical tools can easily summarize the information in order to improve response time and facilitate decision making for managers, designers, and other stakeholders to a project. What cannot be modelled cannot be properly managed. Any model must allow proper identification of a problem’s source, or even anticipate them upstream. The aim is to improve the level of coordination and the ability to identify problems. Karavakis et al (2010) mention that the extraction of the desired data is facilitated from simple graphical interfaces.
Visual representation usually allows for faster data exploration and often provides better results, especially in cases where automatic algorithms fail (Keim, 2002). According to Friedman (2008) the main goal of data visualization is to communicate information clearly and effectively through graphical means. Bertin (2005) notes that visual perception has three sensitive variables: the two planar dimensions and the variation of the mark on the plane. For comparison, sound perception and its representations (such as scriptural or mathematical), possess only two variables. Graphs are understood differently than text, i.e. the former is understood globally, whereas the latter is understood sequentially. In addition, graphs can act as both a type of artificial memory and as a research tool in that they allow for the simultaneous display of the general structure, as well as the details and exceptions: they can show the leaves, the branches and the whole tree at the same time (Bertin, 2005).

1.2 Actual Limitation for Graphical modeling of Project schedules

Kuo et al (2010) states that the development of methods of presenting information in building a multi-mode system will improve access to and understanding of the project information required for each. They also state that although technological developments today enable the development of high performance tools, the fact remains that the current planning software only partially meets the demand of managers. Francis and Miresco (2006b) remark that many weaknesses are associated with the existing scheduling software. None of this software is intended for the planning of all types of projects. In addition, they are only directed by activities and cannot graphically use the other constraints, such as resources or work area, to present a production schedule. We can also remark that the proposed graphical schedule is global. These systems do not use multiple sheets, like spreadsheets, in order to manage lots separately. They also do not use multiple layers, as CAD does, in order to lay out data and constraints on different layers, thus allowing managers to improve the graphical visualizations of the schedule. Consequently, we can note the complexity encountered in the following the project schedule on screen (Fisk 2010; Francis 2004).

Francis and Miresco (2006b) states that the actual situation of project scheduling demonstrates that traditional methods seem to be unable, individually, to answer all planners’ needs, to solve multiple kinds of problems or to represents all types of projects. The managers have to deal with various project types and they are confronted with problems of different natures. Modeling information using several strategies and displaying them on numerous angles of points of view seems to be appropriate as a decision-making tool. It is thus relevant to model simultaneously more than one scenario and to perform analyses in order to improve the works coordination, optimize the performance execution, reduce risks and minimize uncertainties. In addition, the quality of needed information to be displayed on the project schedule model, and the required level of detail depends on the role and position of an entity in the project and the hierarchical reporting of the manager. As an example for a building project, the primary role of the general contractor's project manager is to manage the project site. This manager is responsible for coordinating the deliverables of the subcontractors, monitoring the progress of work, quality control and insurance and health security, managing workspaces, storage areas, the vertical and horizontal circulation of materials on site and the reverse cycle for recycling and scrap. Schedules and progress monitoring are preferably arranged according to the price schedule. The sub-contractor's manager is responsible for the planning, coordinating and monitoring of the daily or weekly progress of work teams. He also manages the supply according to the site progress.

Francis and Miresco (2014) state that subcontractors and general contractors do not share the same goals. Figure 1 shows the intersection between two schedules, the vertical for the general contractor and the horizontal for the subcontractor. The general contractor organizes project planning and monitoring vertically in which he coordinates the work and deliverables of the various subcontractors. He is interested in completing the project within time and budget. The sub-contractor promotes the optimal use, the leveling and the improvement of the productivity of his teams between the different projects in which he is involved to the detriment of the overall health of these projects. Francis and Miresco (2013) state that a schedule capable of providing a user-friendly tabular and graphical interface, able to easily structure project information, able to adapt to work in an interactive, changing environment, and accept productivity variation, is necessary for everyone on the site, especially the foremen and superintendents.
This paper discusses the application of the Chronographical Approach to modeling different types of projects, such as buildings and infrastructure. The graphical approach describes how the schedule information can be communicated using tabular and graphical interfaces, in order to manage specialties, locations, means, processes and constraints on different strata and show them either separately or combined using layering, sheeting, juxtaposition, alterations and permutations while allowing for groupings, hierarchies and the classification of project information. In this way, graphic representation becomes a living, transformable image (Francis 2013).

1.3 The Chronographical Modelling Approach

As designed by Francis (2013), the Chronographic Approach analyses the graphical representation of the schedule and discusses the suitable visual parameters and approaches. The main goal is to communicate information clearly and effectively using tabular and graphical means. The Chronographic Approach defines five categories, called Entities (Table I) as modelling parameters:

- The Physical Entities represent all the elements required to perform the construction operations (e.g. activities, labor, permanent materials, operators or haulers, construction site locations).
- The Associative Entities indicate the dependencies among the Physical Entities. They can represent: Relationships and Constraints; Hierarchy; Grouping; c) Layering and Sheet; and Attributes.
- The Functional Entities characterize the Physical or Associative Entities. These entities may denote deterministic relations, decisional or probabilistic functions or Temporary Functions.
- The Scale Entities designate the external measuring units (e.g. Time, Cost, Quantity, % Progress, Risk, Performance, or Resources) or internal measurement.
- The Direction Entities present the coordinates on up to three Cartesian axis systems. Each axis allows for no scale, single scale with cumulative data, or grouping.

<table>
<thead>
<tr>
<th>Physical (PE)</th>
<th>Associative (AE)</th>
<th>Functional (FE)</th>
<th>Scale (SE)</th>
<th>Direction (DE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities / Deliverables</td>
<td>Relationships &amp; Constraints</td>
<td>Deterministic ; Probabilistics &amp;</td>
<td>Time</td>
<td>No axis (Cyclic scales)</td>
</tr>
<tr>
<td>Direct &amp; Indirect Labours</td>
<td>Hierarchical</td>
<td>Heuristic</td>
<td>Cost</td>
<td>Single axis</td>
</tr>
<tr>
<td>Operators / Haulers</td>
<td>Grouping</td>
<td>Fixed and variables</td>
<td>Quantity</td>
<td>Two axis</td>
</tr>
<tr>
<td>Permanent materials</td>
<td>Layering</td>
<td>Optimization</td>
<td>% Progress</td>
<td>Scaled, Grouped or none</td>
</tr>
<tr>
<td>Emplacements</td>
<td>Sheet (Sub)</td>
<td>Decision</td>
<td>Performance</td>
<td>Three axis</td>
</tr>
<tr>
<td>Type of contract</td>
<td>Attributes</td>
<td>Generalized</td>
<td>Risk</td>
<td>Scaled, Grouped or none</td>
</tr>
</tbody>
</table>

Table 1: Entity Types (Francis, 2013)
2 APPLYING THE CHRONOGRAPHICAL APPROACH FOR MODELLING DIFFERENT TYPES OF PROJECTS

Managers have to deal with various project types and they are confronted with problems of different natures. To answer these various needs, managers must currently handle information within several incomplete methods, which are incompatible between each other. Although the existence of several scheduling methods is criticized because of the lack of compatibility, the existence of a complete model, which can present information within different and compatible facets, is considered as an optimal solution (Francis and Miresco 2006b). To meet this objective, the Chronographic Approach analyses the layout of the user interface in the spatial dimension and discusses the suitable visual parameters and their associated values. The main goal is to communicate information clearly and effectively through a visual graphical representation of the schedule.

Francis (2013) describes the preparation steps for the project schedule using the Chronographical Model. First, we should define the necessary Physical and Associative Entities that simulate the construction operation: a) the work breakdown structure (WBS) for deliverables, activities and tasks; the work location breakdown structure (WLBS), by dividing the site locations; b) the Organization Breakdown Structure (OBS) for the composition of project teams and specialities. Then we define the attributes’ entities and we define the Cartesian axis and their measurements. We can use zero to three Cartesian axes; external and internal measurement scales; hierarchy, grouping, layering, sheeting and attributes; relationships and constraints to model construction operations through the Physical Entities (e.g. activities, labour, permanent materials, operators or haulers, construction site locations).

The result is the presentation of the same project schedule through different compatible approaches. The planner has the ability to switch from one approach to another by changing the graphical parameters. In this way, graphic representation thus assists planners in solving problems of a variable nature, and simplifying site management while simultaneously utilizing the visual space as efficiently as possible.

2.1 Linear Projects

Developed by the US Navy Department in the early fifties, linear methods are designed to ensure continuity of resource use and support a stable and optimized production. Trimble (1984) mentions that schedules oriented by resources are more realistic than those dominated by activities. These methods show graphically any imbalance due to uneven progress of activities and quickly allow the manager to quantify the deviation (Khisty 1970).

These methods have been the subject of countless improvements either through their graphical models and their methods of calculation. These methods are therefore well-suited to road, highway, railway and...
pipeline projects. We note that within these projects the machinery and the work teams operate continuously in a linear way. The difference with the simulation methods based on CYCLONE is that simulation are used to optimize the production, versus a target of linearity and operating in parallel way between the successor activities for the linear methods.

Figure 2 shows a linear project for installing a drainage system. In these types of projects, mainly the activities are linear. However, the schedule could combine simultaneously linear activities (such as excavation and backfill) and repetitive activities (such as manholes). The approach uses two axes. Time is shown as the scale of the horizontal axis and the units (meter) scale the vertical axis.

2.2 Repetitive Projects

Repetitive projects are projects where assigning tasks are usually repeated from unit to unit or from floor to floor. This differentiates them from the linear projects where machinery is operating continuously. We can distinguish two types of repetitive projects: a) Vertical projects such as multi-storey building; and b) Horizontal projects such as the construction of several similar units.

2.2.1 Repetitive Vertical Projects

In repetitive vertical projects, such as a multi-storey building, some activities are non-repetitive activities, such as the foundation and the roof, while others are repeated from one floor to another, such as structure, architectural finishing and services.

![Figure 3: Example of scheduling Repetitive Vertical Projects](image)

Figure 3 proposes an approach that uses two axes. Time is shown as the scale of the principal direction. The second direction shows the different levels: Foundation (non-repetitive) and repetitive floors (1 to 4). Thus, these projects combine mainly repetitive activities (structure and finishing), and occasionally non-repetitive activities (Foundation and Roof) or linear operations (Envelope). Team work describes the detailed operation of these buildings symbolizing the Physical Entity. In this figure we can track the sequence of work of each team on the different floors.

2.2.2 Repetitive Horizontal Projects

In repetitive horizontal projects, such as the construction of several similar units, most activities are repetitive. In these horizontal projects the work of several units can be planned simultaneously to accelerate the project schedule. The number of specialty teams can be calculated by the quotient of the duration required to complete a single unit by the total time available to complete the work of this specialty for all units.

Figure 4 proposes an approach that uses two axes. Time is shown as the scale of the principal direction. The second direction shows the repetitive horizontal buildings. Team work describes the detailed operation of these buildings symbolizing the Physical Entity. In this figure we can track the sequence of
work of each team on the different buildings. For example, the buildings’ foundations are executed by two teams: “Found 01” and “Found 02”. The team “Found 01” consecutively executes the buildings 1, 3, 5 and 7 (see also Figure 5). The time required for building is 4 days and the total duration of the work of this team is 16 days.

![Diagram of scheduling Repetitive Horizontal Projects](image)

Figure 4: Example of scheduling Repetitive Horizontal Projects

The utilization of resources as a second direction represents an effective solution for showing resource allocation and levelling. Manpower occupations are easily optimized and work over-load or under-load are avoided. Francis (2013) classifies this approach as “Chrono-Allocation Modelling: Using Resources as a second direction”. Figure 5, shows an approach with two directions. Time shows the scale of the principal direction. The second direction shows teams. This example uses: two (2) teams for foundation works, three (3) teams for structure; four (4) teams for finishing. It should be noted that teams use a scale of dark colours and building uses a scale of light colours.
2.3 Non-Repetitive Projects

Non-repetitive projects are projects where the intervening work teams are specific. Generally, there are only a few repetitive activities. This type of project is well-planned through a time-scaled Precedence network (unfortunately not modeled by commercial scheduling software) or a Gantt/Precedence Diagram, modeled by commercial scheduling software such as MS-Project or Primavera. The difference is that time-scaled Precedence networks plot activities in parallel and in series while in a Gantt/Precedence Diagram each activity is drawn on a separate line resulting in the non-optimal use of the modeling area.
Figure 6 shows a non-repetitive project modeled with the Chronographic Method. The difference between this method and the time-scaled Precedence network is the use of internal divisions and internal relationships as function of quantities or productions (Francis and Miresco 2006a). In this figure, the activities that represent the implementation of walls are divided into four internal divisions as a function of quantities or work steps. The two first divisions are critical while the two other divisions possess margins. The three activities Electricity, Doors & Windows and Plumbing are related to the end of the first internal division with Finish-to-Start relations. Their end dates should be completed before the start of the last division of the implementation of walls.

2.4 Scheduling Projects by Working Areas

Most building project activities are carried out by subcontractors. As a result, the majority of project resources are assigned to subcontractors who are responsible for the planning and management of their work programs. Thus, project planning complexity is generally related to the coordination of the subcontractors’ work. The planners of multi-storey building projects also face many other difficulties such as avoiding conflicts of use within limited workspace, the organization of on-site traffic to avoid congestion, the supplying, handling, and storage of project materials, and waste management and recycling (Francis and Miresco 2013). Kuo et al (2010) quote that assembly sequences require an interface of spatial and temporal information. Therefore, a schedule oriented by work areas is considered to be an appropriate approach for planning building projects.

Figure 7: Example scheduling Projects by Working Areas
Figure 7 shows the construction work during week 12. In this plan, we can see: a) Areas 1, 2, 3 and 9 are vacant demonstrating underutilization of the work area; b) the conflict between teams 1 and 2 in Zone 4; and c) team 3 is used at the same time in both zones 6 and 8. Using this type of planning we can easily manage conflicts and adjust the plan manually during weekly site meetings without complex calculations.

3 CONCLUSION

The present paper discusses the application of the Chronographical Approach to modeling different types of projects, such as buildings and infrastructure. The main concern is studying the modalities of information representation. The graphical approach describes how the schedule information can be communicated using tabular and graphical interfaces, in order to manage specialties, locations, means, processes and constraints on different strata and show them either separately or combined using layering, sheeting, juxtaposition, alterations and permutations while allowing for groupings, hierarchies and the classification of project information. The Chronographical Approach defines the graphical parameters that model the construction operation, establishes constraints, and determines directions and scales. Using these parameters, the planner can schedule the construction operation by laying out project information under diverse approaches. The result is the presentation of the same project schedule through different compatible approaches. The planner has the ability to switch from one approach to another by changing the graphical parameters. In this way, graphic representation becomes a living, transformable image, thus assisting planners in solving problems of a variable nature, and simplifying site management while simultaneously utilizing the visual space as efficiently as possible. The use of understandable visual communication methods facilitates the sharing of information while aiding in planning and controlling project activity, including the improvement of productivity, performance and effectiveness.

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AMÉLIORER LES PROCESSUS DE COMMUNICATION SUR LES CHANTIERS DE CONSTRUCTION À L'AIDE DES TECHNOLOGIES MOBILES ET DES TECHNOLOGIES INFONUAGIQUES

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Résumé: L'industrie de la construction est un secteur dans lequel la circulation de l'information, entre les diverses disciplines de projet impliquées, est intense. Paradoxalement, on constate que le secteur de la construction repose sur un processus de communication s'appuyant sur un format papier ainsi que sur des moyens obsolètes, tels que le téléphone, le télecopieur ou le courriel, afin de partager et d'accéder aux données de projet. Pourtant, malgré le fait que les problématiques de circulation de l'information se répercutent sur l'ensemble des phases de construction, on observe que la phase de réalisation est de loin celle qui dépend le plus de l'information et qui, malheureusement, est la moins informatisée. En considérant le rythme avec lequel évoluent les tablettes et les téléphones intelligents, les technologies mobiles (TM) offrent désormais des moyens efficaces afin de remplacer la communication papier sur le chantier par des solutions numériques et infonuagiques. Cet article traite des résultats d'une recherche visant à comprendre comment le déploiement des TM et des technologies infonuagiques peut améliorer l'accès à l'information et faciliter la communication entre les intervenants, lors de la phase de réalisation. L'objectif principal de ce papier est de démontrer les bénéfices à employer ces technologies sur les chantiers lorsqu'il s'agit d'un contexte d'administration de projet. Les résultats de cette recherche s'appuient sur la réalisation de trois études de cas dans lesquelles un total de 58 intervenants ont participé aux diverses étapes de cette étude, échelonnée sur une période de quinze mois. L'ensemble des données est issu de la réalisation d'observations \textit{in situ}, d'entrevues et de l'envoi de questionnaires.

Mots-clés : Technologies mobiles (TM), technologie infonuagique, NTIC, environnement virtuel, BIM, Traitement de l'information.

1 INTRODUCTION

L'industrie de la construction est un secteur dans lequel il y a une intense circulation de l'information entre les diverses disciplines de projet (Hewage et Ruwanpura, 2006). La réussite des projets repose donc sur la capacité des intervenants à échanger de l'information fiable, cohérente et en quantité suffisante afin de réaliser le produit (Deibert, Hemmerk et Heinzl, 2009). Paradoxalement, on observe que les projets de construction reposent sur un processus de communication s'appuyant sur un format papier et sur des moyens obsolètes, tels que le téléphone, le télecopieur ou le courriel, afin de partager et d'accéder aux données de projet (Dave, Boddy et Koskela, 2010). Malgré le fait que les problématiques de circulation de
l'information se répercutent sur l'ensemble des phases de construction, on constate que la phase de réalisation est de loin celle qui dépend le plus de l'information et qui, malheureusement, est la moins informatisée (Tam, 1999). Le papier demeure le moyen le plus répandu, afin de collecter l'information et de la partager, et ce, en dépit des améliorations informatiques de ces dernières années, par exemple, les technologies mobiles (TM) telles que des tablettes et des téléphones intelligents. Considérant le rythme avec lequel ces outils évoluent, les TM offrent désormais des moyens, afin de remplacer la communication papier sur les chantiers, par des solutions numériques performantes. En parallèle, les recherches concernant les nouvelles technologies de l'information et de la communication (NTIC) évoluent et celles-ci énoncent que ce type de technologies offre de nouveaux moyens de communication plus performants, en améliorant notamment le traitement, la mise en mémoire, la diffusion et l'échange de l'information parmi les intervenants. Parmi ces technologies, les plateformes infonuagiques se sont relevées des outils pouvant contribuer à l'amélioration des processus de communication. Ceci s'explique en raison de la centralisation de l'information sur « des serveurs distants interconnectés par Internet, permettant un accès en réseau, à la demande, à un bassin partagé de ressources informatiques configurables, externalisées et non localisables »1. Les technologies nuagiques offrent conséquemment, des alternatives à l'hébergement et aux traitements de données conventionnelles, par des services virtuels disponibles pour les intervenants de projet, et ce, non seulement partout où ils le souhaitent, mais aussi, en temps réel. Malgré tout, peu de recherches exposent véritablement les améliorations de ces outils, notamment en raison d'un manque de recherche et de développement (R&D) dans le secteur de la construction.

Cet article traite donc des résultats d'une recherche visant à comprendre et définir comment le déploiement des TM et des technologies infonuagiques peut améliorer l'accès à l'information et faciliter la communication entre les intervenants, durant la phase de réalisation. Celle-ci se décomposse en deux phases soit, une évaluation du taux de pénétration des TM dans l'industrie de la construction du Québec (Phase 1) (Frenette et al., 2014) et, une réalisation d'études de cas, afin de développer un cadre d'opération issu d'une collecte de données in situ (Phase 2). Cet article présente la phase 2 de cette recherche qui expose les bénéfices observés, lors de l’emploi d’applications logicielles sur les chantiers.

2 LA GESTION DE L'INFORMATION SUR LES CHANTIERS ET LES TECHNOLOGIES MOBILES

Lebeau et Plourde (2003) ont défini que l'industrie de la construction représente un secteur singulier, en raison de la nature temporaire de ses équipes de travail, ayant pour principale conséquence d'affecter la coordination des équipes de réalisation et de gestion de projets. Pourtant, le cheminement de l'information est une composante essentielle affectant toutes les autres séquences d'interventions dans la chaîne d'approvisionnement (Koskela, 2000). Les recherches Koskela (2000) démontrent l'importance de la gestion de la production en phase de réalisation et elles identifient que les processus de production actuels négligent l’aspect de la circulation de l'information (Koskela, 2000). Pourtant, il est reconnu que la mauvaise gestion de l'information a un impact sur le processus de décision, résultant ainsi à d'importantes pertes de temps et d'argent lors de la phase de réalisation (Lucas, Bulbul et Thabet, 2013). Cette situation est liée à une coordination inefficace et inadéquate de l'information, résultante d'une communication insuffisante, inopportune, imprécise et contradictoire lors des échanges de données (Lucas, Bulbul et Thabet, 2013).

2.1 Les problématiques de gestion de l’information sur les chantiers

L'industrie de la construction repose sur des processus traditionnels d'acquisition et d'échange de données (Dave, Boddy et Koskela, 2010). Des études ont pourtant démontré que l'intégration des technologies, et particulièrement des TM sur les chantiers, a un potentiel considérable d’accroissement de l’efficacité des processus de communication, au sein des équipes de projet (Chen et Kamara, 2005). À l'occasion, on observe que 65 % des reprises de travaux effectuées par les entrepreneurs sont attribuables à de l'information insuffisante sur le chantier, perturbant le taux de production des équipes de travail (Bowden, 2005). Il est déterminé que le manque de correspondance dans les méthodes de gestion

1 Source : Office de la langue française. [En ligne]. [http://www.oqlf.gouv.qc.ca/] (Consulté 16/06/14).
d'information des divers intervenants est directement responsable du manque d'information sur le terrain (Bowden, 2005). Afin de pallier à ces problématiques, les intervenants ont besoin de moyens efficaces, pour échanger d'information dynamique, afin de coordonner les exigences et les objectifs ainsi que résoudre les conflits, dans un environnement où l'évolution des données, des documents et d'information est en perpétuel changement (Dossick et Neff, 2011). En contrepartie, on constate que la coordination de l'information est complexe, en raison de la pression du calendrier, des exigences de productivité et des diverses méthodes de travail des entreprises impliquées dans le processus.

2.1.1 L'accès à l'information

L'accessibilité à l'information est un enjeu critique pour le succès des projets. En revanche, pour être efficace, l'information disponible doit être de qualité et en quantité suffisante afin d'être utile pour les intervenants (Saram et Ahmed, 2001). L'acquisition et le transfert de l'information représentent donc des éléments majeurs dans le succès de l'administration des projets (Tsai, 2009) et il a été établi que les TM peuvent avoir un rôle à jouer en matière d'accessibilité aux données de projet. Saidi, Haas et Balli (2002) ont appliqué six critères d'évaluation afin d'établir le potentiel des TM à augmenter le temps effectif de travail sur le chantier soit : 1) le suivi de qualité, 2) suivi des matériaux, 3) suivi des quantités, 4) suivi des fiches signalétiques, 5) l'accès aux plans de construction et 6) les demandes d'information. Ils ont alors constaté que d'importants délais de production pourraient être évités grâce à l'utilisation des TM en chantier. Ce constat s'appuie sur le fait qu'un temps de contrôle qualité pourrait être potentiellement réduit d'environ 50 à 70 % en raison d'un meilleur échange de données entre les intervenants de projet.

2.2 Les problématiques d'adoptions technologiques

Le secteur demeure une industrie réfractaire aux changements et elle est réticente à adopter de nouveaux processus axés vers l'usage des technologies et les TM ne font pas exception (Bowden, 2005). Les raisons invoquées font état de la perception d'un manque de retour sur les investissements et de la rareté d'exemples concrets de réussite d'implantation de ce type de technologie. On observe alors que le fait que leur apparition soit relativement récente, le manque d'études de cas et la perception d'un faible rendement de l'investissement ajoutent un frein à leur mise en place définitive (Bowden, 2005). En se penchant sur cette problématique, on observe que l'industrie est celle qui investit le moins dans les NTIC et l'enseignement supérieur (Dale, Mun et Kevin, 2005). Ce manque de financement entraîne en conséquence, des lacunes sur le plan des connaissances et n’incite pas le secteur à revoir ses pratiques. Il contribue également à une résistance aux changements généralisée, qui représente la première source d'échec d'implantation des technologies au sein des entreprises (Maurer, 1996), appuyant ainsi cette prise de position et les nombreux cas d'échecs subis par le secteur par rapport à l'intégration des TM. Ce constat vient soutenir l'importance de la R&D en soutien au secteur.

2.3 Les technologies mobiles et les technologies nuagiques en chantier

À la lumière de certaines recherches, l'évolution des TM apporte des fonctionnalités et des retombées respectant les contraintes de mobilité des intervenants. D'abord, parce que les appareils sont de plus en plus petits, légers et portables s'adaptant davantage aux activités d'une industrie mobile (Lee, Cheng et Cheng, 2007). Ensuite, il a été défini trois types de bénéfices issus de l'usage des TM soit : 1) l'amélioration de la saisie d'information en chantier, 2) l'amélioration de l'accessibilité aux informations de projets et 3) la réduction des erreurs en chantier par l'amélioration de l'intégrité des données (Bowden, 2005). On observe également que l'exploitation des TM offre des moyens de transformation de données brutes, en informations utiles pour la gestion rapide de celle-ci (Gamage, 2011). Couplés aux technologies nuagiques, les TM peuvent s'avérer une composante à forte valeur ajoutée, afin de centraliser, partager et gérer l'information à travers l'ensemble des équipes de projets, par exemple, en offrant la possibilité au personnel de terrain d'être informé rapidement des activités et des événements de chantiers (Trupp et al., 2004). Selon une étude conduite par Forgues et Staub-French (2013), les technologies infonuagiques apporteront d'importants changements dans le secteur notamment en raison qu'il y a de plus en plus de solutions orientées vers ces types de services. Les études concernant l'implémentation des technologies en construction font état de quelques déductions qui expliqueraient cette tendance migratoire vers des solutions infonuagiques, soit :
- les frais d'accès se font mensuellement, éliminant des investissements coûteux en infrastructure;
- tous les intervenants ont un accès en tout temps aux plateformes, aux outils et aux données;
- les problèmes d'interopérabilité et de gestion des versions logicielles sont éliminés.

2.4 Les TM et l'infonuagique au service des projets de construction

À la lumière de ce qui précède, l'adoption des nouvelles technologies, en phase de réalisation, représente une avenue prometteuse, afin de pallier aux enjeux actuels du secteur. Les raisons justifiant cette position sont que l'exploitation de ces outils permettra aux intervenants d'accéder rapidement et simplement à un large ensemble de données. D'une part, par l'intermédiaire d'outils adaptés aux conditions de chantier, c'est-à-dire des appareils légers, petits et portables. Ensuite, en raison d'une information centralisée à l'aide des technologies infonuagiques, permettant d'améliorer le traitement, la gestion et la diffusion de l'information sous diverses plateformes informatiques, telles que des ordinateurs et des plateformes mobiles. En revanche, on constate que les principaux obstacles à l'atteinte de leur potentiel et de la mise en place de ceux-ci sont liés, d'une part, à l'obsolescence rapide des technologies et, d'autre part, à l'absence de standards d'utilisation (Venkatraman, 1994). Il est alors primordial que les entreprises et utilisateurs demeurent à l'écoute des avancées technologiques de ces outils et que la R&D soit en mesure d'accompagner le secteur de la construction dans la modernisation de ses pratiques.

3 MÉTHODOLOGIE

Cette recherche-action s'appuie sur la réalisation de trois études de cas réalisées in situ dans le but d'identifier les retombées réelles d'exploitation des TM, lors de la phase de réalisation. La sélection de ces études de cas fait suite au développement du canevas construit lors de l'enquête réalisée en Phase 1 (Frenette et al., 2014). Ces choix s'appuient sur le fait que ces entreprises représentent les niveaux les plus avancés en matière de déploiement et du contexte d'utilisation de TM au Québec. L'étude de cas A représente un entrepreneur général. L'étude de cas B est constituée d'un consortium d'entrepreneurs généraux, tandis que l'étude de cas C est un donneur d'ouvrage. L'échantillon est orienté vers les intervenants de chantier responsables du suivi des différentes activités, lors de la phase de réalisation, soit les intervenants de terrain, de gestion et de surveillance. L'étude de cas A est constituée d'intervenants de terrain, tels que les surintendants, les contremaîtres ainsi que les intervenants de gestion, tels que les gestionnaires de construction. L'étude de cas B est constituée d'intervenants de surveillance, tels que ceux de contrôle de la qualité et d'intervenants de terrain, tels que le contremaître de l'entrepreneur spécialisé. Finalement, l'étude de cas C est constituée d'intervenants de surveillance, tels que les inspecteurs de chantier du donneur d'ouvrage, ainsi que d'intervenants de gestion, tels que les gestionnaires de construction.

3.1 Méthode de collecte de données

Cette recherche-action se décompose en cinq étapes : 1) envoi d'un questionnaire de démarrage, 2) entrevues semi-dirigées de démarrage, 3) observation en chantier, 4) envoi d'un questionnaire de fin et 5) entrevue semi-dirigée de fin de test. L'objectif des étapes 1 et 2 est d'identifier les besoins et les défis actuels des intervenants de chantier. L'objectif de l'étape 3 est d'observer in situ l'utilisation de la TM. Les étapes 4 et 5 visent à déterminer les bénéfices réels obtenus suite à l'usage des TM en soutien au mécanisme de traitement de l'information lors de la phase de réalisation. L'Analyse quantitative s'appuie sur des métriques établies lors du projet pilote et ils correspondent à 1) Économie de temps, 2) Suivi des coûts, 3) Suivi de la qualité et 4) Gestion de projet. L'analyse qualitative s'appuie sur l'observation en chantier permettant d'étudier les différents contextes d'utilisation en situation réelle, en fonction des choix technologiques réalisés. Un total de 58 participants ont participé à l'étude. 44 ont répondu au questionnaire de l'étape 1, tandis que 30 participants ont été rencontrés en entrevue en étape 2. En étape 3, 21 participants ont été observés dans leur environnement, sur une période de 1 mois. Un total de 46 participants ont répondu au questionnaire en étape 4, tandis que 8 participants ont été rencontrés en étape 5. L'ensemble des cadres responsables de l'intégration des TM a été rencontré en entrevue, afin de connaître la justification de l'implantation de ces outils dans leur contexte. Les études de cas A et
B utilisent des applications logicielles de nature commerciale, tandis que dans l'étude de cas C, on a fait usage d'une application de conception maison. L'ensemble des questionnaires qui ont été produits est inspiré des travaux réalisés par Rivard (2000), Bowden (2005) et Ruwanpura, Hewage et Jergeas (2008).

3.2 Analyse des données

Les résultats présentés s'appuient sur des axes de bénéfices identifiés, à la suite d'essais effectués lors de la réalisation d'un projet pilote conduit par Forgues et Staub-French (2013). Ces axes de bénéfices sont des champs de transformation regroupés sous cinq thématiques, dont quatre seront présentées dans cet article. Les données obtenues à l'aide des différents questionnaires ont été traitées et compilées à l'aide d'un chiffrier électronique, tandis que les données obtenues à la suite des entrevues ont été transcris à mot à mot afin d'être codées, traitées et comparées. Les données issues de la période d'observations ont permis d'appuyer les résultats obtenus par des citations et des artefacts.

4 CADRE CONCEPTUEL

4.1 En route vers une maturité dans l'utilisation des TM

À la suite de la présentation des résultats de l'enquête provinciale (Phase 1), un cadre conceptuel a été proposé et les résultats ont été présentés dans l'article de Frenette et al. (2014). Ce cadre s'appuie sur les différents types d'exploitation des TM en fonction de la nature et du type d'utilisation des applications mobiles exploitées par les différentes entreprises participantes. Il a été défini, à l'aide des données issues des entrevues avec des intervenants clés des entreprises innovantes et la Figure 1 en présente le canevas.

![Diagramme de maturité exploitation TM](image)

Figure 1 - Diagramme de maturité d'exploitation des TM en phase de réalisation

Ces catégories permettent de connaître la maturité des entreprises, en fonction du type d'applications utilisées, s'appuyant sur le degré de complexité de mise en place. En l'occurrence, la consultation de documents (N1) correspond au plus bas niveau de maturité tandis que l'administration et la gestion de projets (N4), au niveau le plus élevé. Spécifiquement, les catégories 1 à 3 demandent des changements mineurs au sein des entreprises et représentent des usages passifs de la TM. En revanche, la catégorie 4 représente des changements majeurs dans les pratiques d'une organisation et requiert un usage actif des utilisateurs. La principale raison de cette coupure est que les catégories 1 à 3 n'imposent pas de changements majeurs dans les méthodes de travail et ne demandent pas de révision des processus de travail, telle que suggère la catégorie 4. Ces catégories permettent alors d'évaluer la maturité des entreprises en fonction de l'utilisation des TM dans les projets. Suite à l'analyse des résultats de cette phase, il a été établi que le Niveau 4 est celui qui demande le plus d'efforts, lors de l'implémentation, et ce, tant d'un point de vue financier que celui de la transformation des pratiques. En revanche, ce niveau est celui ayant le plus haut potentiel de transformation et d'amélioration des mécanismes de traitement et de gestion de l'information lors de la phase de réalisation.
5 CONTEXTE D'EXPLOITATION DES TM ET DES TECHNOLOGIES INFONUAGIQUES

5.1 Étude de cas

Chacune des entreprises a effectué son choix technologique en fonction de son rôle et de son mandat dans les projets. Le Tableau 1 présente le sommaire du contexte des études de cas ayant participé à cette étude et les applications logicielles qui leur sont associées.

Tableau 1 - Technologies mobiles sélectionnées et fonctionnalités de base

<table>
<thead>
<tr>
<th>Étude de cas</th>
<th>Étude de cas</th>
<th>Étude de cas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rôle</td>
<td>Entrepreneur</td>
<td>Consortium d'entrepreneurs</td>
</tr>
<tr>
<td>Période d'intervention</td>
<td>8 mois</td>
<td>12 mois</td>
</tr>
<tr>
<td>Contexte d'exploitation</td>
<td>Usage interne seulement</td>
<td>Usage avec l'ensemble des disciplines du projet</td>
</tr>
<tr>
<td>Niveau de maturité¹</td>
<td>Niveau 3</td>
<td>Niveau 4</td>
</tr>
</tbody>
</table>

¹ Veuillez consulter l'article Frenette et. al. (2014) pour obtenir de l'information supplémentaire concernant le niveau de maturité.
² Application logicielle développée par l'entreprise

Note : Liste de fonctionnalités non exhaustive, veuillez consulter les sites web ou guides d'utilisation du fabricant.

5.2 Technologies mobiles

5.2.1 Smart-use

*Smart-Use* est la solution logicielle sélectionnée par l'étude de cas A et correspond à une application de consultation et d'annotation de documents de niveau 3. Celle-ci est conçue pour centraliser des documents PDF 2D et pour permettre leur annotation. Cette application peut être utilisée sur trois plateformes différentes, soit sur un ordinateur, sur une tablette PC ou sur une table *Smart-Use*. Le Tableau 2 présente différentes caractéristiques de l'application logicielle.

Tableau 2 : Fonctionnalités de l'application *Smart-Use*

<table>
<thead>
<tr>
<th>FONCTIONNALITÉS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Comparaison de plans par superposition;</td>
</tr>
<tr>
<td>• Couche d'annotation par usager;</td>
</tr>
<tr>
<td>• Gestion des mises à jour des documents;</td>
</tr>
<tr>
<td>• Outils de mesure (longueur, surface, volume);</td>
</tr>
<tr>
<td>• Administrateur responsable des comptes;</td>
</tr>
<tr>
<td>• Identification de groupes de plans.</td>
</tr>
</tbody>
</table>

5.2.2 Latista

*Latista* correspond à une application logicielle d'administration et de gestion de projets de catégorie 4. Elle est conçue pour capturer l'information en temps réel, sur le site de construction et le Tableau 3 présente différentes caractéristiques de cette application logicielle. *Latista* a été mis en place afin de permettre aux intervenants de contrôle de la qualité de créer des listes de tâches et de travaux à compléter sur une base de données partagée, afin de diminuer le temps de partage de l'information aux autres disciplines.

Tableau 3 : Fonctionnalités de l'application *Latista*

<table>
<thead>
<tr>
<th>FONCTIONNALITÉS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Création de séquences d'opérations;</td>
</tr>
<tr>
<td>• Recherche par filtre (type de travaux, etc.);</td>
</tr>
<tr>
<td>• Production de rapports;</td>
</tr>
<tr>
<td>• Automatisation de l'envoi de rapports;</td>
</tr>
<tr>
<td>• Historique des entrées de données;</td>
</tr>
<tr>
<td>• Historique de modification des données;</td>
</tr>
<tr>
<td>• Service de notifications automatisées.</td>
</tr>
<tr>
<td>• Accès aux plans 2D;</td>
</tr>
</tbody>
</table>
5.2.3 Rétroaction de chantier

*Rétroaction de chantier* est une application logicielle de niveau 4, développée par l'entreprise afin de standardiser les journaux de chantier, en fonction d'un découpage des travaux qui correspond au devis technique produit lors des phases de conception et de planification du projet. Le Tableau 4 présente différentes caractéristiques de l'application logicielle. Cette standardisation de la collecte de données permet une rétrospective juste et rapide des travaux exécutés en fonction des travaux estimés.

**Tableau 4 : Fonctionnalités de l'application *Rétroaction de chantier***

<table>
<thead>
<tr>
<th>FONCTIONNALITÉS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Réalisation de journaux de chantier;</td>
</tr>
<tr>
<td>Réalisation croquis personnelles;</td>
</tr>
<tr>
<td>Création de notes personnelles;</td>
</tr>
<tr>
<td>Notification pour ajustement sur rapport;</td>
</tr>
<tr>
<td>Identification des conditions météo;</td>
</tr>
<tr>
<td>Identification des incidents (environnement ou sécurité);</td>
</tr>
<tr>
<td>Prise de photos et accès aux plans.</td>
</tr>
</tbody>
</table>

6 RÉSULTATS

Cette section traite des données obtenues après l'exploitation des TM, lors de la phase de réalisation des différentes études de cas et s'appuie sur les métriques établies, lors de la conduite du projet pilote. Dans le cadre de cet article, seules les 3 principales retombées sont présentées, suite à l'usage des applications mobiles sélectionnées par les différentes études de cas. Il est à noter que les résultats présentés ci-dessous varient en fonction des résultats obtenus, suite au questionnaire de fin d'essai acheminé aux participants de chacune des études de cas.

6.1 Économie de temps

Cet axe de bénéfices présente les résultats obtenus suite à l'exploitation des applications logicielles. Le Tableau 5 expose le classement des trois éléments principaux identifiés par les usagers des différentes études de cas.

**Tableau 5 - Bénéfices - Économie de temps**

<table>
<thead>
<tr>
<th>Étude de cas A</th>
<th>Étude de cas B</th>
<th>Étude de cas C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapidité d'accès à l'information 3,33</td>
<td>Rapidité de partage de l'information 3,56</td>
<td>Rapidité d'acquisition de l'information en temps réel 3,25</td>
</tr>
<tr>
<td>Rapidité d'acquisition des données en temps réel 3,33</td>
<td>Identification des problèmes sur le site 3,33</td>
<td>Rapidité d'accès à l'information de chantier 3,25</td>
</tr>
<tr>
<td>Optimisation de mes tâches 2,61</td>
<td>Rapidité d'acquisition des données en temps réel 3,22</td>
<td>Rédaction de rapports journaliers 2,88</td>
</tr>
</tbody>
</table>

Échelle
0 - Aucun impact 1 - Impact mineur 2 - Impact modéré 3 - Impact important 4 - Impact très important

*Question : À la suite de votre usage de TM, évaluez l'impact de son utilisation sur le suivi des coûts du projet.*

En dépit de la vocation différente des applications logicielles en vigueur, on constate que les utilisateurs ont senti un impact important dans leur pratique, lors de l'exploitation de ces outils, dans une perspective d'économie de temps. On observe que le niveau d'impact est élevé, et ce, indépendamment du type d'usage des trois études de cas.

---

2 **Voir étude complète** : Frenette, Sébastien. 2015. « Améliorer les processus de communication sur les chantiers de construction à l’aide des technologies mobiles et des technologies infonuagiques ». Mémoire de maîtrise en génie de la construction, Montréal, École de technologie supérieure, 248 p. (sous-presse)
6.2 Suivi des coûts

Cet axe de bénéfices présente les résultats obtenus suite à l'exploitation des applications logicielles. Le Tableau 6 expose le classement des trois éléments principaux identifiés par les usagers des différentes études de cas.

Tableau 6 - Bénéfices - Suivi des coûts

<table>
<thead>
<tr>
<th>Étude de cas A</th>
<th>Étude de cas B</th>
<th>Étude de cas C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Résolution des problèmes sur le chantier</td>
<td>2,39</td>
<td>Résolution des problèmes sur le site</td>
</tr>
<tr>
<td>Diminution de la reprise de travaux</td>
<td>1,61</td>
<td>Diminution de la reprise des travaux</td>
</tr>
<tr>
<td>Prédictibilité du chantier (coût de projet)</td>
<td>1,00</td>
<td>Établir des indicateurs de performance</td>
</tr>
</tbody>
</table>

Échelle

0 - Aucun impact 1 - Impact mineur 2 - Impact modéré 3 - Impact important 4 - Impact très important

Question : À la suite de votre usage de TM, évaluez l'impact de son utilisation sur le suivi des coûts du projet.

D'abord, l'application logicielle ayant eu le plus gros impact est celle de l'étude de cas B, soit Latista. En se penchant sur ses fonctionnalités, on constate que cette application vise, non seulement à rendre disponibles les plans de projet, mais aussi offre la possibilité de mettre en place des séquences d'opération personnalisées. Les rencontres auprès des participants ont permis de mettre en lumière que l'exploitation de cette application permet de sauver des coûts en raison de la mobilité et de la rapidité avec laquelle, l'information peut circuler au sein des différents acteurs du projet.

6.3 Suivi de la qualité

Cet axe de bénéfices présente les résultats obtenus suite à l'exploitation des applications logicielles. Le Tableau 7 expose le classement des trois éléments principaux identifiés par les usagers des différentes études de cas.

Tableau 7 - Bénéfices - Suivi de la qualité

<table>
<thead>
<tr>
<th>Étude de cas A</th>
<th>Étude de cas B</th>
<th>Étude de cas C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardisation de l'information</td>
<td>1,9</td>
<td>Suivi des événements de chantier (déficiences, etc.)</td>
</tr>
<tr>
<td>Collecte de l'information sur le chantier</td>
<td>1,7</td>
<td>Contrôle de la qualité du projet</td>
</tr>
<tr>
<td>Contrôle qualité du projet</td>
<td>1,6</td>
<td>Standardisation de l'information</td>
</tr>
</tbody>
</table>

Échelle

0 - Aucun impact 1 - Impact mineur 2 - Impact modéré 3 - Impact important 4 - Impact très important

Question : À la suite de votre usage de TM, évaluez l'impact de son utilisation sur le suivi des coûts du projet.

Cet axe de bénéfices est celui exposant le plus grand écart entre les différents cas d'usage des TM. On observe que les applications de niveau 4, soit d'administration et de gestion de projets, ont une forte valeur ajoutée dans le contexte de ce pôle d'amélioration. D'abord, on constate que l'étude de cas C est celui ayant obtenu l'impact le plus important lors de son exploitation. Toutefois, son temps d'exploitation est de loin supérieur aux deux autres études de cas impliquées dans l'étude. De plus, son contexte d'exploitation est axé vers une exploitation locale, ce qui limite son champ d'action sur les autres disciplines. En revanche, l'étude de cas B, dans laquelle les TM ne sont utilisées que depuis quelques mois, exploite ces outils dans un contexte global, c'est-à-dire, avec l'ensemble des disciplines de projets. En se penchant de plus près sur les résultats, on constate que les participants ont mentionné avoir un meilleur suivi des événements de chantier et du contrôle de la qualité. Les résultats de cette étude de cas
justifient alors que l'exploitation d'une application logicielle, permettant la mise en place d'une séquence d'opérations et jumelée à une utilisation collective de la TM, permet d'atteindre de plus grandes retombées sur le projet.

6.4 Gestion de projet

Cet axe de bénéfices présente les résultats obtenus suite à l'exploitation des applications logicielles. Le Tableau 8 expose le classement des trois éléments principaux identifiés par les usagers des différentes études de cas.

Tableau 8 - Bénéfices - Gestion de projet

<table>
<thead>
<tr>
<th>Étude de cas A</th>
<th>Étude de cas B</th>
<th>Étude de cas C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partage de documents de projets</td>
<td>3,17</td>
<td>Recherche et contrôle de l'information</td>
</tr>
<tr>
<td>Communication avec mon équipe</td>
<td>2,56</td>
<td>Partage de l'information avec les différentes entreprises</td>
</tr>
<tr>
<td>Coordination avec les différentes entreprises</td>
<td>2,06</td>
<td>Partage de documents de projet</td>
</tr>
</tbody>
</table>

Échelle

0 - Aucun impact 1 - Impact mineur 2 - Impact modéré 3 - Impact important 4 - Impact très important

Question : À la suite de votre usage de TM, évaluez l'impact de son utilisation sur le suivi des coûts du projet.

De manière globale, on constate que l'exploitation des TM a un impact de modéré à important pour l'ensemble des études de cas. Pourtant, on observe qu'en fonction des applications logicielles utilisées, les critères d'amélioration varient en fonction du type de technologies sélectionnées. Par exemple, dans le contexte de l'étude de cas A, le partage de documents est le critère ayant le plus haut taux d'impact, tandis que celui de l'étude de cas B, la recherche et le contrôle de l'information est le principal point d'amélioration. Ces résultats mettent en lumière que l'exploitation des applications logicielles, permettant d'effectuer une administration et une gestion de l'information, permet d'atteindre un haut niveau d'impact sur les mécanismes de gestion de projet dans le secteur. Ceci s'explique par le fait que l'environnement de chantier représente un secteur en évolution et que l'information doit non seulement y circuler rapidement, mais doit être accessible à un maximum d'intervenants.

7 DISCUSSION ET CONCLUSION

À la lumière des résultats présentés, les TM ont le potentiel d'améliorer les processus de communication dans le secteur, et ce, indépendamment de la technologie sélectionnée. Cependant, cette recherche demeure exploratoire en raison de la grande diversité des applications et de leurs usages dus à leur faible coût. Malgré tout, l’ensemble des participants a perçu des bénéfices à leur usage :

« L'usage de l'application est véritablement devenu incroyable, c'est devenu un outil indispensable pour le suivi des travaux en chantier. Je fais non seulement ma surveillance de chantier, mais je prépare également mes rencontres de coordination avec mon patron. Sans l'application, je me dis que cela aurait été impossible d'avoir un suivi aussi présent et d'avoir toute cette information à disposition. »

Surveillant qualité

Mais naturellement les retombées sur le projet varient en fonction du type de technologies sélectionnées et des stratégies de déploiement. Par exemple, dans l'étude de cas A, et les bénéfices de l'application de communication sont plutôt orientés vers la rapidité d'accès à l'information et le partage de documents. En revanche, dans l'étude de cas B, application d'administration et de gestion a été mise en place et elle a été accompagnée d'une séquence d'opération personnalisée a été établie grâce à l'application d'administration et de gestion de projet. On constate alors que le niveau d'impact des TM, lorsqu'utilisé dans un contexte administratif, permet d'atteindre des niveaux de rendement plus élevés, considérant le fait qu'elles soient exploitées dans un cadre collaboratif. Parallèlement, l'exploitation de l'application logicielle de l'étude de cas C, dans un contexte interne, a permis à l'entreprise de standardiser
l'information collectée sur le terrain. Cet aspect est d'ailleurs un point fort de l'exploitation des applications d'administration et de gestion, car elles appellent à redéfinir les critères de saisie d'information, afin de faciliter le traitement de données. Plusieurs intervenants ont d'ailleurs mentionné ne plus vouloir revenir en arrière, suite à leur expérience avec les applications logicielles d'administration et de gestion de projet.

En résumé, il en ressort que les TM offrent des solutions particulièrement bien adaptées à la gestion de l'information sur le chantier. Cependant, le grand nombre et la diversité des applications disponibles rendent l'identification des applications et leur déploiement complexe, ouvrant de multiples perspectives pour des recherches futures.

Bibliographies

PRELIMINARY INVESTIGATION OF THE IMPACT OF PROJECT DELIVERY METHOD ON DISPUTE RESOLUTION METHOD CHOICE IN PUBLIC HIGHWAY PROJECTS

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Abstract: The use of alternative project delivery methods (PDMs) is perceived to create collaborative environments that result in less adversarial relationships between construction parties, which consequently leads to less disputes. While many research studies investigated the alternative PDMs’ impact on cost, schedule, quality, and sustainability, there is limited research to empirically investigate the impact of the PDM on the dispute resolution process choice. This aim of this paper is to conduct a preliminary investigation on how PDMs’ choice has affected Department of Transportation (DOTs) selection of the dispute resolution method (DRM). To achieve this objective, the researchers conducted content analysis of three State DOTs’ specification documents, both for Design-Bid-Build (DBB) and Design-Build (DB) PDMs. Results show that a stepped process is used in all three states with some form alternative DRM being used before resorting to litigation to provide opportunity for prevention and early resolution of disputes. In terms of PDM effect on the DRM, one state used an amicable dispute resolution process that fosters partnerships in DB and not in DBB projects, while another used partnering efforts regardless of the PDM employed. Also, the use of non-binding DRBs in another DOTs’ DB specifications before resorting to binding DRM provide opportunity for amicable ADR methods to be used before being escalated to litigation. This study serves as a preliminary investigation of how PDM choice could affect the way disputes are handled and results show that there is no consistent manner on which the dispute resolution process is selected based on PDM.

1 INTRODUCTION

Being a very complex and competitive industry in which participants with different expertise, talents, and levels of knowledge work together to achieve set objectives, conflicts become inevitable. If conflicts are not well managed and resolved in a timely manner, they quickly turn into disputes, which prevent the successful completion of the construction project (Cakmak & Cakmak, 2014). With 10 to 30 percent of construction projects having serious disputes and one in four construction projects having a claim, disputes can become very expensive. Transactional costs for dispute and claims resolution may total $4 - $12 billion per year. Such costs include lawyers and witnesses fees, employees’ salaries and overhead (who divert from productive profit-making work to litigation activities), in addition to construction process inefficiencies and delays, and ultimately the costs of hostile relationships that remove any opportunity for profits from repeat business (FFC 2007).
Acknowledging the fact the construction disputes will occur inevitably, the construction industry has made tremendous progress in developing more efficient and amicable methods for dispute prevention and resolution. Paradoxically, experts frequently refer to the construction industry as being on the innovative edge regarding dispute resolution (ENR 2000). One of the early decisions that prevents disputes on a project is selecting the most appropriate project delivery and management method (FFC 2006). It has been conceived that the use of traditional PDMs and low bid process often create adversarial relationships between the parties involved compared to alternative PDMs that are characterized by being highly collaborative intending to replace the individual parties’ success with overall project success. In line with the various contract conditions that reflect the collaborative-based approach of alternative PDMs, the dispute resolution process selected should portray the level of collaboration expected on the project, i.e., offer opportunity for using amicable dispute resolution process before resorting to hostile DRMs. However, to date, there has been little research conducted, especially on highway infrastructure projects, to investigate this notion and its implication on the project management. Therefore, this research aims to conduct a preliminary investigation on the impact of different PDMs on selection of the dispute resolution process by the State Departments of Transportation (DOTs). In essence, has the use of more collaborative forms of PDMs resulted in selecting less adversarial Dispute Resolution Methods (DRMs)? In order to achieve this objective, the paper first introduces the various forms of PDMs and DRMs used in the construction industry. Then, the result of a content analysis that was conducted to compare the current dispute resolution practices in various PDMs is presented.

1.1 Project Delivery Methods

PDMs define the relationship, roles, and responsibilities of project team members and the sequence of activities required to provide a facility. The particular method through which a given construction project is designed and constructed is an important consideration prior to beginning a project, as it has a significant impact on cost, risk, and the overall schedule. Examples of PDMs used in the construction industry are the traditional design-bid-build (DBB), design-build (DB), construction manager at risk (CMR), integrated project delivery, and public-private-partnerships. This paper will mainly focus on DB and DBB PDMs.

In DBB, the traditional and most popular form of PDM, the owner hires an engineer to design the project in its entirety, creating both the plans and specifications that identify all the project parameters. The project is then put up for a competitive bid after which a separate firm is hired to serve as the general contractor. Project award is usually based on the lowest responsive bid. Some of the challenges with this system are the adversarial relationships among project participants and lack of contractor’s input during design leading to potential change orders. In case of DB PDM, the owner hires one entity to serve as both the contractor and the design professional. This set-up also allows contractor’s input during design, single point of responsibility for construction and design, and fast-track delivery. However, there is potential loss of owner’s control specifically loss of checks and balances. Over the past 15 years, use of DB has greatly increased in the U.S., making this delivery method one of the most significant methods in design and construction today (DBIA n.d.). Research has found that the DB PDM is more effective in large and complex projects (Koncher and Sanvido 1998). Other than contractual PDM method implementation, the U.S. Army Corps of Engineers developed the partnering process in the 1980s to fundamentally change the manner in which contractual parties relate to each other – creating a cooperative team approach rather than the more historically common adversarial approach. Partnering do not modify any existing contractual requirements; it is a voluntary process, and joint costs are typically shared by the parties. Partnering involves working together as a team, developing a common set of project goals, open communication and access to information, empowering participants to resolve issues at the lowest appropriate organizational level, reaching decisions and solving problems quickly and by consensus, and maintaining the relationship throughout the project (AAA 1996).

PDMs is a well-researched topic in construction research. Most studies conducted, in public highway projects, focused on comparing various PDM in terms of their performance (cost, schedule, sustainability, and quality). Warne (2005) conducted a performance assessment of DB contracting for highway projects in terms of schedule, cost, quality, and owner satisfaction, by gathering information on 21 DB highway projects ranging in size from $83 million to $1.3 billion. Shrestha et al. (2012) also focused on highway project investigating project performance metrics of 130 DB large highway projects in Texas. Results, in
both studies, showed that the selected projects were built faster using DB than they would have been with DBB (Warne 2005, Shrestha et al. 2012). As DB is more widely being implemented, studies whether on the national or state level are continuously being conducted to evaluate DB projects’ performance (FDOT 2004; FHWA 2006). In January 2006, FHWA published the results of a comprehensive national study conducted to evaluate DB contracting effectiveness, from different states that were taking the lead on DB implementation. Research studies were also conducted to evaluate quality such as the Arizona DB projects quality study (Ernzen and Feeney 2002), quality qualifications assessment in DB solicitation documents (Gransberg and Molenaar 2004) and a synthesis of how quality is handled in DB projects (Gransberg et al. 2008). In another study, Minchin et al. (2013) compared time and cost performance of 60 projects from Florida DOT (FDOT) and found that DBB projects outperform DB projects in terms of cost. As can be seen, most research discussed earlier have considered cost, time, and quality but there hasn’t been any major work that directly addresses the relationship between PDM use and disputes/dispute resolution process, especially as related to highway projects.

1.2 Disputes and Claims

With all the PDMs discussed and different degrees of collaboration among parties involved, the complexities involved in construction projects and the magnitude of risks, it is still a fact that construction industry is characterized by being one of the most adversarial industries generating disputes and claims. Disputes occur on construction projects for many reasons such as schedule targets, acceleration, coordination, culture, differing goals, and delays conditions. Claims would generally occur if the contractor requests additional compensation for deviations from original contract or the owner seeks compensation for contractor’s failure to meet contractual requirements (FFC 2007). In Korea, Acharya and Lee (2006) identified six critical construction conflicts: site conditions, local people obstruction, errors and omission in design, double meaning in specification, excessive quantity of works, and difference in change order evaluation. Sigitas and Tomas (2013) hypothesize that the true cause of construction-related conflicts is unsuccessful communication among the construction project participants.

There are different methods to resolve disputes on construction projects. Litigation is the traditional method employed in courts, where all parties are subject to all of the forms of discovery, such as interrogatories, requests for admission, document production demands, and depositions. The parties then have a trial, which if they are dissatisfied by its results, they can appeal. Historically, litigation has had a reputation for being a long expensive process. In the public sector, there are often requirements that contractors must first file a government claim and go through an administrative hearing procedure before they can proceed to arbitrate or litigate their claims. This is known as Government Claims Procedure (Klinger 2009). According to the American bar, Alternative Dispute Resolution (ADR) methods are increasingly used in the construction industry in lieu of or as a step preceding litigation, as they can handle disputes quicker and are relatively inexpensive. Some of these ADR could be binding to assure parties that they will not have to resort to outside litigation to settle disputes (Dettman and Harty 2008).

Commonly used ADR methods include: step negotiation, mediation, Dispute Review Boards (DRBs), and arbitration. Step Negotiation requires the individuals getting directly involved in dispute to seek resolution by direct negotiation. In the event of resolution not being reached within a certain period, the dispute is taken to the next level which could continue to senior level of each organization. According to Texas Civil Practice and remedies code 154.023, “mediation is a forum in which an impartial person, the mediator, facilitates communication between parties to promote reconciliation, settlement, or understanding among them.” Whether it is during the course of construction or after the project is complete, mediation is arguably the most satisfying DRM. It can occur as early in the process as the parties are able to organize a mediation and identify a mutually agreeable mediator (Klinger 2009). DRB, on the other side, involves three neutral experts who visit the site periodically and monitor progress and potential problems that might lead to disputes. Once a dispute occurs, it is brought to the board who conducts an informal hearing and issues an advisory opinion that could be either binding or non-binding. DRB cost is typically 0.15% of the total construction cost which is far less than using arbitration or litigation. Finally, arbitration is a non-judicial forum to settle disputes; its benefit emerges from the fact that construction disputes often require the decision-maker to be well versed in technical and industrial matters, in addition to legal issues (Yates and Smith 2007). However, in a survey conducted in the U.S., 31 out of 42 arbitrators reported
that “arbitration is becoming too much like court litigation and thereby losing its promise of providing an expedited and efficient means of resolving commercial disputes…” (AAA 2010, p.42).

Few papers address the topic of disputes occurrence and contracting strategy/PDM. The Federal Facilities Council (2007) compiled a report of presentations given by speakers who are experts in resolving construction disputes. Using the Pentagon renovation project, the report highlighted how projects transferring more risk to contractor and using a low-bid process are more prone to having claims. Contracts should portray realistic risk assignment to parties rather than convey the bargaining powers of the parties. In addition to inequitable risk allocation, the report addressed disputes’ causes that are attributable to the contracting/bidding strategy such as low bid process, poorly developed contracts, and lack of project management procedures (FFC 2007). Another interesting observation by Independent Project Analysis’s study conducted on projects of diverse types was that, in contrary to the perception that fewer claims are anticipated in shared risk contracts, no difference was seen between claims’ frequency on shared risk versus contractor-allocated risk contracts. This was attributed to inappropriate risk allocation strategies. The study also looked at DRM choice showing that arbitration encouraged inflated claim values while other forms such as DRBs and mediation did not affect claim frequency (FFC 2007).

Two other studies, one in Malaysia and the other in UK reported that alternative PDMs reduced disputes frequency (Ndekugri and Turner 1994, Yusof et al. 2011). Mante et al. (2012) conducted a preliminary study on dispute resolution by analyzing DRM provisions in standard contract forms showing that regardless of the PDM, the same dispute resolution provisions were used. The paper also reinforced our literature review that the amount of research done related to PDM and dispute reduction/resolution is limited.

The previous sections show that, on one side, there are many DRMs, with varying degrees of hostility, that evolved to manage the numerous claims/disputes that occur on construction projects while on the other side, there are many forms of PDMs, some of which are assumed to create more collaborative environments less prone to disputes. Although there seems to be a strong link between PDM use and dispute process selected, there has not been any consolidated research conducted to investigate the effect of PDMs choice on selection of DRMs or process, especially as related to public highway projects.

2 METHODOLOGY

This aim of this paper is to conduct a preliminary investigation on how the choice of different PDMs has affected how DOTs are currently selecting the DRM used. To achieve this objective, the researchers conducted content analysis of three State DOTs’ specification documents, both for the traditional PDM and DB PDM. The aim of the content analysis was to develop valid inferences using a set of procedures from the documents studied (Neuendorf 2002). The three state DOTs studied were Florida DOT (FDOT), Ohio DOT (ODOT), and Colorado DOT (CDOT). These three State DOTs were selected because they have a well-established DB process. CDOT started using DB on a few projects in the 1990’s after obtaining FHWA Special Experimental Project Number 14 (SEP-14) – Innovative Contracting program approval, however, in 1999, the Colorado State Legislation was officially obtained allowing DB use. As for FDOT, DB has been permitted by all agencies for all types of design and construction since 1997. ODOT represents also one of the early participants in SEP-14 in 1990, to test and evaluate DB, among other PDMs, as a potential effective method to deliver highway projects (DBIA, n.d.). Over the past few decades, DB has been increasingly used by ODOT in projects of different characteristics.

Specification documents were retrieved from the DOTs’ websites (Table 1). In cases where it was not possible to locate the DB standard specification, DOT DB projects solicitation documents were studied to identify the dispute resolution process used. It was assumed that the specification document was for traditional PDM if no specific PDM was specified. Six state DOT specification/bid documents from the three DOTs, together with three FDOT solicitation documents, were analyzed to determine the process followed from the occurrence of the event giving rise to the claim until resolution of the claim using any form of DRM. The content analysis of the documents focused on three main aspects; 1) how DOTs define the word ‘claim’ and ‘dispute’, 2) the process that precedes resorting to the formal DRM, if stated, and 3) the formal DRM employed. After each State DOT specifications were analyzed, the traditional versus the
alternative PDM specification document was compared to infer the differences (if any) between the DRM and the process utilized to resolve in each of these State DOTs given different PDM.

<table>
<thead>
<tr>
<th>State DOT</th>
<th>Traditional project delivery</th>
<th>DB project delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>- Standard Specifications for Road and Bridge Construction – 2011</td>
<td>RFP documents (Book 1 DB Contract Provisions) for the following projects:</td>
</tr>
<tr>
<td></td>
<td>- Construction and Material Specifications – 01/01/2013</td>
<td>- I-25 North - 2012</td>
</tr>
<tr>
<td>Florida</td>
<td>- Standard Specifications for Road &amp; Bridge Construction - 01/01/2013</td>
<td>- Design-Build Specifications – 09/08/2014</td>
</tr>
<tr>
<td>Ohio</td>
<td>- Construction and Material Specifications – 01/01/2013</td>
<td>- Revisions to 2013 Construction &amp; Material Specifications for DB Projects–12/31/2012</td>
</tr>
</tbody>
</table>

3 Results & Analysis

3.1 Colorado DOT

Both CDOT 2011 Standard Specifications for Road and Bridge Construction (with no PDM specified), here in after called ‘2011 CDOT SS’, and the RFP documents (Book 1 DB Contract Provisions) define dispute as a “disagreement”. As per 2011 CDOT, dispute is a “…disagreement concerning contract price, time, interpretation of the Contract, or all three between the parties at the project level regarding or relating to the Contract”, or as the DB RFP documents, disputes could be disagreements “resulting from a change, delay, change order, another written order, or an oral order from the Project Director or his designee…” Claim on the other side, as per the DB project RFP documents (Book 1 Contract Provisions), is defined as “…a separate demand by the Contractor for: (i) a time extension which is disputed by CDOT, or (ii) payment of money or damages arising from work done by or on behalf of the Contractor in connection with the Contract which is disputed by CDOT. A claim will cease to be a Claim upon resolution thereof, including resolution by delivery of a Change Order or Contract amendment signed by all parties.” Thus, as per CDOT, the process starts with a dispute that is then elevated to a claim, if not resolved at the project level.

The 2011 CDOT SS (traditional PDM) document subsections 105.22, 105.23, and 105.24 detail the dispute resolution process. It states that either party can initiate the resolution process when an issue arises that cannot be resolved between the parties. CDOT follows a stepped-process that starts at the project level and can be escalated all the way to litigation or arbitration (Figure 1). The process starts with the contractor providing a written notice of dispute to the project engineer about the failure of the parties to resolve the dispute. This notice is then followed by a request for equitable adjustment (REA) -within 15 days- which should include supporting documents such as nature of the circumstance which caused the dispute, statement explaining provision of the contract, and all evidences. Within 15 days of receiving the REA, the engineer meets with the contractor and in seven days issues a written decision on the merits of the dispute. If the contractor does not accept the decision, the contractor provides notice to the resident engineer who meets with the contractor as well as the project engineer within 7 days of receiving the contractor’s written notice, on a weekly basis for a period up to 30 days, to discuss and resolve the dispute. If dispute remains unresolved, the project engineer directs it to DRB.

CDOT specifies two types of DRB in their provisions: “On Demand DRB” and “Standing DRB”. “On Demand DRB” is the default DRB to be used unless the project contract documents specify otherwise. On Demand DRBs constitute only one member, if the dispute value is less than $250,000, and three members in larger dispute values. However, Standing DRBs always have three members that are selected during the preconstruction stage and will meet regularly during the course of the project. Standing DRBs (as per the standard special provision dated November 6, 2014 that revises CDOT’s Standard Specifications for Road and Bridge Construction) are typically used in projects that are larger than $15 million, involving complex construction or structures or multiphase construction, with major traffic...
impacts, or other complicating factors that could lead to disputes. Standing DRB remain in effect all through the duration of the project and are in full force until all disputes are resolved.

![Figure 1: Typical CDOT dispute resolution process](image)

Whatever the DRB type selected, once the project engineer initiates the DRB process, parties will need to submit prehearing submittals that include all supporting documents/evidence. At the hearing, both parties present their positions. After the meeting has been closed, the DRB shall issue its recommendation and the DRB and parties shall agree on the time (maximum time being 30 days) for analysis and review of the issuance of the recommendation. DRB’s chairperson signs and sends the signed recommendation and all documents to the parties who will have 10 days to request clarifications. If the parties are not satisfied with the recommendations, other forms of nonbinding dispute resolution could be optionally used such as mediation or as CDOT specifications section “claim for unresolved disputes” states, the contractor can “file a claim” that starts by a written notice of intent to file a claim to the Region Transportation Director (RTD). Based on documents submitted, RTD issues a decision, which if not accepted by the contractor could be escalated to the Chief Engineer. If contractor is not in agreement with the Chief Engineer’s decision, the contractor can initiate litigation or binding arbitration (following American Arbitration Association’s Construction Industry Arbitration Rules) to finally resolve the claim. The standard special provision, dated November 6, 2014, that revises 2011 CDOT SS notes that the same process should be used in DB projects unless the Standards & Specifications Unit approves a SSP modified version.

On the other side, CDOT DB Manual (dated April 15, 2006 and revised on June 11, 2014) states that the DB Request for Proposals (RFP) follows a structure that includes Book 1 (Contract terms and conditions component) and Books 2 through 5 (Technical components). Depending on the DB type (a Streamlined DB or a standard DB), 2011 CDOT SS could remain as an integral part of the contract requirements or could be completely replaced by Book 1. The authors could not locate Book 1 template so three DB projects RFPs were reviewed to identify the DRM process followed; I-25/Cimarron Street (US 24) Project issued 2014, I-25 North Project issued 2012, and SH 285 Reconstruction – Wadsworth to Federal Project issued 2008. The significant difference in the DB projects compared to the process described in the 2011 CDOT SS is the steps preceding the dispute resolution process initiation. Under Article 19 entitled “partnering”, the RFP documents state that the dispute resolution process described shall not apply until “…the normal CDOT-Contractor issue resolution efforts through partnering are not successful…” The RFPs of the projects studied either then refer to dispute resolution section of the 2011 CDOT SS as being an integral part of the contract document or completely replace it by a similar stepped process that concludes with the Chief Engineer’s decision followed by litigation. As for the DRB type, one of the DB projects used standing DRB while the other used on-Demand DRB, which makes DRB type project-specific (following the requirements explained earlier) rather than related to the PDM used.

### 3.2 Florida DOT

FDOT Standard Specification for Road and Bridge Construction dated January 2015 (with no PDM specified), here in after referred to as 2015 FDOT SS, defines Contract Claim as a “… written demand submitted to the Department by the Contractor … seeking additional monetary compensation, time, or other adjustments to the Contract, the entitlement or impact of which is disputed by the Department.” p. 3. No definition was found in 2015 FDOT SS documents for the word “dispute”. 2015 FDOT SS Article 5.12
entitled "preservation, presentation and resolution of the claim" details the claim resolution process including time frames and submittals required. The process must start with "submission of timely notice of intent to file a claim, preliminary time extension request, time extension request, and the certified written claim..." to the Engineer before contractor can seek any formal claim resolution process including litigation. Claims by contractors cannot also be filed to litigation or arbitration before FDOT grants the contractor final acceptance of all the work. The Engineer, after submittal of all required documents, will have 90 or 180 calendar days depending on the contract amount to respond to the contractor. It is interesting though to note that 2015 FDOT SS contains a paragraph in multiple sections stating that ultimately "Statewide Disputes Review Board in effect for this Contract will resolve any and all disputes that may arise involving administration and enforcement of this Specification...the determinations of the Statewide Disputes Review Board for disputes... will be binding on both the Responsible Party and the Department, with no right of appeal by either party." p.297. Accordingly, some of the disputes could be escalated to the binding DRB, while the 2015 FDOT SS was not specific about the other forms to be used in other types of works where Statewide DRB was not specifically listed.

On the other side, FDOT’s DB specifications document dated September 8, 2014 added two entire sections to the procedures followed in conducting DRBs that discusses both DRB and Statewide DRBs and details the choice of the members, schedule, responsibility of each party, and basis of payment in each. DRBs are used essentially when normal dispute or claim resolution is unsuccessful and by either the choice of the DOT or the Contractor. The steps involved in dispute resolution start with the contractor filing a written protest with the Engineer within 15 days after the event and states its reasons for objection. The Engineer then responds to the written protest within 15 days of receiving it and in its response furnish the contractor with its decision. This decision is final unless the contractor files a written appeal to the Engineer within 15 days. In this case, the issue is referred to the DRB by the parties involved. The DRB then fixes a date to conduct the hearing. All evidence to the claim or disputes must be submitted to the board within 15 days before the date set by the board. The owner/contractor would provide a position paper that outlines the dispute/claim nature and scope together with the basis for entitlement. During the hearing, all parties shall be given the opportunity to be heard and provide their evidences. Within 15 days of completing the hearing, the board shall give recommendations of the dispute or claim to the parties involved. Also, within 15 days of receiving the board’s recommendations, the parties involved shall respond whether or not they accept the recommendations. It is noted that in the Section regarding DRBs “both the Department and the Contractor should place great weight on the Board’s recommendation, it is not binding” (Article 8.3.7.4) while in the section regarding the Statewide DRBs “recommendations of the Board will be binding on both the Department and the Contractor.” (Article 8.3.8.1). Thus, DRB hearings of any unresolved disputes/claims needs to supersede any initiation of arbitration or to filing a lawsuit, while in Statewide DRBs, DRB decisions are final and binding. Figure 2 shows the stepped process used in FDOT.

![Figure 2: Typical FDOT dispute resolution process](image)

### 3.3 Ohio DOT

ODOT Construction and Material Specifications dated January 1, 2013 (with no PDM specified), here in after referred to as 2013 ODOT SS, defines claims as “Disputes that are not settled through Steps 1 and 2 [discussed below] of the Dispute Resolution and Administrative Claim Process. The Dispute becomes a Claim when the Contractor submits a Notice of Intent to File a Claim." p. 6. Disputes, on the other side, are defined as “Disagreements, matters in question and differences of opinion between the Department's personnel and the Contractor." p.7. So in essence, disputes are escalated to claims.
ODOT’s introduces the dispute resolution process under Section 108.02 ‘Partnering’ where ODOT sets partnering as the “proactive effort and spirit of trust, respect, and cooperation among all stakeholders in a project…” p.46. Figure 3 shows ODOT’s dispute resolution process, which is a stepped approach to be followed in sequence. The contractor should first provide immediate oral notification to the Engineer once a circumstance that might result in changes evolves. Both the contractor and engineer should discuss various mitigation efforts such as re-sequencing activities and acceleration, and the engineer should try to resolve the issue expeditiously. If the engineer does not resolve the issue in 2 working days from oral receipt of notice, contractor should provide a written notice. If these mitigation steps do not resolve the issue under consideration, the contractor should escalate the issue to the ‘Dispute Resolution and Administrative Claims Process’ that should be totally exhausted before filing a claim in the Ohio Court of Claims. Figure 3 shows the stepped process followed by ODOT:

- **Step 1: On-Site Determination:** Engineer meets the contractor’s representative within two days of Contractor Written Early Notice receipt in an attempt to reach a resolution. The Engineer then issues a Step 1 written decision within 14 days. If no resolution is reached, dispute is escalated to next level.

- **Step 2: District Dispute Resolution Committee (DDRC):** Each District establishes a DDRC for deciding disputes that escalate to Step 2. Within 7 days of receipt of Step 1 decision, a written notice is submitted to the District Construction Administrator (DCA), followed by all the dispute documentation required (such as additional compensation requested and narrative of disputed work) in 14 days. After which, in 14 days, the DDRC meets with the contractor and issues a decision.

- **Step 3: Director’s Claims Board Hearing (Board) or ADR:** Within 14 days, if contractor is not in agreement with the decision reached in Step 2, a written notice of intent to claim filing is to be submitted to the Dispute Resolution Coordinator that requests either a Board hearing or an acceptable ADR method. This is the point in time where the ‘dispute’ becomes a ‘claim’. In case of a Board hearing, the Board hears the claim on behalf of the Director and submits a written recommendation to the Director who takes the final decision which is considered the final step of the Dispute Resolution Process within ODOT. In case of ADR choice, binding arbitration or mediation could be selected and agreed upon by the parties. The neutral third party will now have complete control of the claim.

![Figure 3: Typical ODOT dispute resolution process](image)

Looking through ODOT document “Revisions to 2013 C&Ms for DB Projects” dated December 31, 2012, the same dispute resolution process is followed on DB projects, as this section was not amended.

4 DISCUSSION

Figure 4 shows a comparison between the three DOTs’ dispute resolution processes moving from a dispute to be resolved on the project level to a formal claim involving third party control. Both CDOT and ODOT define claim as the level succeeding the failure to resolve a dispute. Based on the documents analyzed, all states have some sort of stepped resolution process whether on DB or DBB method. The use of the stepped process provides an opportunity for the parties to resolve disputes at the job site level in a more efficient manner before resorting to lengthy and costly DRMs such as arbitration or litigation. CDOT had the maximum number of steps, followed by ODOT, then FDOT. Different forms of ADR were used in the three states with DRB (in its various forms) being used in all three. CDOT used either standing (specific for the project) or on-demand DRBs based on the characteristics of the project in both PDMs. FDOT used standing non-binding DRBs generally and State wide binding DRBs in specific designated work types of the project. The binding nature of the Statewide DRB in FDOT’s process raises
the concern that once the parties are unable to resolve the dispute at the project engineer level, the process is rapidly escalated to a costly adversarial process involving lawyers. ODOT, on the other side, formed a DDRC that is similar to FDOT’s Statewide DRBs yet issues non-binding decisions that could be further elevated to other forms of ADR.

<table>
<thead>
<tr>
<th>CDOT</th>
<th>FDOT</th>
<th>ODOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partnering Efforts</td>
<td>Project Level Negotiations</td>
<td>Mitigation Steps w/ Engineer</td>
</tr>
<tr>
<td>(in case of DB projects)</td>
<td>Project Engineer</td>
<td>(oral &amp; written notification)</td>
</tr>
<tr>
<td>Project Engineer</td>
<td>Project Engineer</td>
<td>Step 1: On-site Determination of Engineer</td>
</tr>
<tr>
<td>Resident Engineer</td>
<td>DRB</td>
<td>Step 2: District Dispute Resolution Committee</td>
</tr>
<tr>
<td>(Standing or on-demand)</td>
<td>(Standing non-binding and/or Statewide Binding)</td>
<td></td>
</tr>
<tr>
<td>Mediation</td>
<td>DRB</td>
<td>Step 3: Board or ADR (mediation OR binding arbitration)</td>
</tr>
<tr>
<td>(optional)</td>
<td>(Standing non-binding and/or Statewide Binding)</td>
<td></td>
</tr>
<tr>
<td>Region Transportation Director</td>
<td>Arbitration or Litigation (in case non-binding DRB preceding)</td>
<td></td>
</tr>
<tr>
<td>Chief Engineer</td>
<td>Litigation (in case mediation preceding)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: State DOTs dispute resolution process comparison reflecting both DB and DBB processes

Both ODOT and CDOT mandate the use some form of partnering/mitigation process before initiating a dispute resolution process and move through a stepped process passing through DRB, as well as in some cases a mediation process and in all cases ends up with arbitration or litigation. In CDOT specification documents, it was interesting to see how partnering was listed as an integral process in DB projects but not in DBB projects. As for FDOT, the main difference observed between DBB and DB specification standards was how in DBB projects - other than Statewide to be used under specific work disputes- there were no mention of the DRM method to be employed if the contractor is not in agreement with the engineer’s decision. In DB specifications, however, non-binding DRB was added as an option to be used generally. Finally, ODOT did not amend the dispute resolution section in its DB specification.

5 CONCLUSIONS

Results of this preliminary investigation show the some states (e.g. CDOT) must be realizing that alternative PDMs necessitate the use of a dispute resolution process that is more amicable and fosters partnerships while others are using mitigation/partnering efforts (ODOT) regardless of the PDM. A stepped process in general is preferred in all states with some form ADR (DRB mostly and mediation sometimes) being used before resorting to litigation. It is anticipated that early resolution of disputes through transparent procedures in an environment that fosters understanding, communication, and cooperation will ultimately result in less disputes escalating to claims. While, the contribution of the study is significant, there are several limitations that need to be addressed in future studies. First, the external validity of study is limited to three states DOTs (Colorado, Florida, and Ohio); therefore, other studies should be conducted to explore DRM being followed in the remaining DOTs not only in the standard specification but also as pertinent to the project specifics. Second, this study was limited to conducting content analysis on current documents and lacks empirical support; future studies should be conducted to collect empirical data from completed projects and analyze the impact of various project delivery methods and dispute resolution process on disputes occurrence and resolution. Third, this study just looked at the DRMs provided by owners and does not provide any insight towards the behavior of stakeholders in a project. There is a common belief that more integrated PDMs provide a more collaborative environment and as a result reduce potential of disputes in a project. Future studies should be conducted to test this hypothesis statistically. Finally, a study should be conducted to understand how the choice of a stepped
process versus the other affect the numbers of claim that evolve and the number of claims that move to litigation and how, if any, the stepped process help reduce the number of claims in these DOTs compared to others. Despite of these limitations, this study addresses an important knowledge gap and paves the way for future in-depth studies regarding dispute prevention and minimization and alternative PDMs.

References


INTEGRATED ASSET MANAGEMENT OF WATER AND WASTEWATER INFRASTRUCTURE SYSTEMS - BORROWING FROM INDUSTRY FOUNDATION CLASSES

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Abstract: Viewing water and wastewater infrastructure systems from a network or functional viewpoint down to an individual component goes hand in hand with life-cycle management. Therefore, three concepts are incorporated: (1) Strategic Planning; (2) Tactical Planning; and (3) Operational Planning. The data relevant to each of these areas are generated and managed by software applications that operate in isolation. A multi-level integration can link and share data among strategic, tactical, and operational asset management plans. The Industry Foundation Classes schema concept is used to develop a framework to support efficient sharing and management of data and planning information among strategic, tactical and operational asset management plans of the water and wastewater infrastructure systems. The proposed multi-level integration framework is comprised of a comprehensive database of water and wastewater infrastructure physical asset inventory, financial and consumer sectors that stores and manages flow of information through strategic, tactical, and operational asset management plans. Data are identified by reference of time and date (temporal) and by physical relation of data to the location of a facility in the water and wastewater infrastructure networks (spatial). The proposed framework enables the integration and interoperation of various domain-specific software applications through developing and maintaining a multi-level integration of strategic, tactical and operational asset management plans based upon the Industry Foundation Classes data model concept. Municipalities and water utilities can use the findings to make optimized asset management decisions.

1 INTRODUCTION

Grigg (2012) defines infrastructure asset management as “an information-based process used for life-cycle facility management across organizations”. This paper proposes a multi-level integrated asset management framework to store and manage flow of information through strategic, tactical, and operational asset management plans for water distribution and wastewater collection networks. The data relevant to each of these asset management planning models are generated and managed by software applications that operate in isolation. A multi-level integration should enable water infrastructure stakeholders and software developers to extract and exchange the required data and information from any of the strategic, tactical, and operational asset management planning model using a centralized neutral data file.

Environment Canada (2004) defines the water infrastructure system as comprised of “water treatment plants that purify our water, the water mains in the ground that transport water, and the towers and reservoirs that store water. The term includes the sewer pipes that carry away wastewater and the
sewage treatment plants that treat wastewater before returning it to the environment ...". The other components of a water infrastructure system that include water and wastewater treatment plants, towers, and reservoirs are outside the scope of this study.

2 BACKGROUND

Froese (2003) indicated that information technologies (IT) play an effective role in architecture, engineering, construction, and facilities management (AEC/FM). Various domain-specific software applications are used to facilitate most of the AEC/FM design and management tasks, and the information entered into all of these computer tools describes the same physical project (Froese, 2003).

To facilitate efficient sharing and management of data between AEC/FM, the topic of interoperability has become one of the main areas for research and development in IT for the AEC/FM sectors (Froese, 2003). Froese, (2003) defines Interoperability as “the ability for information to flow from one computer application to the next throughout the lifecycle of a project which relies on the development and use of common information structures”.

To develop an integrated AEC model structure, model-based systems have been known as the main empowering technology (Halfawy and Froese 2002). Caldas and Soibelman (2003) noted that model-based systems are being utilized more and more to support exchanging information among AEC/FM projects. Industry Foundation Classes (IFCs) are one of the most remarkable of these model-based systems. IFCs have had significant positive impact on integration and interoperability.

2.1 Industry Foundation Classes

The IFCs specification is developed by the International Alliance for Interoperability (IAI). The IFC specification is a neutral data format to describe, exchange, and share information among AEC/FM industry projects (Caldas and Soibelman, 2003). The latest version is IFC4 and is available at buildingSMART International Ltd.

The IFCs data model is substantially built in a hierarchical structure, and its object-oriented design enables complex relationships to exist between entities (Dimyadi et al., 2008). Entities can be physical objects such as watermain pipes, service connections, valves, etc. or conceptual entities such as processes, budgets, scheduling details, etc..

Froese (2003) noted that the scope of the IFCs is limited to the building industry and should be extended to a broader range of civil infrastructure to include the entire built environment. To some extend this has happened in the industrial sector with ISO 15926. This research presents a framework to support efficient sharing and management of data and planning information among strategic, tactical and operational asset management plans for the water and wastewater infrastructure systems, and to enable the integration and interoperation of various domain-specific software applications through developing and maintaining multi-level integrated asset management plans based upon the IFC data model concept. A critical functionality of a multi-level integration of strategic, tactical and operational asset management plans is the requirement to link and manage the inter-dependencies of these data, and to enable different applications to share these data through the use of the integrated asset management model.

Strategic planning is a long-term (10+ years) group of activities including capital planning, operational and maintenance planning, policy planning, risk management, and life-cycle costing at the management level of an organization. The organization policy levers and the level of service are established at this stage of planning. Embedded in and dependent on strategic planning, a tactical planning (2-10 years) cycle is required to prioritize capital works activities as well as operating and maintenance (O&M) activities, and to flag candidates for capital works and O&M activities. Operational planning is defined as plans that specify details on how overall objectives are to be achieved (Robbins and Coulter, 1996) and to implement tactical plans.
2.2 EXPRESS Modeling Language

EXPRESS (ISO 10303-11, 1994) is an internationally standardized general-purpose data modeling language in contrast to a domain-specific data modeling language. The data model structure is often represented using the EXPRESS-G notation—a graphical modelling language subset of EXPRESS language (ISO 10303-11, 1994) used for identifying model classes, data attributes and their relationships. Every object which is drawn in EXPRESS-G can be defined in EXPRESS. However, not every object which can be defined in EXPRESS can be drawn in EXPRESS-G (ISO 10303-11, 1994). This section presents the basic symbols used in the EXPRESS-G data modeling language.

2.2.1 Classes

Classes are identified in a rectangular box with solid lines and the name of class is enclosed in the box (ISO 10303-11, 1994). Figure 1 shows three examples of classes where Iwis means integrated water infrastructure system.

![Figure 1: Classes (Entities)](image)

2.2.2 Data Types

EXPRESS-G consists of four main data types as follows:

a) Simple data types

There are seven simple data types: BINARY, BOOLEAN, INTEGER, LOGICAL, NUMBER, REAL, and STRING which are shown in Figure 2. A simple data type is presented as a solid rectangular box with its name enclosed and a double vertical line at the right hand side of the box (Figure 2).

![Figure 2: Simple data types in EXPRESS-G data modeling language](image)

b) Enumeration data type

Data attributes can be described in an enumeration data type when there is a range of possible values and the attribute may only choose one value from the possible range. This data type is shown in a dashed lines rectangular box with a double vertical bar to the right. The name of enumeration data is enclosed into the box. Figure 3 shows an enumeration example for IwisPipeMaterial that enables the IwisPipeMaterial to choose only one type of pipe material.
c) Defined data type

A simple STRING data type can be used to define a data type but there are some types of data that require a detailed description. In this case a defined data type is used to make a clear description for a defined type of data. Figure 4 shows an example of a defined data type in EXPRESS-G. This type of data is shown in a dashed lines rectangular box with its name enclosed into the box.

```
WaterUtility
```

Figure 4: An example of defined data type in EXPRESS-G

d) Select data type

A select data type enables data attributes to choose the class based upon different purposes. For example, the IwisWaterDistributionElement enables selection of, watermain pipe, valve, hydrant or service connection (Figure 5). Select data type is shown in a rectangular box with dashed lines and a double vertical bar on the left hand side. The name of the data type is written in the box.

```
IwisWaterDistributionElement
```

```
IwisServiceConnection IwisHydrant IwisValve IwisWatermainPipe
```

Figure 5: An example of select data type in EXPRESS-G

2.2.3 Relationships

Mandatory and optional relations are two types of attributes that are related to a class. The value of attributes must be given when a Mandatory relation is assigned to a class. However, it is not necessary for the optional attributes. Figure 6 shows an example of a mandatory and optional relation to IwisWaterDistributionElement where TotalLength has a mandatory relation and TotalVolume is considered an optional relation.

```
REAL
TotalLength
```

```
REAL
TotalVolume
```

```
IwisWaterDistributionElement
```

Figure 6: An example of a mandatory and optional relation in EXPRESS-G
The above discussion briefly introduced the EXPRESS-G data modeling language for the purpose of this study. A detailed discussion on this graphical data modeling language can be found in ISO 10303-11 (1994).

3 MULTI-LEVEL INTEGRATION FRAMEWORK

There are inter-dependencies and relationships that exist between strategic, tactical and operational (STO) asset management plans for water and wastewater infrastructure systems. The data relevant to each of these areas typically generated and managed by separate software applications that operate in isolation. Multi-level integration of STO planning is intended to link and manage the inter-dependencies of these plans. The IFCs schema concept is used to develop a centralized database management system that enables the interoperability of various function-specific tools and the exchange of data among different asset management planning disciplines.

The proposed multi-level integration framework is comprised of a comprehensive database of water and wastewater infrastructure physical infrastructure assets with financial and consumer sectors that exchanges and stores data through strategic, tactical, and operational planning (Figure 7). An Integrated Water Infrastructure System (IWIS) database stores and manages flow of information between strategic, tactical, and operational planning models. Data will be identified by reference to time and date (temporal) and by physically relation of data to the location of a facility in the water infrastructure network (spatial).

![Diagram](image)

Figure 7: The Research vision for Multi-Level Integration

3.1 Asset Management Plans

This section presents the typical steps required to develop strategic, tactical and operational asset management plans for water infrastructure systems.
3.1.1 Strategic Planning

The implementation steps for strategic planning of a water infrastructure system are categorized as follows (adopted from Uddin et al., 2013):

1. establish policy levers
2. establish level of service performance (consumer satisfaction) policies
3. categorize urban water infrastructure networks needs and funding sources
4. estimate long-term (10+ years) financial performance
5. prepare long-term (10+ years) capital works program
6. prepare long-term operating and maintenance program

Types of modeling techniques used for this level of planning currently include financial spreadsheets, simple data base management systems (DBMS), system dynamics models, large business oriented models, scenario based models, etc.

3.1.2 Tactical Planning

The implementation steps for tactical planning of a water infrastructure system are summarized as follows (adopted from Uddin et al., 2013):

1. prioritize all capital works activities,
2. prioritize all operating and maintenance (O&M) activities,
3. flag specific activities for capital works, and
4. flag specific activities for O&M activities

Types of modeling techniques used for this level of planning currently include deterministic mathematical modeling, simulation, optimization, etc..

3.1.3 Operational Planning

The implementation steps for operational planning of a water infrastructure system are categorized in the three disciplines of (1) engineering and design, (2) construction, and (3) operation and maintenance within a water utility (adopted from Uddin et al., 2013):

1. Engineering & Design
   1.1. perform structural and hydraulic analysis
   1.2. analyze cost effectiveness of project level alternatives
   1.3. prepare plans and specifications and perform actions
   1.4. analyze cost effectiveness of O&M activities
   1.5. analyze cost effectiveness of capital works

2. Construction
   2.1. perform capital works

3. Operation & Maintenance
   3.1. perform structural and hydraulic analysis
   3.2. perform O&M activities
   3.3. collect condition assessment and financial data

Types of modeling techniques used for this level of planning currently include simulation models, “what-if” scenario models, sensitivity analysis, modeling infeasibilities, opportunity costs and marginal economic value, etc.
The implementation steps of the above asset management plans need to be considered when developing the neutral strategic-tactical (ST) and tactical-operational (TO) data files to recognize data and planning information to be exchanged between the strategic, tactical and operational planning models.

### 3.2 Neutral Data Files

The neutral strategic-tactical and tactical-operational data files are divided into the three subtypes of neutral physical infrastructure asset, finance and consumer data files (Figure 8). A brief description of each subtype is presented in this section. The division into these three sectors is established in the literature and is used in systems dynamics models developed for strategic planning (Rehan et al., 2011, Rehan et al., 2013 and Rehan et al., 2014).

![Figure 8: A hierarchy of the neutral data files](image)

#### 3.2.1 Physical Infrastructure Asset Sector

This sector represents the asset inventory of water distribution and wastewater collection networks. The physical condition of the water network is classified based upon the age distribution of water pipes (e.g. in 25-year increment). The physical condition of the wastewater network is divided into five variables based upon the internal condition of the pipes using the UK’s Water Research Centre rating system proposed in the fourth edition of the Sewerage Rehabilitation Manual.

#### 3.2.2 Finance Sector

This sector describes the network’s financial condition including revenues, expenses, fund balance, debt, utility user fee, etc. Revenue is the utility’s income that is calculated based upon user fee, total water consumption, and total generated sewage. Fund balance is the difference between the revenue and expenditures of the network in dollars value, and user fee is the unit cost of water and sewage ($/m^3$) that a utility charges its consumers to cover the expenses associated with the water and sewage services.

#### 3.2.3 Consumer Sector

This sector presents the behavior of consumers in response to user fee oscillations (i.e. water demand) and level of service delivered to them. This sector establishes the policy levers and level of service performance (consumer satisfactions) policies.

The neutral strategic-tactical (ST) and tactical-operational (TO) data files will be developed to support efficient sharing and management of data and planning information among strategic-tactical and tactical-
operational models using EXPRESS-G data modeling language. Figure 9 shows a high-level example of the integrated water infrastructure system model structure displaying in EXPRESS-G.

![Diagram of integrated water infrastructure system model structure in EXPRESS-G](image-url)

Figure 9: A High-level example of the integrated water infrastructure system (Iwis) model structure in EXPRESS-G.
4 CONCLUSIONS

This paper reviews the basic concepts of Industry Foundation Classes and the EXPRESS-G data modeling language. A framework is proposed to integrate strategic, tactical and operational asset management planning models for the water and wastewater infrastructure systems. Further work is needed to completely develop the proposed multi-level integration framework. It is important that the developed neutral IWIS data files are reviewed by the water infrastructure industry experts and software developers to ensure that the specification is validated universally by the agreement of a wide cross section of water infrastructure industry experts and does not rely on a particular region. It should also be demonstrated with various currently utilized software packages. The proposed framework is the first known approach for data integration, sharing, and exchange between strategic, tactical, and operational asset management planning models of the water and wastewater infrastructure systems. In practice, this framework should enable water infrastructure stakeholders and software developers to extract and exchange the required data and information from any of the strategic, tactical, and operational planning model using a centralized IWIS neutral data file.

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References


INTEGRATION OF PREDETERMINED MOTION TIME SYSTEMS INTO SIMULATION MODELING OF MANUAL CONSTRUCTION OPERATIONS

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Abstract: Simulation modeling is a powerful tool widely used for designing construction processes and improving the efficiency of operations. However, there is often difficulty in estimating the duration of manual tasks for simulation purposes due to its dependence on the physical attributes of the worker performing the task. When designing a new process, there is usually a lack of sufficient data regarding the required duration for manual tasks, and in the case of evaluating and improving existing processes, there is no benchmark data for workers’ performance to enable comparison of the efficiency of the existing process. This study attempts to address this issue by exploring micro-motion-level simulation modeling in order to provide standard motion time required to perform a manual task for effective workplace design. The research method involves integrating a Predetermined Motion Time System (PMTS) into discrete event simulation, which provides the production planner with a standard task duration within which a worker must complete the task without delays or idling. As a case study, a manual task taking place in the production line of a construction steel fabrication company has been modeled using the developed automation tool in order to verify the feasibility of the proposed approach. The results show high correlation between the simulation model output and the actual time data from the jobsite and confirm the validity of the approach and its effectiveness in evaluating the productivity of the existing operations and providing detailed information for process improvement.

1 INTRODUCTION

Construction simulation is a powerful tool that enables analysis of different scenarios of the work process in order to optimize the use of available resources. Decision makers and production planners can highly benefit from simulation modeling in order to increase the productivity of construction operations. One of the most essential pieces of information required to create effective simulation models is time data. It is crucial to use accurate and realistic time information to represent the duration of the various tasks of a simulation model. Production planners usually use company historical data to calculate the duration of different activities. However, due to the uniqueness and complexity of manual tasks, it is difficult to record sufficient historical time data pertaining to manual tasks. Also, in the case of assessing and improving existing work processes, there is a lack of benchmark data for workers’ performance to enable comparison of the efficiency of the existing process. Estimating the duration of manual tasks is difficult due to the variety of factors affecting it and also its dependence on the physical attributes of the worker performing the task. Time studies can be conducted to obtain estimates of manual task durations but require a substantial amount of time. As a result, Predetermined Motion Time Systems (PMTS) have been developed that provide a standard task duration within which a worker must complete a task without...
delays or idling. By taking advantage of PMTS, construction practitioners can use more reliable estimates of the duration of manual tasks, and thus develop more realistic and efficient simulation models. This study explores micro-motion level simulation modeling and integrates PMTS into discrete event simulation to automatically calculate the standard duration required to perform a task based on simple design data used as input.

1.1 Simphony Platform for Special Purpose Simulation

Simphony (Hajjar and AbouRizk 1999) is a simulation modeling platform that enables creating general and special purpose simulation tools. In this context, Special Purpose Simulation (SPS) is defined as (AbouRizk and Hajjar 1998):

[A] computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself.

Simulation theory, application domain, and object-oriented programming are the main components of creating a special purpose simulation tool (Ruwanpura et al. 2001). Simphony provides a structured approach to developing user-friendly SPS templates and offers a comprehensive set of services under its framework including a discrete event simulation engine, a trace manager, statistics collection, graphing, random number generation, and report generation (AbouRizk and Hajjar 1998). This study uses Simphony as a discrete event modeling platform in order to develop a special purpose simulation focusing on manual tasks at a motion level. The developed SPS is compatible with Simphony’s general purpose simulation which enables integrating elements representing manual activities into larger simulation models of the construction operations.

1.2 Predetermined Motion Time System (PMTS)

Various PMTSs have been developed based on studying large samples of diverse manual operations in order to provide a standard time required to perform a task. PMTSs are created based on the assumption that a universal and precise duration can be determined for each basic motion (e.g., moving a finger, grasping an object), and the time for a complete task can be calculated by adding the time values of each basic motion described in the task (Genaidy et al. 1989). The most widely used PMTSs include Methods-Time Measurement (MTM) (Maynard et al. 1948), Maynard Operation Sequence Technique (MOST) (Zandin 1980), and Modular Arrangement of Predetermined Time Standards (MODAPTS) (Heyde 1966). The MODAPTS method is used in this study since it is has more potential applications than earlier PMTSs and is reported to be 25% faster to apply than the latest MTM (MODAPTS 2006). Another advantage of the MODAPTS method is that it describes tasks in human terms rather than mechanical, making it easier to understand (Aft 2000).

MODAPTS was developed by Chris Heyde in 1966 (Stewart 2002) and is widely used in many industries, such as transportation, manufacturing, and health care, due to its simplicity and effectiveness. Designers, production planners, process engineers, and ergonomic analysts can evaluate and improve manual tasks using MODAPTS without the difficulties of recording and analyzing time data (Harputlu et al. 2012). The main concept behind MODAPTS is that all body motions can be expressed as multiples of a single finger movement and the time required to move a finger is called 1 MOD, which is equal to 0.129 second. MODAPTS enables users to describe a manual task as a sequence of motions, known as modules, and calculate an estimate of the standard time to perform the task as the sum of these modules. In order to use MODAPTS, a task has to be decomposed into basic motions defined by MODAPTS and for each basic motion a class and a numeric value (MOD value) has to be assigned. The final duration of the task will be the sum of the MOD values for the basic motions converted into seconds. MODAPTS classes are represented in MODAPTS codes with a capital letter and describe the motion type. Some frequently used MODAPTS classes include Movement, Get, Put, Walk, and Load Factor. As an example, M4G3 can represent the motion of moving the hand 12 inches with the whole arm to grasp a sheet of paper from a desk. For the purpose of this study, the MODAPTS method has been integrated into the simulation
modeling environment, enabling its use based on design data only, without requiring prior knowledge about MODAPTS and PMTS.

2 MICRO-MOTION LEVEL SIMULATION

Using the previously mentioned features of Simphony, the authors developed a micro-motion level special purpose simulation template, named MODAPTS.vb. In order to create a new SPS template, the modeling elements that will be used to create simulation models pertaining to the specific domain have to be first designed and then implemented. Designing these tasks requires thorough understanding of the targeted construction modeling domain (Hajjar et al. 2000). In the case of micro-motion level simulation, the modeling elements will need to represent motions associated with manual activities performed by a worker. In essence, one primary modeling element and six secondary elements were designed and implemented based on the MODAPTS method. The primary modeling element, named ManualTask, represents a manual task performed by a worker and requires some design data as input. Figure 1 shows these design inputs required. Based on the inputs, the simulation will calculate the required amount of time to perform the task based on the MODAPTS standard. As shown in Figure 1, the required set of inputs only includes simple design data (e.g., distance an object is carried, weight of the object, difficulty of grasping the object) that an operation designer or production planner will have at hand during design or redesign of a construction operation. As a result, this model will enable using a reliable standard duration for manual tasks without requiring prior knowledge about PMTS methods. Table 1 describes each attribute of the ManualTask element. This element can be used in any construction operation simulation model in conjunction with other elements of Simphony’s general template to represent a manual task (e.g., lifting, carrying, and placing an object).

Figure 1: Required inputs for the ManualTask modeling element
Six secondary elements have also been developed which encapsulate the lower level activities performed by a worker in order to complete a manual task. These elements include: Get, Move, Put, Walk, BendAndArise and SitAndStand. Figure 2 shows the ManualTask element and also the secondary elements inside the Simphony modeling environment. The secondary elements are designed based on the classes used by the MODAPTS standard. However, a designer not familiar with MODAPTS can also use these elements to model a detailed level motion of a worker. Some of these elements require an input (e.g., distance for the Walk element) and some can be used without any input from the designer (e.g., BendAndArise). The inputs required are the same as the ones used in the ManualTask element, but they are used as the attributes of the corresponding element. As an example, the PutCondition attribute of the Put element, which can be selected as GeneralLocation, WithTidiness, or ExactLocation, is the same as the EndPosition attribute of the ManualTask element.

The Move element represents the task of a worker moving his hand in order to grasp an object or put it down. The input for this task is the distance between the worker's fingers and the object. The Get element represents how a worker will grasp an object, which will either be touching an object (e.g., pressing a button), simple grasp (e.g., grasping a small tool without the need of visual feedback), or impeded grasp (e.g., grasping a particular bolt in a particular orientation from a container of bolts). The weight of the object should also be specified when using the Get element. The Put element deals with the condition of placing an object at a designated location and can be selected as placing an object in a general location (e.g., dropping a bolt into a bin), placing an object in a predetermined location and in a predetermined orientation, or placing an object at an exact location. The Walk element represents the task of a worker walking and requires the walking distance as input. The BendAndArise element represents the task of a worker bending to pick up an object and then arising and the SitAndStand element simply represents the task of a worker sitting and standing, while other tasks might occur in between. The secondary elements have been developed to give the designer or production planner more flexibility during redesign of the operations. The designer can focus on one of the lower level motions and change its attributes to investigate the impact on the simulation results. Furthermore, in cases when only one of these manual

<table>
<thead>
<tr>
<th>Input</th>
<th>Attributes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td></td>
<td>The distance that the worker walks carrying an object.</td>
</tr>
<tr>
<td>EndPosition</td>
<td>GeneralLocation</td>
<td>Placing an object at a general location without attention to its exact position.</td>
</tr>
<tr>
<td></td>
<td>WithTidiness</td>
<td>Placing an object at a predetermined location using visual feedback.</td>
</tr>
<tr>
<td></td>
<td>ExactLocation</td>
<td>Placing an object at an exact location with increased attention.</td>
</tr>
<tr>
<td>RetrievalEnd /</td>
<td>OneInch</td>
<td>Moving a finger less than 1 inch.</td>
</tr>
<tr>
<td>RetrievalStart</td>
<td>TwoInches</td>
<td>Moving a hand 2 inches or less.</td>
</tr>
<tr>
<td></td>
<td>SixInches</td>
<td>Moving a hand about 6 inches.</td>
</tr>
<tr>
<td></td>
<td>TwelveInches</td>
<td>Moving a hand about 12 inches by moving the arm.</td>
</tr>
<tr>
<td></td>
<td>EighteenInches</td>
<td>Moving a hand about 18 inches by moving the shoulder.</td>
</tr>
<tr>
<td></td>
<td>ThirtyInches</td>
<td>Moving the hand about 30 inches by moving the trunk.</td>
</tr>
<tr>
<td>StartGrasp</td>
<td>SimpleGrasp</td>
<td>Grasping an object without the need of visual feedback.</td>
</tr>
<tr>
<td></td>
<td>ImpededGrasp</td>
<td>Grasping an object that is difficult to grasp.</td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td>The weight of the object that is being handled.</td>
</tr>
</tbody>
</table>
activities (e.g., a worker walking without carrying an object) takes place between other non-manual activities, the appropriate secondary element has to be used instead of the primary element.

Figure 2: Modeling elements of the MODAPTS.vb SPS template

3 CASE STUDY

As a case study, the developed SPS template has been used to model manual activities taking place in a fabrication shop of a steel fabrication and construction service provider in Edmonton, Canada. The main base of operations of the company is a 70,000 m² facility comprising six fabrication shops and various manual tasks are performed by workers at these shops in two ten-hour shifts every day. Using micro-motion level simulation is essential for effective modeling of the construction operations at such a facility. The general sequence of operations at the shop is shown in Figure 3. In particular, the manual task of moving drilled steel plates from the drilling equipment and placing them in the designated bins is modeled as an example to illustrate the functionality of the elements in the MODAPTS.vb template. The sequence of motions consists of the worker picking up a drilled plate from the drilling station and walking a few meters to place it in a bin. The average weight of the plates is approximately 20 kilograms and the average size is 40 cm x 40 cm x 5 cm. In order to collect the required data, the task has been observed at the steel fabrication facility and the duration for the worker to perform the task has been recorded using a stopwatch. Also, for each iteration of the task, the weight of the plate that the worker handled, the distance that he walked carrying the plate, and the conditions of grasping (e.g., difficulty of grasping the plate) and placing (e.g., precision of the final location of the plate) the plate was also recorded. This data was collected for 18 instances of the task, with each cycle starting when the worker moved his hands to grasp the plate, until when he placed the plate at the designated bin.
The sequence of the manual tasks in the plate drilling workstation includes the worker collecting the plate from the drilling machine when the drilling is finished, carrying the plate to the designated bin, and placing the plate inside the bin. This whole task can be modeled using the ManualTask element. Figure 4 describes what each of the input attributes of the element represent in this manual activity.
The same task can also be created using the secondary elements. Figure 6 shows the model using the secondary elements and a description of what activity each element represents. It should be noted that the plate handling task is modeled in Figure 5 as the only task for demonstration purposes and it will be used as part of larger construction operation simulation models in construction process design.

Table 2 shows the inputs for 10 instances of the plate handling task and the result of running the simulation model. For each task, the actual time that it took the worker to perform the task at the jobsite is also shown. The MODAPTS code and duration for each task is also calculated in order to compare it to the duration reported by the simulation time. The manual MODAPTS time is calculated for each task by summing the digits (MODs) of the MODAPTS code and multiplying it by 0.129 (1 MOD = 0.129 sec). As shown in the table, the simulation duration is consistent with the MODAPTS duration calculated manually.

![Figure 5: Plate handling model using secondary elements](image)

Table 2: Input and results for the plate handling task

<table>
<thead>
<tr>
<th>Task</th>
<th>Weight (kg)</th>
<th>Distance (m)</th>
<th>Start Grasp</th>
<th>End Position</th>
<th>Retrieval Start (inch)</th>
<th>Retrieval End (inch)</th>
<th>Actual Time (sec)</th>
<th>Simulation Time (sec)</th>
<th>MODAPTS Code</th>
<th>Manual MODAPTS (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>6.5</td>
<td>Simple</td>
<td>General Location</td>
<td>Two</td>
<td>Two</td>
<td>8.2</td>
<td>7.224</td>
<td>M2G1L1W50M2P0</td>
<td>7.224</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>1</td>
<td>Impeded</td>
<td>With Tidiness</td>
<td>Thirty</td>
<td>Thirty</td>
<td>5.1</td>
<td>3.87</td>
<td>M7G3L3W8M7P2</td>
<td>3.870</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6</td>
<td>Impeded</td>
<td>General Location</td>
<td>Six</td>
<td>Two</td>
<td>7.3</td>
<td>7.482</td>
<td>M3G3L3W47M2P0</td>
<td>7.482</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>6</td>
<td>Simple</td>
<td>General Location</td>
<td>Six</td>
<td>Thirty</td>
<td>7.5</td>
<td>7.869</td>
<td>M3G1L3W47M7P0</td>
<td>7.869</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>5.5</td>
<td>Impeded</td>
<td>With Tidiness</td>
<td>Six</td>
<td>Thirty</td>
<td>8.4</td>
<td>7.869</td>
<td>M3G3L3W43M7P2</td>
<td>7.869</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>6</td>
<td>Impeded</td>
<td>With Tidiness</td>
<td>Six</td>
<td>Thirty</td>
<td>8.1</td>
<td>8.385</td>
<td>M3G3L3W47M7P2</td>
<td>8.385</td>
</tr>
<tr>
<td>Task</td>
<td>Weight (kg)</td>
<td>Distance (m)</td>
<td>Start Grasp</td>
<td>End Position</td>
<td>Retrieval Start (inch)</td>
<td>Retrieval End (inch)</td>
<td>Actual Time (sec)</td>
<td>Simulation Time (sec)</td>
<td>MODAPTS Code</td>
<td>Manual MODAPTS (sec)</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
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<td>----------------------</td>
<td>-------------------</td>
<td>----------------------</td>
<td>---------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>5</td>
<td>Impeded</td>
<td>General Location</td>
<td>Two</td>
<td>Two</td>
<td>6.7</td>
<td>6.321</td>
<td>M2G3L3W39</td>
<td>6.321 (49x0.129)</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>6</td>
<td>Simple</td>
<td>General Location</td>
<td>Two</td>
<td>Two</td>
<td>8.2</td>
<td>7.095</td>
<td>M2G1L3W47</td>
<td>7.095 (55x0.129)</td>
</tr>
<tr>
<td>9</td>
<td>12</td>
<td>5</td>
<td>Impeded</td>
<td>With Tidness</td>
<td>Six</td>
<td>Twelve</td>
<td>6.7</td>
<td>6.966</td>
<td>M3G3L3W39</td>
<td>6.966 (54x0.129)</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>4.5</td>
<td>Impeded</td>
<td>With Tidness</td>
<td>Six</td>
<td>Twelve</td>
<td>6.2</td>
<td>6.450</td>
<td>M3G3L3W35</td>
<td>6.450 (50x0.129)</td>
</tr>
</tbody>
</table>

Figure 6 depicts the actual time versus the MODAPTS time resulting from the simulation model, visualizing the correlation between the actual time from data collection and the result of the simulation. Each point represents an iteration of the task. A correlation analysis has been performed between the actual time and the simulation time for 18 instances of the plate drilling task and a Pearson product-moment correlation coefficient of 0.96 has been calculated which indicates a very strong relationship.

![Pearson correlation coefficient = 0.96](image)

Figure 6: Correlation between actual time and MODAPTS simulation time

The results of the case study indicate that the proposed approach provides construction managers and production planners with a reliable estimate for the duration of manual tasks based on the MODAPTS system. The developed SPS template can be used to estimate the actual time of non-existing manual tasks based on MODAPTS using the correlation between the simulation time and the actual time from the jobsite. This correlation can be used as a benchmark for worker’s performance to evaluate the efficiency of the ongoing operations and implement improvements.

The developed simulation template, in its current form, can be used to improve the efficiency of manual tasks of construction operations. In future work, the authors will also study incorporating ergonomic analysis into simulation modeling using the developed template, in order to provide the designer with an initial insight into the ergonomic risks associate with the operation design. The model will be linked to motion data by using the secondary elements and automated ergonomic evaluation will be performed to evaluate each manual activity based on standard ergonomic analysis tools.

## 4 CONCLUSION

Despite the wide use of simulation modeling for analyzing the efficiency of construction operations, there is a lack of automated methods to model manual tasks involved in construction processes. As these manual tasks have a considerable impact on the productivity of the operations, having reliable estimates
of the duration of different types of manual construction activities can provide designers and production planners with more accurate production analysis results. The special purpose simulation tool developed in this study provides standard motion time data required for performing manual tasks based on the MODAPTS method inside a simulation modeling environment. One primary element and six secondary elements have been developed to model different types of manual construction activities. These elements can be used in conjunction with the elements of Simphony’s general template to model the manual motions of any construction process simulation model. This study can assist practitioners in modeling construction manual activities based on MODAPTS, without requiring prior knowledge about PMTS methods, and can assist researchers to further explore the impact of manual activities on construction operation efficiency. The correlation between simulation time and actual time can be used to evaluate the efficiency of the ongoing operations by providing a benchmark for production performance.

References


IMPLEMENTATION OF CONSTRUCTION INDUSTRY BEST PRACTICES INTO WORKFLOW MANAGEMENT SYSTEMS

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Abstract: Several research studies have confirmed that identification and adoption of industry best practices drive performance improvements in terms of cost, schedule, and productivity. Best practices specifications facilitate the reuse of experience within a domain. However, they typically offer abstract suggestions and recommendations that include not only explicit, but also tacit knowledge. Key approaches of adopting and promoting best practices include socialization and face to face interactions, such as meetings, workshops, and training. These approaches, however, are not easily scalable to large capital projects, to provide systematic and consistent adoption of best practices throughout different phases of a project or among different projects. An alternative solution is to transform best practices into processes implementable into workflow management systems. In this paper, well-known best practices in the domain of the construction industry and their common characteristics are investigated. A framework is then established for transforming best practices into structured processes implementable into workflow management systems. Only parts of a best practice can be transformed into a structured process. The proposed framework describes which components of a best practice are more suitable for this transformation. The result is a process with the essence of a best practice that can be embedded into and automated through workflow management systems. This approach of integrating construction industry best practices into workflow management systems, not only facilitates consistent implementation of best practices throughout the project lifecycle and within projects, but also improves conformance to those practices, with the end result of improved capital project performance.

1 INTRODUCTION

It is well established from statistical analysis of several projects that effective implementation of best practices and integration of information technologies are correlated with substantial improvements in project performance (Figure 1 & Figure 2). Research studies state that systematic implementation of best practices is one of the most important contributing factors to mega projects’ success (Chanmeka et al. 2012). A best practice might be a single procedure or method, but most usually it is a combination of several policies, rules, procedures, and methods, in a particular domain.
Well-known organizations, such as the Construction Industry Institute (CII), the Construction Owners Association of Alberta (COAA), and the Project Management Institute (PMI), develop and promote best practices pertaining to various aspects of capital project management and delivery. Table 1 presents a list of organizations that develop and promote such practices and the term they use for best practices. However, the systematic and consistent implementation of such practices throughout the lifecycle of a construction project and from project to project remains a significant challenge.

### Table 1: Construction Industry Best Practices

<table>
<thead>
<tr>
<th>Organization</th>
<th>Guidelines referred as</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Industry Institute (CII)</td>
<td>Best Practices</td>
</tr>
<tr>
<td>Construction Owners Association of Alberta (COAA)</td>
<td>Best Practices</td>
</tr>
<tr>
<td>Independent Project Analysis (IPA)</td>
<td>Value Improving Practices (VIPs)</td>
</tr>
<tr>
<td>Project Management Institute (PMI)</td>
<td>Foundational and Practice Standards</td>
</tr>
<tr>
<td>Construction Management Association of America (CMAA)</td>
<td>Standards of Practice</td>
</tr>
<tr>
<td>The Association for the Advancement of Cost Engineering (AACE) International</td>
<td>Professional Practice Guides (PPGs)</td>
</tr>
<tr>
<td>The American Institute of Architects (AIA)</td>
<td>AIA Best Practices</td>
</tr>
<tr>
<td>The American Institute of Architects (AIA)</td>
<td>AIA Contract Documents</td>
</tr>
<tr>
<td>Process Industry Practices</td>
<td>Practices</td>
</tr>
</tbody>
</table>

According to CII, best practices are processes or methods that provide improved results when implemented effectively, and thus, can lead to enhanced project performance. Companies implementing best practices consistently, report higher profits, increased customer satisfaction, and improved safety and productivity. Traditional approaches of adopting best practices include socialization and face-to-face interactions, such as meetings, workshops, and training, which are not easily scalable to large-scale
capital projects. An alternative solution is to transform best practices into workflow processes implementable into Electronic Product and Process Management (EPPM) systems – a type of workflow management system particularly being used for managing mega capital projects. This approach utilizes business process models and workflow engines to facilitate more consistent implementation of best practices throughout different phases of a project or among different projects.

Fundamental improvements in communication and collaboration technologies and the increased use of EPPM systems – that are process-based and workflow-driven – in managing mega capital projects provided the required infrastructure, and facilitate putting this approach into practice. Utilization of EPPM systems and workflow engines offer the advantages of consistency, accuracy, and scalability, and thus can be considered a key tool for adopting best practices in mega capital projects.

2 BACKGROUND

Mega construction projects typically involve many stakeholders from different parts of the world, with diverse organizational structures and cultures, and with distinct specialized expertise. A typical oil and gas project is comprised of a few owners, tens of general contractors, and hundreds of sub-contractors from different firms and disciplines, such as engineering, consulting, construction, and facility management; nevertheless, all striving towards the common goal of completing the project.

This level of cooperation is made possible in part by advancements in communication and collaboration systems in the domain of information technology. This includes essential communication infrastructure provided by the World Wide Web, database management systems, and real-time data exchange services. Furthermore, such multilateral accomplishments have been aided by substantial improvements in systems tailored to projects and corporations. Examples include advanced project management tools, enterprise resource planning (ERP) (Chung, Skibniewski, and Kwak 2009; Ghosh et al. 2011; O’Connor and Dodd 2000), workflow engines (Tang and Akinci 2012; Cardoso, Bostrom, and Sheth 2004), electronic document management systems (Al Qady and Kandil 2013), knowledge-based information systems (El-Gohary and El-Diraby 2010; Kang, O’Brien, and O’Connor 2012), and more specifically electronic product and process management (EPPM) systems (Shahi et al. 2014).

Electronic Product and Process Management (EPPM) Systems are the new technology trend for management of mega capital projects. Their core components are typically a combination of a workflow management system (WfMS), a document management system (DMS), and a collaboration management system. A workflow engine at the heart of the workflow management system facilitates enactment of workflow processes; a document management system supports several types of files and enables sharing and modifying various types of documents. The collaboration management system enables project delivery by collaboration among several stakeholders.

The services that EPPM systems offer encompasses planning, coordination, and management activities within the product and project lifecycle. EPPM systems store and retrieve various types of information regarding the lifecycle of a project, and can be used to mine repositories to capture hidden knowledge, and analyze the acquired knowledge for more informed decision making. This knowledge is typically represented in the form of status and progress reports, lessons learned, cost and performance analysis, etc. through dashboards. Implementation of best practices into EPPM systems involves transforming practices into workflow processes. Thus, distinguishing the differences between practice, process, and workflow is vital. Before establishing a framework for practice to process transformation, this paper discusses these differences.

2.1 Process vs. Practice

A process is a series of well-defined inter-related steps which delivers repeatable, predictable results. Key features of a process include 1) predictable and definable inputs, 2) linear, logical sequence, 3) clearly definable set of activities, and 4) predictable, desired outcome (Lee 2005). An activity is typically considered as a major unit of work comprising more detailed steps called sub-activities. Whenever an activity is considered as the smallest unit of work, it is called a task. A process is typically used in routine
circumstances in which repeatable, predictable results are required. Each necessary step is codified in
detail and there is no spontaneous decision making involved.

A process can be performed manually or can be automated through an information system. For an
automated process, the inputs, outputs, and steps involved should be clearly defined; and to implement a
process in a workflow management system it should be defined in a standard process modeling
language. Typically, automated processes include both automated and manual activities. Request for
Information (RFI) and Change Request (CR) processes are examples of such processes. Processes in
which all of their activities are automated are called fully automated processes, such as the buying
processes in Amazon or eBay.

A practice, on the other hand, is a frequently repeated act, habit, or custom that needs a recognized level
of skill to be performed. It is an un-codified knowledge that results from human experience and
improvisation (Lee 2005). While a practice is still a series of steps, the steps are loosely defined, and the
details of how to perform each step is left to the experts who perform them based on their knowledge,
experience, skill, and judgment. Practices, thus, are more suitable for dealing with uncertain situations
with uncommon or unique results (“IT Catalysts” 2013). Table 2 summarizes key differentiators of
processes and practices.

<table>
<thead>
<tr>
<th>Table 2: Process vs. Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
</tr>
<tr>
<td>▪ Series of well-defined steps</td>
</tr>
<tr>
<td>▪ Deliver repeatable, predictable results</td>
</tr>
<tr>
<td>▪ Well-suited to mass production</td>
</tr>
<tr>
<td>▪ Includes clear steps and details for tasks</td>
</tr>
</tbody>
</table>

### 2.2 Process Modeling Tools and Standards

To implement a process in a workflow management system, it should be defined as a process model
using a standard process modeling notation. Several process modeling languages and standards have
been developed for modeling business processes. Process modeling can be performed either by
representing a process using graphical notations or by representing the semantics of the process using
modeling languages. Using graphical notations is more convenient for communication, reengineering,
and improvement of processes. Recent modeling tools such as XPDL and BPMN support both a graphical
notation and a modeling language. A classification of the most popular modeling tools and standards is
presented in Table 3.

<table>
<thead>
<tr>
<th>Table 3: Process Modeling Tools and Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Classical</strong></td>
</tr>
<tr>
<td>Flowchart 1920s</td>
</tr>
<tr>
<td>Functional Flow Block Diagram (FFBD) 1950s</td>
</tr>
<tr>
<td>Data Flow Diagram (DFD) 1970s</td>
</tr>
<tr>
<td>ICAM DEFinition (IDEF0) 1970s</td>
</tr>
</tbody>
</table>

Business Process Modeling and Notation (BPMN) is the most promising process modeling standard. It
has been designed by the Object Management Group (OMG) with the aim of identifying best practices of
existing modeling tools and combining them into a widely accepted, easy to use language. The same
process model in BPMN may encompass different levels of details, each useful for a particular group of
stakeholders, from business administration people to business analysts and software developers. BPMN defines three levels of process modeling conformance. ‘Descriptive level’, useful in high-level modeling, only includes visible elements and attributes; ‘analytic level’ includes descriptive and a minimal subset of supporting process attributes; and ‘common executable’ offers the elements required for execution of process models. In this paper we use BPMN 2.0 notation for representing sample process models.

2.3 Workflow vs. Process

Workflow and process are similar terms and, in certain situations, might be used interchangeably. However, workflow implies a more specific concept than process. While any group of well-defined interconnected steps with an expected result can be called a process, in a workflow the focus is on the piece of work or information that is being passed through initiation to completion. Therefore, a workflow associated with a particular process might not be involved with all the details that are important for completion of the process, such as recording to a database or calling a web-service, but is more dedicated to the flow of work through all the steps. A workflow thus can be defined as an outline or blueprint of a process. A summary of process and workflow differences are presented in Table 4.

<table>
<thead>
<tr>
<th>Process</th>
<th>Workflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>A process is a series of well-defined inter-related steps</td>
<td>A workflow is considered as an outline of a process</td>
</tr>
<tr>
<td>A process is modeled using modeling tools and implemented by coding the steps</td>
<td>The flow of work in a workflow can be updated without changing underlying code</td>
</tr>
<tr>
<td>A process can be modeled with different abstraction levels: organizational, operational, and implementation levels</td>
<td>The focus is on organizational details, but can include operational and implementation-level details</td>
</tr>
<tr>
<td>The focus is on steps of work</td>
<td>The focus is on the flow of work</td>
</tr>
<tr>
<td>A programmer typically implements a process</td>
<td>A analyst typically can modify the steps and update the flow of a workflow</td>
</tr>
</tbody>
</table>

2.4 Workflow Management Systems (WFMS)

Workflow management and workflow specification are concepts tightly related to business process management and process modelling; however, their approach is rather different. Workflow management involves the automation of processes which are comprised of human and machine-based activities (Hollingsworth 1995) and focuses on the flow of information or work among participants. A workflow specification is an abstraction of a process that might not be concerned with all the details of a task, but in any case it is concerned with the inter-relationship, the inputs and outputs, and the externally visible behavior of tasks (Krishnakumar and Sheth 1995).

Automation of business processes partly relies on the coding of software developers for embedding business processes into information systems. Originally, any modification to the process logic, the sequence of activities, and the execution constraints of a process was affecting the programming code and required software developer's attention. The introduction of object-oriented programming concepts facilitated the separation of process logic modifications from the programming code, and led to the emergence of workflow driven systems. In a workflow management system, features of an application, or tasks of a process, are defined as steps in a workflow, and therefore, the behavior of the system can be modified through changing the steps without any modification to the programming code. Workflow technology, thus, provides separation of business process logic from IT operational support (Hollingsworth 1995).
A workflow engine is responsible for managing and enacting tasks within workflow specifications according to their execution constraints and organizational predefined rules. The execution constraints of a process are typically defined as properties or attributes of tasks in the workflow specification. The Workflow Reference Model (Hollingsworth 1995), developed by the Workflow Management Coalition (WfMC) is a key reference for workflow management systems and their interfaces. Workflow management systems facilitate more convenient design and implementation of processes with less involvement in programming details.

3 PROPOSED FRAMEWORKS

A best practice is a guideline to an improved way of organizing and performing a work. The steps offered in a best practice does not necessarily include well-defined sequence and details, and thus it typically relies on the skills and experience of the actor to fill the gaps, whereas in a structured process the sequence of activities and their execution constraints are completely defined. This paper proposes two frameworks for transformation of best practices into structured processes suitable for implementation via workflow management systems. The frameworks explain how the inherent knowledge of a best practice can be combined with the key characteristics of a structured process, such as well-defined steps, sequence, and execution constraints. In addition, the frameworks clarify how the components of a best practice can be associated with elements of a structured process.

3.1 A Conceptual Framework

A practice as a form of knowledge includes explicit, tacit, and implicit types of knowledge (Anand and Singh 2011; Faust 2007). The explicit is the category of knowledge that can easily be identified, codified, stored, and retrieved, and thus, its implementation and automation is relatively straightforward. Interrelated components of a best practice comprising explicit knowledge can be defined as a high level organizational process. Tacit knowledge is inherent with the skills and experience of people, and is hard to capture and codify, and thus, cannot easily be automated. Tacit knowledge or judgmental steps in a practice can be embedded into manual human-tasks of a process. A fraction of tacit knowledge, that is hard but possible to capture and make explicit, is called implicit knowledge. Implicit knowledge is associated with how a process is defined and how it is implemented. It affects the way a process behaves.

<table>
<thead>
<tr>
<th>Table 5: Types of Knowledge in a Practice and their Association with a Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practice Components</td>
</tr>
<tr>
<td>Explicit Knowledge</td>
</tr>
<tr>
<td>Tacit Knowledge</td>
</tr>
<tr>
<td>Implicit Knowledge</td>
</tr>
</tbody>
</table>

Accordingly, we can associate elements of a process with components of a practice. The structure of the process – which defines what is performed – can be defined based on the explicit knowledge present in the practice. The human-tasks of the process – which is related to who has the capability of performing the task – are associated with the tacit knowledge of the practice. The behavior of the process – which is consistent with how the process is defined – signifies the implicit knowledge of the practice (Table 5).

3.2 A Practical Framework

The practical framework for transformation of a best practice into a process involves two main steps: (1) identify the related components of a best practice and define them as one or more high-level organizational processes, and (2) transform the organizational processes into well-defined structured processes suitable for implementation via workflow management systems. These steps are presented in Figure 3 and are discussed with examples in the following sections.
3.2.1 Practice to Organizational Process

Studying the contents of several known construction industry best practices, such as materials management, lessons learned, zero accidents techniques, and change management, confirms that construction industry best practices either include organizational processes or the related components can be defined as organizational processes. For instance, CII best practice for change management offers five principles, each of which has been defined as an organizational process. Figure 4 illustrates the five principles for change management offered by CII change management best practice (Project Change Management - Special Publication 43-1 1994).

An organizational process is a high level process that includes the conceptual steps of performing work, but does not include all the details of the steps, and the execution constraints that are necessary for implementation of the process. For instance, Table 6 presents an organizational process offered by CII change management best practice for the Evaluate Change principle.
Table 6: Evaluate Change Process (Project Change Management - Special Publication 43-1 1994)

3.1 Determine the time frame for change decision.
   3.1.1 Immediate or high priority decision required? If not, process through routine measures.
   3.1.2 Determine funding source for handling interim approval of a high priority change decision.

3.2 Collect data needed.
   3.2.1 Conduct a thorough analysis on cost, schedule, quality, safety, resources, and other items.
   Evaluate on both direct and associated indirect costs.
   3.2.2 Propose and evaluate alternate solutions and options.

3.3 Identify impacts.
   3.3.1 Finalize impact on cost and schedule.
   3.3.1.1 Primary impacts.
   3.3.1.2 Secondary (indirect/ripple/cumulative) impacts.
   3.3.2 Route to all involved disciplines/functions/organizations for impact.

3.4 Determine final funding source or “who pays” (cost reimbursable, design development, lump sum, and others). If applicable, confirm the interim funding source decision.

3.5 Re-evaluate project feasibility with proposed change included.
   3.5.1 If change makes project unfeasible, determine whether it is a required or an elective change.

3.6 Authorize change and send out notice to all affected organizations/disciplines.

Organizational processes, however, cannot directly be implemented into workflow management systems. They lack the required structure and details. As such, they should be transformed into structured workflow processes.

3.2.2 Organizational to Structured Process

In workflow management systems the flow of work or information among participants is a key characteristic. Thus, to transform a best practice to a structured process, implementable into workflow management systems, the steps of the associated process need to be defined as the flow of work or information among participants. Thus, the roles and responsibilities of participants should first be determined. The Responsibility Assignment Matrix (RACI chart) is a useful tool for this purpose. Then, the flow of work among participants should be identified. Finally steps of the high level process should be defined as activities that are performed by participants along with the flow of work.

In addition, the workflow should be defined as a structured process. A process in which the sequence of activities and their execution constraints are completely defined is called as structured process. To clarify, Figure 5 represents the main activities of a change request (CR) workflow and their sequence. A CR workflow is a formal process for authorizing any change in the scope, cost, or schedule of the project. Figure 6 is a more structured representation of the same workflow.

![Figure 5: Main Steps of a Change Request (CR) Process](image-url)
Formal process modeling tools and techniques, such as Unified Modeling Language (UML), Business Process Execution Language (BPEL), or Business Process Modeling and Notation (BPMN), are typically being used to model a structured process. Such standard notations are required for the automation of structured processes via information systems. Figure 7 presents a change request workflow in BPMN notation.

3.3 Summary

In this paper well-known best practices in the domain of the construction industry are explored, and their common characteristics and components are examined. Further, the differences between practices, processes, and workflows are investigated. Then two frameworks – a conceptual and a practical – are proposed for transformation of best practices into structured processes implementable into workflow management systems. The proposed frameworks suggest that specific components of best practices can more easily be transformed into structured processes. The result is a structured process with the essence of a best practice that can be automated through workflow management systems. Implementation of best practices via EPPM systems offers the advantages of consistency, accuracy, and scalability, and thus can be considered a key approach of adopting best practices in large scale construction projects.
Acknowledgements

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References


IDENTIFYING THE SOURCES OF COMPLEXITY IN THE URBAN TRAIN PROJECT IN PUERTO RICO

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Abstract: The metropolitan area of San Juan in the Commonwealth of Puerto Rico has the highest concentration of vehicles per mile of paved road in the world. In order to improve the public transit system and decrease automobile dependency, the Commonwealth of Puerto Rico decided to embark on a major infrastructure project, which consisted on the design and construction of a heavy rail train to serve the Metropolitan Area of San Juan. The first phase of the project consisted of a 10.69 mile segment with 16 stations. This paper uses a five dimensional project management (5DPM) model and develops a complexity map to identify the sources of complexity in the project. The 5DPM model includes the following dimensions: cost, schedule, technical, context and finance. The results indicate that the major source of complexity in this project was the technical dimension which was complex due to variable site conditions and the owner’s the lack of experience managing a project of this magnitude. Due to its scope and significance, the Urban Train project (Tren Urbano) provided an opportunity to train a group of young professionals who would later assume leadership positions in public projects in the Commonwealth of Puerto Rico. A structured professional development program was created in a partnership between the University of Puerto Rico (UPR) and the Massachusetts Institute of Technology (MIT). The professional development program consisted of 6 key elements: (1) MIT short course in public transportation in Boston, (2) UPR Winter short course on the Urban Train and Transportation in Puerto Rico, (3) Student research project, (4) Professional Practicum (summer work internship) (5) Site visit to an operating transit system, and (6) Possible employment opportunities with contractor or consultant. The paper concludes that including a professional development component in the project benefited the students and faculty who were involved. It also concludes that the professional development program contributed to managing complexity in the technical dimension for future projects and in the context dimension for this project by increasing public support to the project through marketing and dissemination efforts. This paper contributes to the body of knowledge by increasing our understanding on how to manage complexity in large transit projects and how to develop and implement a professional development program that contributes to project success.

1 INTRODUCTION

Public transportation systems are necessary in metropolitan areas to keep the traveling public moving while addressing traffic congestion (Bhattacharjee, S. and Goetz A. 2012). The metropolitan area of San Juan in the Commonwealth of Puerto Rico has the highest concentration of vehicles per mile of paved road.
road in the world. In order to improve the public transit system and decrease automobile dependency, the Commonwealth of Puerto Rico decided to embark on a major infrastructure project, which consisted on the design and construction of a heavy rail train to serve the Metropolitan Area of San Juan (Fosbrook and Gonzalez 1997). The government of Puerto Rico did not have any experience in developing an urban rail system, therefore, they decided to establish a professional development program aimed at creating a group of professionals that could embark in future transportation projects. What better teaching tool that learning by participating in the single largest infrastructure project Puerto Rico had experienced in its recent history? Using this extraordinary opportunity to developed future professionals in infrastructure development showed forward thinking from the part of the government. Many of the students that participated in this project became involved professionally with the planning, design, construction and operation of the Urban Train. The professionals that were involved in the program also developed a special understanding of the project, since they had to interact with the students as mentors. This interaction proved effective during the project. As an example, the design of one of the stations was changed due to the interaction with the students.

Undergraduate and graduate students and professors from engineering, architecture and planning from two campuses of the University of Puerto Rico, namely, Mayaguez and Rio Piedras, as well as from the Massachusetts Institute of Technology (MIT) participated in the program. (González-Quevedo, et al. 1999, González-Quevedo, et al. 2000). The participation of MIT was justified because the metropolitan area of Boston and this particular university is known for its strong involvement in the planning, design and operation of urban rail systems. The interaction among the students, professors, and other professionals from both universities and the public and private sectors proved to be very beneficial for all involved and especially for the project.

1.1 Five-Dimensional Project Management

Traditional project management involves managing three dimensions to successfully complete a construction project. These three dimensions are cost, schedule and technical (also termed quality). Cost is quantifying the scope of work in monetary terms. Schedule are the calendar-driven aspects of the project. Technical are the typical engineering requirements. The traditional approach serves well for routine projects, however, as projects become more complex, optimizing the three dimensions is not enough to successfully complete complex construction projects. The difference between routine projects and complex projects revolves around the level of interaction and uncertainty between aspects of the project that are outside the project manager’s direct control (Gransberg et al. 2013). In order to manage complex projects effectively, the project team must manage five dimensions: the three previously mentioned plus financing and context. Financing is the availability of funding and knowing how the project is going to be financed. Context are the political issues, procurement constraints, environmental requirements, public opinion, acquiring right-of-way, agency preferences/biases, and other similar issues (Shane et al. 2013).

The objective of this paper is to present a case study of a complex transportation project in the Commonwealth of Puerto Rico. The five-dimensional project management model was used to identify sources of complexity and rank each source on a relative basis to create a complexity footprint of the project.

2 METHODOLOGY

This study replicated the case study project protocol methodology that was developed for (the second Strategic Highway Research Program (SHRP 2) research project (Shane et al. 2013). Case studies can be used to gain insight on in-depth personal perspectives, behaviors, meanings, and experiences by obtaining details from a number of relevant or involved sources related to a project (Taylor et al. 2009; Yin 2002). The methodology involved using multiple sources of information including public records, project websites and media coverage, journal articles and interviewing the Secretary of the Puerto Rico Department of Transportation (DTOP). Multiple sources of information were used to cross-check that the information found in the data collection was accurate.
The structured interview questionnaire that was developed for the SHRP2 project was administered during the face-to-face interview with the Secretary of the DTOP. Per the U.S. GAO method, ample time was given to ensure that the interviewee understood each question and that the interviewer understood the responses (U.S. GAO 1991). The interview consisted of structured questions but the interviewee was able to deviate from the questions which allowed the interviewers to obtain valuable information that they had not originally contemplated. The interview also included the completion of complexity maps for the project. Complexity maps are a visual tool to manage complexity by creating a footprint. The first step to create a complexity map is to identify the sources of complexity in each of the five dimension (cost, schedule, technical, context and finance). A list of potential sources of complexity was provided to the interviewee. The interviewee was given the opportunity to select from the list provided as well as add any other sources based on his experience.

The second step is to rank the five dimensions in order of complexity where 5 is the most complex dimension and 1 is the least complex dimension. The third step is to assign a value to each dimension. A routine project with normal complexity has a value of 50. If the interviewee believes that the project is more complex than a routine project, a value higher than 50 is assigned. If the interviewee believes that the project is less complex than a routine project, a value lower than 50 is assigned. No two dimensions can be assigned the same value. The final step is to plot the data on a radar diagram and calculate the area of the pentagon (Gransberg et al. 2013). After the interview was completed, the authors discussed in-depth the data collected on the project (literature and interview) to gain an understanding and document the reasons for project success and the lessons learned.

3 RESULTS

3.1 Project Description

The Tren Urbano project is a heavy rail transit system in the San Juan Metropolitan Area in the Commonwealth of Puerto Rico. The heavy rail transit system connects three municipalities in the metropolitan area of San Juan: Bayamón, Guaynabo and San Juan. The scope includes 10.69 miles of heavy rail, 16 transit stations, and a tunnel. The project construction phase was divided into seven Design-Build contracts, one of them being a large Design-Build-Operate contract which included design, construction, power, communications, train control, signaling and the supply of cars, in addition to operation of the transit system for 5 years with a possible extensions. (Fulcher et al. 2004).

3.2 Complexity Map

The results of the complexity map exercise, as shown in Table 1, were used to determine the complexity footprint of the Urban Train. The results indicate that all five dimensions were significantly more complex when compared with the agency’s routine projects. The complexity footprint (Figure 1) shows that the technical dimension was the most complex. Next each dimension will be discussed separately to allow for identification of the sources of complexity by dimension.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Rank</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>1</td>
<td>75</td>
</tr>
<tr>
<td>Schedule</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>Technical</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>Context</td>
<td>3</td>
<td>85</td>
</tr>
<tr>
<td>Finance</td>
<td>4</td>
<td>90</td>
</tr>
</tbody>
</table>
3.3 Cost Dimension

The original cost estimate was $1.2 billion. Changes in the scope of work and different site conditions increased the cost to $2.25 billion (Railway Gazette 2005).

3.4 Schedule Dimension

The original schedule indicated that the project would be completed in 44 months following the Notice-to-Proceed (NTP). The contract scope had to be increased several times due to additional works that were required to upgrade the aging utilities and to provide local community improvements. The changes in the scope resulted in time extensions. It took almost six years from NTP to project completion (Fulcher et al. 2004).

3.5 Technical Dimension

The technical dimension was ranked as the most complex dimension due to the site conditions where the project was built. The owner recognized during the planning state that the following issues will make the project more complex than routine projects:

- Densely populated historic area
- Variable site conditions
- Uncharted utilities and building foundations
- High water table (Fulcher et al. 2004)

The project was divided into 7 contracts to minimize the risk of a company defaulting and to allow multiple companies to participate in project construction phase. The main contract was a Design-Build-Operate contract, the remaining six contracts were design-build. Having multiple contracts allowed the agency to acquire the right-of-way (ROW) for each segment separately which was necessary to guarantee that the ROW of the first segment was completed prior to the 2000 elections. This reduced the likelihood that the project would be cancelled if the opposing party won the elections.

The owner had no experience designing and building a major transit project which greatly contributed to the complexity of the project. In order to address this weakness for future projects a professional development program was created. Since the lack of skilled project managers spans across the technical
and context dimensions, details about the professional development program will be discussed in the context dimension.

3.6 Context Dimension

The project spanned several state government election periods. During the 1993 and 1996 election periods, the project had bipartisan support. This was not the case during the 2000 elections where the opposition party was against the project due to the cost increase, project delays and concerns about the contractor’s ability to successfully complete the project. In order to keep the project moving forward, a significant effort had to be made to counteract the negative press.

The construction industry in Puerto Rico during the late 1990’s and early 2000’s was booming which resulted in a shortage of skilled labor for the project. In addition to the shortage of skilled labor, there was a shortage of trained young professionals who could assume leadership positions. In order to address this challenge, a structured professional development program was created in a partnership between the University of Puerto Rico (UPR) and the Massachusetts Institute of Technology (MIT). The UPR/MIT/Urban Train Professional Development Program (González-Quevedo et al. 1999, González-Quevedo et al. 2000) was an integral part of the Urban Train Project due to the fact that the government of Puerto Rico realized it needed to develop a group of professionals that could plan, design, construct and operate the Urban Train in its present and future conceptions. The program was managed from the government’s side by the General Management, Architectural, and Engineering Consultants (GMAEC). The University of Puerto Rico through its Civil Infrastructure Research Center (CIRC) managed the project from the university’s perspective.

The professional development program consisted of five major components: 1) an educational experience that lasted a week at MIT during the summer; 2) an educational experience that lasted a week in Puerto Rico early in January; 3) a visit to a city with a fully function heavy-rail public transportation system (e.g., Medellin, Caracas, Bilbao, New York City and Miami); 4) a research experience for the students in a project related to the Urban Train, with the participation of professionals involved in the project as advisors and professors as advisors; and 5) a summer internship with the GMAEC, the government, one of the contractors or designers. The University of Puerto Rico, through its CIRC, kept a record of the accomplishments of the program by measuring the number of students who were involved the professional development program and their career growth. Many of them obtained jobs related to transportation infrastructure development and some of them proceeded to further their studies by obtaining advanced degrees.

3.7 Finance Dimension

The Federal Transit Administration in 1993 included the Tren Urbano in its list of Turnkey Demonstration Projects. Through this arrangement the government of Puerto Rico provided 57% of the financing for the project, while the Federal Government provided 18% through its New Start Funds and 25% from other federal transportation funds. (Scheinberg 2000)

4 CONCLUSION

The five-dimensional project management model was used to develop complexity maps to identify the sources of complexity in the Tren Urbano project. The 5DPM model included the following dimensions: cost, schedule, technical, context and finance. The results indicate that the major source of complexity in the project was the technical dimension due to the site conditions where the project was built and due to the fact that the owner had no experience designing and building a project of this magnitude in the Commonwealth of Puerto Rico. Realizing that a professional development program was needed to address the lack of experience in designing and building complex projects by the owner and transportation professionals in Puerto Rico was a wise decision.

Future extensions of the Urban Train as well as other major rail transportation project will benefit from the creation of a cadre of professionals much better prepared to handle such projects. This program was very
successful and the Commonwealth of Puerto Rico still benefits from having skilled project managers, who were part of the program, managing current projects. The professional development program contributed to managing complexity in the context dimension by increasing public support for the project through marketing and dissemination efforts. This paper contributes to the body of knowledge by increasing the understanding of project managers, transportation professional and academia on how to manage complexity in large transit projects and develop and implement a professional development program that contributes to project success.

The cost and schedule dimensions were ranked the least complex among the five dimensions of complex project management. However, it is important to note that the project experienced significant cost overruns and schedule delays. The main limitation of this study is that the results may not be applicable to other similar projects or other locations.

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TYPOLOGY OF SPACE USAGE ON CONSTRUCTION SITES

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Abstract: Site layout planning and logistics is an important part of effective management of construction projects. A site layout defines where the optimum location for objects such as materials, temporary facilities and equipment on a given construction site are. When properly planned, site layout can improve efficiency, cut down on lost time, and ensure occupational health and safety. Site layout planning includes the three steps of 1) identifying the different objects required on site; 2) determining the relationship between the objects; and 3) optimizing the location of objects based on the defined relationships among them. Previous site layout studies have mainly focused on the development of optimization methods, often without giving sufficient attention to the first two steps. The objective of this study is to determine whether the construction site objects and the relationship between them can be classified using generic typologies, in an effort to standardize object and relationship definitions. The study was conducted using nine (9) case studies of construction sites in Alberta, Canada. Observations on the existing objects and their specific location on the site were recorded. Interviews with the site managers were conducted to identify the “reason” behind the selected location for the objects, and specifically, to define their spatial relationships with other objects on the site. This study found eight (8) generic types that the objects from these case studies can be classified into. It further found four (4) generic spatial relationships between objects. These typologies can be used in the development of future models for site layout planning and other related areas of construction management.

1 INTRODUCTION

Site layout planning and logistics is an important part of effective management of construction projects. A site layout defines where the optimum location for objects such as materials, temporary facilities and equipment on a given construction site are. When properly planned, site layout can improve efficiency, cut down on lost time, and ensure occupational health and safety. Site layout planning includes the three steps of 1) identifying the different objects required on site; 2) determining the relationship between the objects; and 3) optimizing the location of objects based on the defined relationships among them. Previous site layout studies have mainly focused on the development of optimization methods, often without giving sufficient attention to the first two steps. The objective of this study is to determine whether the construction site objects and the relationship between them can be classified using generic typologies, in an effort to standardize object and relationship definitions. The study was conducted using nine (9) case studies of construction sites in Alberta, Canada. Observations on the existing objects and their specific location on the site were recorded. Interviews with the site managers were conducted to identify the “reason” behind the selected location for the objects, and specifically, to define their spatial relationships with other objects on the site. This study found eight (8) generic types that the objects from these case studies can be classified into. It further found four (4) generic spatial relationships between objects. These typologies can be used in the development of future models for site layout planning and other related areas of construction management.
objects. These typologies can be used in the development of future models for site layout planning and other related areas of construction management.

2 METHODOLOGY

The case studies were conducted through the following steps that were applied to all nine (9) site visits invariably.

(1) Site Visit:
Construction sites were visited and walked about with a site expert working on the project (Project Manager, Site Superintendent, or Civil Engineers of Record). During the visit, a list of objects and site space usage on the site was created based on the observations. The specific locations of the observed site objects were marked on the Site-Plot provided by the site expert. Site managers and other site personnel were inquired on the reasoning/logic for specific location of objects on the site. Multiple pictures were taken to accompany notes for the creation of actual site plan.

(2) Developing Actual Site Plan:
After each site visit, the photos taken from the site were cross-referenced with the notes and the marked site plot to develop an actual and precise plan of the site. The actual site plans provide visual representations of the layout of the site for that particular period of time.

(3) Object and Relationships Cataloguing:
As the list of objects and space usage on the site was reviewed, categories of objects were naturally emerged (e.g. equipment, work area). Objects and site space usage were categorized into groups at this point. Similarly, categories of spatial relationships emerged by reviewing the relationship catalogue. Another interesting information extracted from the relationships between pairs of objects were overlap between the reasoning/logic provided by the site expert on why an object was located in a specific area e.g. practicality, convenience, specifications or regulations. Additionally, a qualitative weight (as will be discussed in section 6) was identified for each relationship that expressed how important each relationship was.

(4) Matrix Production & Pair-Wise Comparison:
Using the object catalogue for a site, an object matrix was created and populated with relationships identified between pairs of objects. In a matrix prepared for a site, it is possible to see all relationships between all objects on one particular site. Relationship information indicated in the matrix included the types of relationships, the logic for the relationship, and the qualitative weights identified for the relationships.

(5) Re-visiting Site Plan:
After the object relation matrices were created, the generated site layout was revisited to evaluate its accuracy. Any inconsistencies found between the object relations matrix and the site layout helped to expose a potential error. This error could either be the result of poor site planning, or the result of an inaccuracy in recording site information. Identifying inconsistencies between the site layout and the matrix actually helped in identifying a number of poor choices in assigning locations to the objects on the site.

3 SITE LAYOUT CASE STUDIES

A total of nine (9) construction sites from four (4) different construction companies were visited for this project. The construction companies are referred to as company A through D. The sites varied in size, project type, congestion level, and phase of construction. Table 1 summarized the characteristics of the studied sites. Categories of size scale and congestion scale of the construction sites were defined based on the definitions provided by the site experts as shown in Tables 2 and 3, respectively. Figure 2 depicts some examples of various site size and congestion scales.
Table 1: Information Pertaining to the Nine Case Studies

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Project Type</th>
<th>Site Area (m²)</th>
<th>Size Scale</th>
<th>Congestion Level</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Infrastructure</td>
<td>5700</td>
<td>Medium</td>
<td>Congested</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>Commercial</td>
<td>370</td>
<td>Small</td>
<td>Very Congested</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>Industrial</td>
<td>280</td>
<td>Small</td>
<td>Not Congested</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>Residential</td>
<td>16400</td>
<td>Large</td>
<td>Congested</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>Infrastructure</td>
<td>15500</td>
<td>Large</td>
<td>Congested</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>Infrastructure</td>
<td>15500</td>
<td>Large</td>
<td>Congested</td>
<td>A</td>
</tr>
<tr>
<td>7</td>
<td>Commercial</td>
<td>14000</td>
<td>Medium</td>
<td>Congested</td>
<td>A</td>
</tr>
<tr>
<td>8</td>
<td>Industrial</td>
<td>440</td>
<td>Small</td>
<td>Not Congested</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>Commercial</td>
<td>225000</td>
<td>Very Large</td>
<td>Very Congested</td>
<td>D</td>
</tr>
</tbody>
</table>

Table 2: Categories Used for Size Scale of Construction Sites

<table>
<thead>
<tr>
<th>Size Scale</th>
<th>Site Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>&lt; 1,000m²</td>
</tr>
<tr>
<td>Medium</td>
<td>1,000m² to 10,000m²</td>
</tr>
<tr>
<td>Large</td>
<td>10,000m² to 25,000m²</td>
</tr>
<tr>
<td>Extra Large</td>
<td>&gt; 25,000m²</td>
</tr>
</tbody>
</table>

Table 3: Categories Used for Congestion Scale of Construction Sites

<table>
<thead>
<tr>
<th>Congestion Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not congested</td>
<td>Plenty of open space or the potential to easily expand site limits (either temporarily or permanently). Industrial sites typically fall under this category</td>
</tr>
<tr>
<td>Congested</td>
<td>Limited amounts of open space, but placement of materials out of the current construction phase is still available. There may be limited potential to temporarily expand the limits (e.g. lease more land). Commercial sites outside the urban centres are typically in this category</td>
</tr>
<tr>
<td>Very Congested</td>
<td>Very limited amounts of space. Only materials within the current construction phase can be fit within the site. Temporarily expansion of lease limits is either impossible, or extremely difficult to achieve. Downtown commercial projects are typically in this category</td>
</tr>
</tbody>
</table>
Figure 1: Examples of site size and congestion scales: a) site #2: Small, Very Congested; b) site #5: Large, Congested; c) site #8: Small, Not-congested

4 OBJECT TYPOLOGIES

As mentioned before, as object catalogue for each site was generated, categories of objects emerged based on their general purpose. Eventually, from the objects identified in these case studies eight distinct types of objects were emerged. It should be noted that in the context of this study, an object need not be a physical entity, but might instead be a classification of an area that serves a specific function (e.g. work area). The following are the object types identified in this study:

(1) Site Objects
These objects, as the name suggests, exist on the site, and eliminate available area otherwise usable for site lay-down. These could include trees, traffic thoroughfares, or even portions of the completed project. Site objects create are considered as obstructions in site layout, and should be identified before the mobilization phase, as the may lead to congestion issues further along in the project schedule if ignored.

(2) On-site Facilities
These objects (e.g. office trailers, wash-cars) provide service to construction activities on the site. Facilities are usually fixed, if not very difficult to move. Therefore their location should be given a good amount of forethought. Where to put a facility should depend on its purpose, and the proximity of those who use it to their respective activities. For example, an office trailer may be better suited towards the site parking lot, while the lunch-car might be better suited closer to current work-areas.

(3) Work Areas
These objects are non-physical areas in which a designated work task is being performed. These could include formwork construction areas, concrete pours, or cladding application areas. Actual project progress is happening within these areas, and as such an effort should be made to eliminate possible obstructions within these areas. Simple rules like “only keeping relevant material within a work area” and “keeping work areas close to tradesman related facilities” can go a long way in helping project efficiency.

(4) Paths and Moving Corridors
These objects are non-physical areas designated for use by either mobile equipment, or the transportation of objects. These go all the way from on-site roads on larger sites to hallways within smaller interior sites. The main goal within any operational corridor is to preserve open space. Doing so will result in more efficiency for mobile equipment, and will improve general site safety.

(5) Construction Equipment
Regardless of their size (e.g. pick-up trucks, or full sized crawler-crane)s these objects are grouped as construction equipment. They require the use of operational corridors in order to safely move, and often have their own “safe work” radii. These radii are typically due to either a minimum turn distance, or a rotationary swing radius.
(6) Materials – Laydown/staging areas
On-site materials can be considered the “meat and potatoes” of any given construction site. These are the materials that will be eventually added to the final product and become a part of the structure under construction. Materials are most aptly placed close to their respective work areas (staging areas), but may be placed elsewhere if they are not needed at the time being (laydown area).

(7) Support Objects
These objects are the tools and equipment that are needed to get the construction project done. They may cover a variety of objects such as power tools, heating gas tanks, utility lines, formwork, or anything else that is required in order for construction tasks to be completed. Support objects should never be stored too far away from their respective activities. Doing otherwise could result in unnecessary unproductive time causing workers have to walk back and forth multiple times throughout the day.

(8) Entrances / Exits
These refer to physical or non-physical points along the site boundary limits whereby materials, vehicles, and/or personnel may enter or leave the site. The amount and location of these egress points depends on a multitude of factors. These range from the size of site to the current phase of construction.

5 OBJECT RELATIONSHIP TYPOLOGIES

Different objects on a construction site will inherently have different spatial relationships with one another. The following types of spatial relationship between objects were identified between in this study:

(1) Linear Distance Relationships
These relationships specify that objects be either as close to, or as far away from each other as possible. There is no specified minimum or maximum separation between objects, but either object proximity, or the lack thereof is preferred. For example, it is preferred that portable washrooms be as close to work-areas as possible, but there is no requirement that bounds the washrooms to be within certain distance of a work area.

Figure 2: Linear Distance Relationship

(2) Binary Distance Relationships
These relationships pertain to object relations that are invalid either inside a minimum allowable distance, or outside a maximum allowable distance. These relationships are most relevant in cases of OH&S regulations, or in cases of fixed utility lengths. For example, if only 20m of power cords are available on site, a power tool could be no more than 20m away from the nearest substation and/or generator. Any further and the power tool would cease to work.

Figure 3: Binary Distance Relationship
(3) Containment Relationships
These relationships cover objects that must be either inside of, or outside of other objects found on site. Once again, these relationships pertain most to OH&S regulations, and most typically involve one of the objects in relationship is the work area or storage area for the other object in the relationship. A simple example of this relationship type is the necessity for a fire extinguisher to be found within all relevant work areas. To not satisfy this relationship would be against Alberta OH&S standards, and could result in fines.

![Containment Relationship Diagram](image)

Figure 4: Containment Relationship

(4) Adjacency Relationships
These relationships involve objects that are required to be directly next to the object they are interacting with. These relationships often satisfy some form of functionality between the two objects, and not satisfying them could result in a loss of functionality. An example would be a concrete pump to be adjacent to the pour area. Simply put, if the concrete pump is not next to the pour area, the pour wouldn’t be happening.

![Adjacency Relationship Diagram](image)

Figure 5: Adjacency Relationship

6 QUALITATIVE WEIGHTS FOR RELATIONSHIP

When reviewing the site expert explanations they provided for the spatial relationships they provided for pairs of objects, it was noticed that besides the spatial relationships, they also indicated two other pieces of information; the first one related to the reasoning for the indicated spatial relationship, and the second one their relative importance. For example they indicated the washroom should be close to work areas to improved functionality on the site. In this example, the functionality was the reasoning, and should be was their perceived level of importance. After compiling the reasoning for all relationships provided between pairs of objects in this study, it was noticed that they can be distilled in the nine (9) categories: Functionality, Safety, Specification/Regulations, Barrier, Rear-end swing, Efficiency, Obstruction, Convenience and Interruption. On the other hand, it was noticed that four (4) levels of a relative importance are commonly expressed between different relationships as follow: “Has to be”, “Must be”, “Should be” and “Can be”. These expressed levels of importance can be thought of as qualitative weights for the relationships. An interesting observation was that each level of importance was closely associated with a number of six identified reasoning/logic categories mentioned above. Below is the detailed
explanation on the meaning behind the qualitative weights, and the reasoning commonly associated with them.

(1) Has to Be
This is the strongest level used in expressing the importance of spatial relationship between a pair of objects. If not satisfied, it would either result in a halt in construction, or would compromise safety. The following are reasons that were closely tied to the "has to be" relationships.

• **Functionality**: The use of one object is required for the operation of another. For example, a gas powered heater will not function without a gas source; therefore it has to be close to a propane tank within the length of a standard gas line.

• **Safety**: Governments and contractors alike are responsible to adhere to the Occupational Health and Safety Standards that dictate certain objects relationships. These relationships have to be satisfied under the Professional Engineering code of conduct (e.g. APEGA in Alberta). Not doing so would be both unlawful and irresponsible.

• **Specifications**: Certain objects and work areas carry a list of specifications that need to be adhered to at all times. Typically these specifications have to deal with regulations of the professional associations or recommended usage of the equipment. Not adhering to these specifications are also against Professional Engineering Code of Conduct and cannot be tolerated on the site.

(2) Must Be
This qualitative weight expresses the second highest level of importance for spatial relationships between objects. These are relations that if not satisfied, many not cause a halt to the construction altogether, but would result in large and unnecessary delays. The reasons could include:

• **Barrier**: Certain objects, when misplaced, can be a barrier to other operations on the site. A barrier, as defined here, is what would require large mobile equipment and/or a large time investment in order to remediate. A typical example is misplacing a large facility inside an excavation zone. The excavation activity cannot proceed as planned until the facility is removed by large mobile equipment.

• **Rear-end swing**: Certain large pieces of mobile equipment, such as excavators carry with them a rear end swing radius. This is the radius that projects from the tail of the equipment and should be free when the equipment is rotating about itself. Keeping objects outside this radius is a must, otherwise it can create delays in the operations of the equipment.

(3) Should Be
*Should be* weights are used for relationships that are intuitive with everyday operations, yet would result in considerable delays if they are not satisfied. The following are typical reasons:

• **Efficiency**: These are relations that if not satisfied will slow down the daily operations on the site and possibly cause delays. Efficiency-related relationships are those crucial to either the worker’s daily operations, or the function of the object. An example of this would be to ensure that a worker has all of his or her required raw materials in his or her designated work area.

• **Obstruction**: Certain objects, when misplaced, can be obstructive to the objects working around them. Obstructive typically cause a delay in construction, but would not require as large of an effort as barriers to remediate. For example, a garbage dumpster misplaced inside of an operational corridor can be moved out of the way with small mobile equipment, and without much hassle.

(4) Can Be
The lowest weight expressed for an object relationship is the *Can Be* category. These are relations that exist to make the overall operations on the site smooth. The following are typical reasons:

• **Convenience**: This reasoning is used when it is preferred to locate an object in a certain location as opposed to another to add to worker’s convenience. Similar to efficiency reason, not satisfying a worker’s convenience can slow down their daily operations. Unlike efficiency-related
relationships, convenience relationships are secondary to either the worker’s daily operations, or the function of the object. For example placing the tool crib near a particular work area. It would be nice for the worker to not have to walk long to the tool crib, but not very crucial as they would only have to cover the distance 2 or 3 times in a work day.

- **Interruption:** Misplaced objects can be obstructive to the operations of the site. Interruptions cause a delay in construction, but can be easily, and relatively quickly, remediated. An example is removing a misplaced truck from the operational corridor.

7 QUANTIFYING QUANTITATIVE WEIGHTS

In order to enable the use of weights in optimization models, they need to be quantified. This section proposes an approach for the quantification of the weights. Quantification of weights can start by assigning a default score to the four weights for example: has to be (100); must be (75); should be (50); and can be (25).

In the next step, Pairwise comparisons are performed on the matrix of the identified objects for a specific project. Pairwise comparisons are a series of analytical techniques borrowed from the field of Psychometrics. Traditionally, Pairwise comparisons are used to solve otherwise insolvable qualitative problems with iterative quantitative results. The comparison method used in this study is a simplified version of the Thurstone Method (Thurstone, 1297). The comparison begins by going row by row in the Object Relations Matrix to identify and compare relationships that have similar quantitative weights. For example in Figure 6, there are two relations related to Object 1 (one with Object 2 and one with Object 4) with the “should be” weight. It needs to then be decided by the site planner, which of the two is more important. This decision must be based from the perspective of the object in the subject row (Object 1 in this example). This is to say “If I were to place Object 1 on site, would I prefer it to be closer to Object 2, or Object 4?

![Figure 6: Pairwise comparison – identifying conflicts](image)

The objects determined to be less important are downgraded by a defined points, for example 5 points. If there are more similar weights in one row, then another point downgrade is applied to each until there are no two similar weights in one row. In the above example, it was determined that Object 4 is less important to Object 1 than Object 2. As a result, the quantitative weight assigned to the relationship between Objects 1-4 was lowered to 45 (Figure 7).
Once all the similarities in the rows are addressed, the qualitative weights are averaged out with their duplicate cells on the other side diagonal side of the matrix (e.g. Object 1-4 relation vs. Object 4-1 relation). This allows for weights to be analyzed from the perspective of both objects in each individual relation. In the above example, the weight of the relationship between Objects 1 and 4 is averages to 47.5 (Figure 8). This approach allows for defining a clear preference for the importance of satisfying the defined spatial relationships between objects in a systematic manner. As a result, the quantitative weights taken from site experts can be converted to quantitative scores and used in site management applications such as site layout optimization models.

8 SUMMARY AND CONCLUDING REMARKS

The main objective of this study was to identify the typology of space usage on construction sites that can be used in applications developed for site management. This study used nine (9) different construction sites with various size and congestion levels and collectively observed over seventy seven hundred (7700) object relationships. This study could identify eight (8) types of objects, four (4) types of spatial relationships, nine (9) typical reasons for the implementing a spatial relationship between two objects, and four (4) importance weights defined for relationships based on the observations and explanations of the site experts. These typologies can be used in future applications for site management to ensure all aspects of different projects can be accommodated in an application.
Using the relations and weights described for the objects on each site by the site expert, the existing layout of each site was then reviewed to see the adherence to the described relationships. It was interesting that there were a number of “common mistake” trends among the studied sites. The most commonly observed of these trends was the tendency for contractors and/or sub-contractors to infringe within the bounds of operational corridors. On small sites with limited mobile equipment, blocking op-corridors is less of an issue. On the other hand, on large sites with dozens of subs present, a blocked corridor could lead to massive delays in project schedule. Another persistent trend was for contractors to organize materials on the site on a first-come-first-served convenience, rather than tradesman convenience. This trend was more present on smaller sites, as there was typically both a lack of operational corridors, and minimal distance for trades people to travel. While this trend could have little overall effect in project schedule of small projects, it would result in daily inconveniences for workers, and at times, trades people who were less than pleased about how lay down had occurred.

Another interesting observation was that contractors seemed to be commonly prepared with a plan B in cases where a relationships with high importance (Has to be) cannot be satisfied. Contractors were often prepared for such circumstances and an alternative plan prepared in order to save schedule. For example, due to the important role of a tower crane, a heavy-duty crawler was often available on the site in case the tower crane became inoperable. Having such contingencies in place is critical to schedule, therefore these substitutive relations of such nature were expressed as “Must” category.

Whether a relation is considered a “should be” or a “can be” was sometimes difficult. The two weights seem very similar in nature, and one might think of it as almost judgmental to differentiate between the two. A good rule of thumb to follow when trying to evaluate whether a relationship is “Should Be” or “Can Be” is to ask, “Would my worker have ample cause to complain to me if I did not satisfy this relation? If the answer is “Yes,” then it is likely a “Should Be” relationship. If the answer is “No,” or if the worker has no real reason to complain, then it is likely a “Can Be” relationship.

Clearly this study is only scratching the surface for identifying typology of objects and relations for construction sites that can be used in related applications. Construction sites are complex by nature and developing site management applications and solutions have proven to improve efficient planning and management of construction sites. Identifying typology of objects and site space usage can assist in ensuring such applications are applicable to more sites, rather than providing solution to specific cases. More studies are required to ensure the identified typologies are indeed representative of the space usage and relations used in all construction sites.

References

IMPLEMENTING ALTERNATIVE TECHNICAL CONCEPTS IN DESIGN-BIDBUILD PROJECTS

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Abstract: This paper details the results of two in-depth case studies conducted on agencies that implemented Alternative Technical Concepts (ATC) in conjunction with the procurement of low bid Design-BidBuild (DBB) construction projects. The Missouri and Michigan Departments of Transportation (DOT) each chose to pursue early contractor involvement in DBB projects but used two completely different approaches. Missouri allowed ATCs to be proposed virtually without limitation on seven DBB projects; whereas, Michigan chose to only consider ATCs on the Maintenance of Traffic (MOT) Plan for two DBB projects. The paper found both approaches to be successful, generating tangible cost and/or time savings for each DOT. It also proposes two frameworks for developing ATC procurements using either a limited or full scope approach. The paper’s primary finding is that ATCs can be implemented at any level if the agency thoughtfully develops the project’s solicitation documents. It also finds that limited scope ATCs, like the MOT ones in Michigan provide a mechanism to experiment with the DBB ATC process and gain the required understanding of the mechanics of the procurement without increasing the risk the agency must assume.

1 INTRODUCTION

The rapid spread of alternative project delivery methods for delivering infrastructure projects is the result of the critical requirement to rapidly rebuild the deteriorating transportation infrastructure of the United States (US). Specifically, state DOTs are using design-build (DB), construction manager/general contractor (CMGC), or construction manager at-risk (CMR), and at times design-bidBuild best-value (DBB-BV) contracts to take advantage of the design and construction industry’s ideas for alternative design and construction solutions to highway projects. In 2010, the US FHWA implemented its Every Day Counts (EDC) program, which is designed to identify and deploy technical and procedural innovations that promote the “shortening project delivery, enhancing the safety of our roadways, and protecting the environment... it’s imperative we pursue better, faster, and smarter ways of doing business” (Mendez 2010 emphasis added). The EDC program offers to reduce the amount of state matching funds required for a federal-aid highway project if the DOT employs one or more of the approved EDC innovations. Both DB and CMGC delivery are on that list as are Alternative Technical Concepts (ATC).

An ATC is defined by the FHWA as "a request by a proposer to modify a contract requirement, specifically for that proposer’s use in gaining competitive benefit during the bidding or proposal process... [and] must provide a solution that is equal to or better than the owner’s base design requirements in the invitation for bid (IFB for DBB) or request for proposal (RFP for DB) document.‖ (FHWA 2012). Entertaining ATCs as a part of the pre-award procurement process is one method that has proven to yield novel solutions to
complex design and construction problems on a wide range of projects. ATCs are definitely a smarter way of doing business by bringing the collective experience and creativity of all project stakeholders to bear on a given project.

ATCs have been used on US DB projects since 2002 and as such, are a well-tested approach to soliciting competing technical solutions for a given design problem. Their use in DBB projects was first seen in 2011 when the Missouri DOT (MoDOT), impressed with the quality of their DB projects, decided to include ATCs on certain traditional DBB projects. At a meeting for interested contractors, MoDOT explained its motivation for including ATCs in the DBB project to replace the structurally deficient Hurricane Deck Bridge over the Lake of the Ozarks in the form of the following equation:

"BOLD Approach = Industry + MoDOT = One Team = Best Value" (MoDOT 2011)

The meeting stimulated several bold ATCs including two that proposed to completely realign the bridge from its baseline alignment. The low bidder's ATC realignment permitted it to bid $8.0 million below the engineer's estimate for the baseline design. Two of the five bidders did not propose ATCs and their bids were roughly $10 million more than the low bidder. The results clearly showed the promise found by permitting the construction contractor to make substantive changes to a project's final design and proved that the process accrues tangible savings to both the agency and the taxpayer. Therefore, the objective of this paper is to detail the ATC process applied to DBB projects in Missouri and Michigan. It will also propose a framework for a generic DBB ATC that is founded on the outcome of the two case studies.

2 BACKGROUND

Many of the studies on construction procurement have found that early contractor involvement in the project's planning and design yield benefits to the owner in terms of constructability, which in turn saves both time and cost (Hoffman et al. 2009; McMinimee, et al. 2009; Carpenter 2012; Coblenz 2012; Hitt 2012; Horn 2012). The literature also shows that contractor design input contributes to a more effective design with reduced errors and omissions via the direct application of construction knowledge (Yates and Battersby 2002). Furthermore, West (2012) argues that “contractor design input is [a] benefit... because it enhances constructability and innovation and creates potential for cost savings through effective design solutions.” The Massachusetts DOT (2012) chose to implement ATCs “to avoid delays and potential conflicts in the design.” Taking these findings with the enhanced quality of final construction documents leads to the conclusion that implementing ATCs effectively provides a new level of design quality control through the involvement of the contractor in reviewing the solicitation and design documents and identifying errors, omissions, and ambiguities. In West's (2012) words, the practice creates a “form of price clarification, eliminating confusion and potential misunderstanding by mandating information-rich communications.”

2.1 Confidential One-on-One ATC Meetings

NCHRP Synthesis 455 on ATCs (Gransberg et al. 2014) found that that most agencies implementing ATCs conduct confidential one-on-one meetings where competing contractors are allowed to present ideas for potential ATCs. The objective of these meetings is first to permit contractors to float their ideas for ATCs past the owner and get a quick decision as to whether or not the agency was likely to approve the change. Secondly, if the response is positive, the one-on-one meeting provides a mechanism where the owner and the contractor can discuss the details of the potential change and reach agreement on whether the proposed ATC is “equal to or better than” the baseline design as required by federal regulations. The confidentiality of these communications is the key to success as competing contractors will not offer up their good ideas if they believe the concepts will become known to their competitors (Smith 2012). Randy Hitt, PE of the MoDOT describes his agency's approach to confidential ATC meetings by saying: “Confidentiality in the ATC process is very important for the success of the ATC process. Great care needs to be taken when exchanging files and emails” (Hitt 2012). Another paper written by a contractor expressed the same sentiment from the other perspective: “Trust in the Owner's confidentiality, objectivity and fairness is paramount” (Smith 2012).
In the agencies where one-on-one meetings are not authorized, the competitors were typically asked to submit a written ATC proposal for review and approval. In most cases, there was a deadline established for submission and either a one or two week period for the owner's review and decision to be returned to the competitors. Regardless of the presence of one-on-one meetings, most DOT policies provide for confidentiality of the outcome of the ATC review/approval process.

2.2 Applying ATCs to DBB Procurements

Implementing DBB ATCs entails a shift in the procurement culture to permit contractors to confidentially propose changes to a project’s scope and get the full benefit of their innovation by allowing them to be the only competitor that is allowed to submit a bid on the project as modified by the approved ATC. NCHRP Synthesis 455 (Gransberg et al. 2014) found that guaranteeing confidentiality permits competing contractors to build a competitive edge with their ATCs and is widely used in DB projects. The synthesis also found that it stimulates innovative approaches to delivering a project that were not considered by the agency during the baseline planning and design process.

At this point, it must be noted that the aim of the paper is not to advocate the use of ATCs on every DBB project. The ATCs, like alternative project delivery methods, should be applied to a specific project after careful thought and a determination that the project stands to benefit from the construction contractor’s pre-bid input to the project’s design. In most cases, this means that the transportation agency engineer has found that there are several promising options for the contractor’s means and methods, which once identified, will drive one or more of the details of the final design. Knowing the information before award could conceivably accrue benefits in terms of cost and/or time savings. An example would be designing the size and length of bridge members based on a contractor’s actual reach and pick constraints for a barge-mounted crane.

A second aspect of the ATC method that was found by those DOTs that used the tool is that the decision to include ATCs should be made as early in the project development process as practical. Ideally, it would be made before the project’s National Environmental Policy Act (NEPA) clearance is completed to minimize the chances that public commitments made during the NEPA process do not reduce ATC potential benefits or stifle them altogether. The Missouri DOT learned this lesson on its Hurricane Deck Bridge project and the details of their experience are contained in the subsequent case study discussion. In essence, a project with a high potential for beneficial ATCs must pass through the NEPA process with as much flexibility of final design configuration as possible. This constitutes a shift in the environmental permitting process away from the current mode of “be as specific as possible” to a less restrictive mode that provides the agency as much latitude as possible while remaining in full compliance with the laws of both the State and the Federal Government. The net result is that planners, designers, and construction personnel must be jointly involved in the ATC decision at the earliest point—when the project scope is defined.

Thus, to maximize the value made possible by implementing ATCs, a much higher level of internal collaboration is needed for a longer period of time by the agency. This means that agency planners may need training to recognize the features of a project that make it a good candidate for ATC solicitation. Deciding to change an agency’s culture with respect to environmental commitments requires a certain amount of moral courage and the willingness of upper management to support bold changes in historic agency design standards. It also requires support to allow a low-bid construction contractor to furnish options for changing the design.

2.3 ATC Process Models Found in the Literature

NCHRP Synthesis 455 found that DBB ATCs can be implemented in two different forms. The first, called a “full scope ATC,” allows interested contractors the freedom to propose ATCs on the entire scope of work. The second is called a “limited scope ATC” and specifies those portions of the scope of work on which ATCs are being solicited. Table 1 lists the advantages and disadvantages of both types. To highlight a few, limited scope ATCs may not be able to improve the construction schedule or realize significant cost savings as opposed to full scope ATCs where large number of options are proposed for
time and cost savings. However, the issue of confidentiality and environmental commitments - that could be impacted significantly- is more complex in the full scope compared to the limited scope ATC. In addition, in terms of maintenance of traffic in the limited scope approach, the impact to MOT is easier to measure due to highly focused scope of ATCs compared to the full scope ATC where the entire project might be eligible to modification to optimize MOT and the baseline MOT design may not be compatible with the ATCs proposed. In essence, while both ATC approaches have been implemented successfully, NCHRP Synthesis 455 found that the limited scope ATC was a less radical change to the traditional DBB procurement process and indicated that as DBB ATCs proliferate that most will probably be the limited scope variety (Gransberg et al. 2014).

Table 1 Advantages and Disadvantages of Full Scope vs. Limited Scope ATCs (FHWA 2012)

<table>
<thead>
<tr>
<th>Issue</th>
<th>Full Scope ATC</th>
<th>Limited Scope ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project delivery schedule</td>
<td>Large number of options to save time during construction</td>
<td>ATC review process might delay award</td>
</tr>
<tr>
<td>Construction cost</td>
<td>Large number of options to save money</td>
<td>Difficult to verify potential savings before award</td>
</tr>
<tr>
<td>Confidentiality before award</td>
<td>--</td>
<td>Large number of ATCs increases the active efforts to maintain confidentiality.</td>
</tr>
<tr>
<td>Environmental commitments</td>
<td>Expands opportunities to implement innovative protection measures</td>
<td>Requires a thorough analysis to ensure commitments are not impacted</td>
</tr>
<tr>
<td>Right of way acquisition</td>
<td>May reduce the amount of ROW required for temporary access during construction</td>
<td>Approving an attractive ATC may require additional ROW</td>
</tr>
<tr>
<td>Utility Coordination</td>
<td>May reduce the amount of utility coordination and relocation required.</td>
<td>Approving an attractive ATC may require additional utility coordination and/or relocation effort.</td>
</tr>
<tr>
<td>Maintenance of traffic</td>
<td>Makes the entire project eligible to modification to optimize MOT</td>
<td>Baseline MOT design may not be compatible with some ATCs</td>
</tr>
<tr>
<td>Construction staging</td>
<td>Makes the entire project eligible to modification to optimize staging</td>
<td>--</td>
</tr>
</tbody>
</table>

3 METHODOLOGY

The study utilized two primary research instruments: literature review, including a content analysis of agency ATC solicitation documents, and formal case studies of projects in Missouri and Michigan. The primary objective of the case study protocol was to supplement the knowledge framework created through the literature reviews and agency solicitation documents with the deeper knowledge of the project participants. Literature review and content analysis provide the researcher with the “what” of a given project, but structured interviews with case study project participants provide the “why” for the decisions made and the events observed in the project.
3.1 Case Study Protocol

The literature review and content analysis drove the case study data collection and the sought to identify with information collected in the literature review to validate case study conclusions. The choice of projects to further investigate as in-depth case studies was determined based on the availability of participants and documentation on DBB ATC projects. Only two US states, Missouri and Michigan, have implemented ATCs on DBB projects. At the time of this writing, Missouri has completed roughly ten projects and Michigan has done two. In-depth case studies will serve as a critical source of information in this research. The analysis will be conducted on the following three levels:

1. Analysis of DBB ATC projects of different sizes, different states, and different methodologies as identified in the literature review.

2. Interviews of public transportation agency personnel, contractors, and consultants with DBB ATC project management experience.

3. Published reports of DBB ATC case study projects from the highway sector.

3.2 Case Study Selection

The primary input to the case studies was gathered through structured interviews with agency personnel, contractors, and consultants that have been part of teams involved with DBB ATC projects. The structured interview outlines were developed using the method prescribed by the US Government Accountability Office (GAO 1991). The GAO method states that structured interviews can be used where “information must be obtained from program participants or members of a comparison group… or when essentially the same information must be obtained from numerous people for a multiple case-study evaluation” (GAO 1991). Both these conditions apply to this study; therefore, the tool is appropriate for the research.

The process involves developing a questionnaire that was made available to each interviewee prior to the interview and then collecting responses in the same order using the same questions for each interviewee. The information was gathered using both face-to-face and telephonic interviews. Per the GAO method time is allotted to ensure that the interviewee understands each question and that the data collector understands the answer. Additionally, interviewees were also allowed to digress as desired, allowing the researchers to collect potentially valuable information that was not originally contemplated. The output is used to present the agencies’ perspective on various points analyzed in the subsequent tasks.

The case study details were collected using Yin’s methodology (Yin, 2004). The use of these instruments in conjunction with the comprehensive review of the literature allows the researcher to not only maintain a high level of technical rigor in the research but also follow Yin’s three principles in the process of research data collection: 1) Use of multiple sources, 2) Creation of a database, and 3) Maintaining a chain of evidence (Yin, 2004).

Based on the page limitations for this paper, the Hurricane Deck Bridge Replacement Project in Missouri and the US-10 Rehabilitation Project in Michigan were selected. The fundamental rationale was to be able to compare to a project that utilized a full scope ATC with one that used a limited scope ATC process. Additionally, the Missouri project ATC extensively changed the baseline bridge design and can be compared to the Michigan project where only the MOT plan was changed from the baseline. The result provides a basis for proposing frameworks for each ATC process type.

3.3 Case Study Project Details and Background.

Two case study projects were selected to evaluate the differences in the Missouri and Michigan DBB ATC processes. Table 2 contains a synopsis of each project’s details. It shows that the MoDOT Hurricane Deck Bridge project ATC was the most comprehensive as it not only changed the bridge’s structural design, but also changed its alignment. Alignments of federal-aid highway projects that have received NEPA clearance are considered to be fixed and a change triggers a potential re-review (Hitt 2012). To
compound the complexity of implementing this alternative, MoDOT had chosen to avoid potential design liability issues by advancing approved ATC designs to the point where biddable quantities could be generated. Hence, the issue of confidentiality became very complicated as a NEPA re-review puts the technical details of the ATC into the public domain. Additionally, since three contractors submitted ATCs, MoDOT’s design consultant had to maintain three separate design teams for each of the ATCs to protect against accidental revelation of one contractor’s ATC to another.

Table 2 Case Study Project Details. (adapted from Gransberg et al. 2014).

<table>
<thead>
<tr>
<th>Item</th>
<th>Hurricane Deck Bridge</th>
<th>US-10 Rehabilitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agency</td>
<td>Missouri DOT</td>
<td>Michigan DOT</td>
</tr>
<tr>
<td>Initial Estimated Project Value</td>
<td>US$ 40.4 million</td>
<td>US$ 22.0 million</td>
</tr>
<tr>
<td>Contract Award Value w/ATCs</td>
<td>US$ 32.3 million</td>
<td>US$ 21.1 million</td>
</tr>
<tr>
<td>Type ATC</td>
<td>Full Scope</td>
<td>Limited Scope</td>
</tr>
<tr>
<td>Project Baseline Scope</td>
<td>Replace existing 2,260 foot bridge</td>
<td>Rehabilitation of 8 bridges and 6.9 miles existing roadway</td>
</tr>
<tr>
<td>Nature of ATC</td>
<td>Build bridge on new alignment; reduce steel quantities by 50%</td>
<td>Maintenance of traffic plan to complete project in 1 season instead of 2.</td>
</tr>
<tr>
<td># ATC received</td>
<td>3 from 5 contractors</td>
<td>6 from 5 contractors</td>
</tr>
<tr>
<td>Cost Savings</td>
<td>US$ 8.1 million</td>
<td>US$ 0.9 million</td>
</tr>
<tr>
<td>Time Savings</td>
<td>2 weeks</td>
<td>12 months</td>
</tr>
</tbody>
</table>

MoDOT had several issues that needed to be handled differently than the standard DBB procurement process. For example, to address the environmental issues, MoDOT identified the selected alternative in the Environmental Assessment, while ensuring the environmental document made reference to the ATC process. This is in addition to having FHWA involved in the environmental discussions with MoDOT team from day one. The ATC team had open communication with the environmental office and even disclosed potential designs that could trigger a re-review of the NEPA document if they weren’t originally covered. In terms of design liability, MoDOT decided to assume the design liability of the proposed ATC to avoid creating issues of transfer of design liability and eliminate the need to offer a stipend for the effort costs invested by unsuccessful bidders in ATC design. Since confidentiality for the contractors is considered key to the success of the ATC process, MoDOT took several measures to ensure confidentiality. First, the agency’s design consultant assigned four individual design teams to work on the different ATC designs. The design teams had to also exercise great caution in keeping separate proposals independent of each other. Secondly, MoDOT created an external sharepoint site secure to each contractor engaged in the ATC process. This ensured that the proposers had no idea who the other proposers were and what ideas were being discussed. Finally, confidentiality imposed two major constraints on the normal bidding process, 1) the final proposed improvement could not be revealed to the public until the bidding stage and thus, MoDOT only advertised that they were allowing contractors to propose alternate ideas for construction and 2) MoDOT could not finalize the right of way negotiations as they couldn’t share what the change in footprint impact with the property owners (Hitt 2011).

As for the US-10 project, MDOT provided contractors the opportunity to include pricing for a pre-approved ATC(s) in their proposals. Proposers were allowed to bid either the MDOT baseline design or their approved ATC(s). If the ATCs submitted by the proposers required NEPA re-review or modifications to previously approved permits, the proposer has to bring it up for MDOT and FHWA approval. Since this project presents a "limited scope" implementation of ATC, ATCs on this project were limited to staging and traffic control on US-10 mainline, in contrast to MoDOT Hurricane Deck Bridge project where the contractors were to assume the risk of preliminary and final design costs for their approved ATC. The issue of confidentiality was also addressed in the Notice to Bidders document by stating that “MDOT expressly reserves the right to adopt any specific [Conceptual ATC] CATC or ATC as standard practice for use on other contracts administered by MDOT, whether the CATC or ATC is accepted or rejected....
CATC or ATC shall not be used by MDOT until after the award of this project." MDOT considered all the ATCs submitted as confidential and as such were not to be shared with other bidders. In addition, the review team members were required to sign a confidentiality agreement to guarantee confidentiality (MDOT).

4 CASE STUDY ANALYSIS

4.1 Case Study Procurement Analysis

Table 3 shows that the time required to procure a full scope DBB ATC is roughly 10 months. Whereas, the limited scope DBB ATC was roughly 6 weeks. Thus, it can be concluded that the decision to permit full scope ATCs has a measurably longer time frame to permit interested contractors to generate their alternatives and to permit the DOT time to evaluate and approve those that it finds attractive.

Table 3 Case Study Project Timelines (Hitt 2012).

<table>
<thead>
<tr>
<th>Event</th>
<th>Hurricane Deck Bridge Date</th>
<th>US 10 Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractor Information Meeting</td>
<td>February 10, 2011</td>
<td>April 10, 2013</td>
</tr>
<tr>
<td>Commission Confirms Base Design</td>
<td>March 1, 2011</td>
<td>-</td>
</tr>
<tr>
<td>30% Plans Posted on Website</td>
<td>March 1, 2011</td>
<td>-</td>
</tr>
<tr>
<td>Contractor CATC meetings start</td>
<td>March 1, 2011</td>
<td>April 10, 2013</td>
</tr>
<tr>
<td>60% Plans Posted on Website</td>
<td>May 27, 2011</td>
<td></td>
</tr>
<tr>
<td>Last day to submit ATCs</td>
<td>August 15, 2011</td>
<td>May 3, 2013</td>
</tr>
<tr>
<td>Pre-bid deliverables due</td>
<td>November 10, 2011</td>
<td>May 10, 2013</td>
</tr>
<tr>
<td>Bids Due</td>
<td>December 10, 2011</td>
<td>May 22, 2013</td>
</tr>
<tr>
<td>Total Time Elapsed</td>
<td>303 days</td>
<td>42 days</td>
</tr>
</tbody>
</table>

4.2 Case Study Process Analysis

Figures 1 is a generic DBB ATC solicitation, submittal, evaluation and approval process seen in each DOT. MoDOT process occurs in four project development and delivery phases. The process starts with ATCs announcement inclusion on a given project together with the posting of current plans to permit contractors to get familiar with the project and begin developing ATCs. Conceptual ATCs (CATC) are then received and expeditiously reviewed and approved to provide contractors quick decisions on their ideas attractiveness to MoDOT. CATCs are discussed in confidential one-on-one meetings which are then followed by formal ATC submission, evaluation, and approval. Once approved, MoDOT advances the ATC-modified design to a stage where biddable quantities could be produced. It is then the contractor’s decision whether or not to bid the approved ATC. If the contractor wins, MoDOT completes the redesign to finalize the construction documents (FHWA 2014). MDOT uses essentially the same process with the major difference being the amount of time allotted to evaluation and approval as shown in Table 3. Therefore, one can conclude that the amount of time allotted to the ATC process is directly related to the amount of scope that can be changed by ATCs.

4.3 Case Study Discussion

The case studies provide good examples of two different ATC approaches implemented successfully in DBB projects. The key motive for ATC implementation in both is early contractor involvement in generating scope changes and the cooperative effort to find a best value innovative solution. MoDOT’s ATC approach showed that obtaining early contractor involvement is possible on a traditional low bid DBB highway project. Such an approach also was strongly supported by its local design and construction industry partners; in the words of one Missouri contractor, “We elected to pursue ATCs because we felt
we could derive a solution that would be more economical for us to build than the baseline design” (Hitt 2012).

However, based on the two cases, key elements emerge for ATCs successful implementation (1) environmental process, (2) time commitment for project delivery, (3) confidentiality, and (4) design liability. As NEPA came largely into play with an ATC that involved the realignment of the Hurricane Deck bridge, MoDOT had to handle environmental procedural issues in a manner that did not compromise the confidentiality of the ATCs. It also had to maintain high levels of internal collaboration between planners, designers, and construction personnel as well as continuous evaluation impending NEPA commitments against their possible impact on potential ATCs. One of the instrumental factors in an agency’s culture with respect to environmental process change is the willingness of upper management to support fundamental changes in historic agency design standards.

The Figure 1 procurement framework shows that providing contractors adequate time to develop and refine their proposed ATCs is critical to the process. Contractors need more time than the amount in a routine bidding period to explore potential ATCs and to get approvals from the agency to proceed. It is seen how time frames are highly dependent on the scale and type of the project, together with the individual agency and contractor capabilities. Whether the process involves a full or the limited scope approach, confidential one-on-one meetings are instrumental in an ATC process to vet possible ATC concepts. Both agencies addressed confidentiality by different means such as having different teams on different design proposals in MoDOT’s project or the confidentiality agreements used by MDOT. The last important aspect is the issue of design liability for the proposed ATC design. MoDOT assumed full liability of design development in its full scope approach, and MDOT decided to have the proposing contractors fully develop their designs using approved MDOT consultants. Lastly, both DOTs found that permitting contractors to bid the baseline design was important to keep contractors who don’t understand/trust the ATC process in the competition.

5 CONCLUSIONS

The aim of this paper is to detail the ATC process applied to DBB projects in Missouri and Michigan and accordingly propose a framework for a generic DBB ATC founded on the outcome of the two case studies. Two projects were selected; Missouri’s Hurricane Deck Bridge project in and Michigan’s US-10 Rehabilitation project. Both projects implemented ATCs in DBB yet using two different approaches: a limited or full scope approach. MoDOT allowed contractors to propose ATCs without limitation while MDOT Michigan chose only to consider ATCs on the MOT. Through analyzing both projects, three major conclusions are reached. First, both approaches are proven to be successful through generating tangible cost and/or time savings for each DOT. However, limited scope ATCs will prove easier to implement on DBB projects for an agency trying it for its first time as it provides a mechanism to experiment with the DBB ATC process and gain the required understanding of the mechanics of the procurement without increasing the risk the agency must assume. The impact found by the Michigan limited scope approach case was to essentially extend the 30 day bidding period by 12 days. Second, ATCs can be implemented at any level if the agency thoughtfully develops the project’s solicitation documents. The clarity of the instructions and the proposal requirements such as the EPA and permit requirements/constraints are key issues that need to be addressed in the solicitation documents. Finally, the analysis of the two cases emphasizes the importance of confidentiality and one-on-one meetings to the success of the ATC process.

Acknowledgements

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Figure 1: Generic ATC Process
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EXPEDITING EMERGENCY CONSTRUCTION PROCUREMENTS: CASE STUDIES IN SUCCESS

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Abstract: While the law allows public transportation officials to do what it takes to resolve the emergency, they are expected to maintain an extremely careful balancing act between expeditiously resolving the crisis and abusing their authority to circumvent the routine full and open competition process using the emergency as justification. The ability to waive standard procedures comes with the requirement to use that authority both sparingly and wisely. This paper presents analysis case studies of expedited emergency projects from nine states that range from a $550,000 landslide repair to a $234 million interstate highway bridge replacement. The cases also cover emergency projects delivered by design-bid-build, construction manager/general contractor, design-build and indefinite delivery/indefinite quantity contracts. The paper finds that the major factor for successful emergency procurement is for the owner to utilize procurement processes with which it is familiar. It also finds that owners need to allow as much competition as time and circumstances permit to reduce the probability of a substantive protest. Finally, it recommends anticipating an emergency and making advance preparations is the fastest way to react to an emergency and the surest method for avoiding protest.

1 INTRODUCTION

“In both [US] federal and state law, the use of emergency procurement procedures allows for limited competition in selecting a contractor… however, this limitation must be carefully utilized and fully documented” (Perry and Hines 2007 italics added). Herein, lays the heart of the primary procurement dilemma for public officials attempting to expeditiously deliver the design and construction services necessary to resolve an infrastructure availability crisis. The law grants broad latitude regarding suspending statutory competition requirements in an the emergency situation, officials are also expected to the legal tightrope between expeditiously resolving the crisis and potentially abusing the authority to suspend full and open competition while using the emergency as justification. Emergency powers come with the requirement to use that authority both sparingly and wisely throughout the crisis. The New Mexico Department of Transportation (DOT) emergency procedures manual (2007) puts it this way: “Lack of planning does not constitute an emergency.” Another author evaluating the difficulties of emergency procurement puts it this way: “Perhaps a good rule of thumb is, when in doubt, bid it out.” (Houston 2011).

The primary research objective was to identify trends in successful emergency construction project delivery via the analysis of case study projects. Secondarily, the research sought to determine the impact of limiting competition during emergency procurements and identify effective practices for providing as much competition as practical that can be replicated in future emergencies.
2 BACKGROUND

Many of the studies on the deteriorating condition of the North American transportation system find that public agencies must deliver critical infrastructure projects “better, faster, cheaper” (Atzei et al. 1999; Richmond et al. 2006). However, when an emergency occurs and removes an essential piece of the infrastructure such as a major bridge, the alternatives for optimizing the procurement process narrow to the point where only one of the three previous components remain, and that one is time, i.e. “faster.” While “better” (quality) and “cheaper” (cost) are still of concern, they take a lesser priority until service is restored. Then, the public attention often switches to an analysis of value for money from a retrospective viewpoint. The attention often criticizes the procedures used by the agency to restore service as quickly as possible. The result is that public agencies have expended much time and money to develop emergency management plans supported by a preapproved set of expedited procurement procedures.

2.1 Spectrum of Emergencies

The pressing need to expedite the delivery of an emergency project normally arises unexpectedly, and the magnitude of the response can range from very little to a declaration of a national disaster. When the emergency is large enough to make national news like Hurricane Sandy on the US east coast or the Interstate 35W bridge collapse in Minnesota or the 2013 ice storm in Ontario, public officials must implement expedited procurement procedures to restore vital network links with the media scrutinizing their work every night on the evening news. While high profile emergency projects are well-known, the more typical case is a local emergency caused by flashing flooding washing out a culvert on a rural road or a freeway overpass damaged and closed from a traffic accident. These mundane local emergencies sometimes go unmentioned in the news, but are just as critical to drivers traveling through the locality and require the agency to exercise just as much speed to restore service and remove threats to life and property. The difference in the two situations can be the construction industry’s willingness to accept a change in customary rules ensuring free and open competition for construction projects. In major disasters, the publicity encourages a “do whatever it takes” attitude due to the emotions surrounding the event that are rarely present in the localized incidents. Nonetheless, agencies have found ways to successfully resolve both large and small emergency disruptions to network service. Therefore the purpose of this paper is to evaluate the collective experience with expedited procurement procedures to deliver both design and construction services for emergency highway projects.

2.2 Legal Constraints on Emergency Procurements

Based on local statutes, most public agencies are given the power to take whatever action is determined necessary to insure health, safety and welfare of the community in an emergency. For example the Florida statutes (2010) state: “The political subdivision has the power and authority to waive the procedures and formalities otherwise required of the political subdivision by law pertaining to: performance of public work and taking whatever prudent action is necessary to ensure the health, safety, and welfare of the community; entering into contracts [and] incurring obligations...” This verbiage applies to awarding emergency highway contracts by the Florida DOT. Most, if not all, US state codes provide similar authority to ignore routine statutory competition constraints in an emergency where the time it takes to follow the routine procurement process would or could exacerbate the impact to the health and safety of the community.

The United States Code (2000) authorizes public agencies to provisionally suspend its construction bidding regulations for contracts awarded for emergency situations. Normally, the Federal Highway Administration’s (FHWA) requires consultant contracts to be awarded on a competitively negotiated basis to the best qualified offeror based on the Brooks Act (23 CFR §172.5a3) and contracts for construction to be awarded on the lowest responsive and responsible bidder to be approved for federal funds. Additionally, roads designated as eligible for federal-aid are also eligible for federal funds administered by FHWA. Title 23 USC §125 authorizes emergency relief (ER) funding for the “repair or reconstruction of highways, roads, and trails, … that the Secretary finds have suffered serious damage as a result of— (1) natural disaster over a wide area, such as by a flood, hurricane, tidal wave, earthquake, severe storm, or landslide; or (2) catastrophic failure from any external cause.”
Further complicating the mobilization of assets to cope with an emergency event is the requirement for gain approval from and coordinate with resource agencies to meet the requirements of the National Environmental Policy Act (NEPA). The Council on Environmental Quality (CEQ), which issues the implementation guidance for Federal NEPA actions, states: “Where emergency circumstances make it necessary to take an action with significant environmental impact without observing the provisions of these regulations, the Federal agency taking the action should consult with the Council [on Environmental Quality] about alternative arrangements. Agencies and the Council will limit such arrangements to actions necessary to control the immediate impacts of the emergency. Other actions remain subject to NEPA review.” (Perry and Hines 2007). Once the immediate threat to “the health, safety, and welfare of the community” has been resolved by interim emergency repairs, the agency must shift to conventional contracting procedures to award any remaining work (UDOT 2011).

3 METHODOLOGY

The study utilized two primary research instruments: literature review, including a content analysis of agency emergency management documents, and formal case studies of a cross-section of emergency projects. An effort was made in the review of relevant literature to not only seek the latest information but also historical information so that any change over time in emergency procurement practices could be assessed with the current state-of-the-practice. The content analysis of DOT emergency procedure documents from 38 states using a protocol proposed by Neuendorf (2002) constituted the second source of information. Both these instruments supported the third line of independent information: the case studies.

3.1 Case Study Protocol

The literature review and content analysis drove the case study data collection and the sought to identify projects from across the spectrum of emergency transportation projects with procurement aspects of specific interest to the study. The final group of case study projects highlights a specific emergency procurement issue that was address using expedited procurement procedures for emergency project delivery. The case studies were collected using a methodology detailed by Yin (2004). Yin’s approach requires that case study data be collected in conjunction with the comprehensive review of the literature. Thus, it allows the researcher to not only maintain a high level of technical rigor in the research but also follow Yin’s three principles in the process of research data collection: 1). use of multiple sources; 2). creation of a database, and 3). maintenance of a chain of evidence (Yin 2004). Thus, information gleaned from the case studies can be combined with information collected in the literature review to validate case study conclusions.

3.2 Case Study Selection

The primary objective in this paper is to analyze the value of bringing the contractor into the design process. Therefore, the following criteria for the final set of case study projects were applied:

- “Range of project delivery methods – design-bid-build (DBB), construction manager/general contractor (CMGC), design-build (DB), and indefinite delivery/indefinite quantity (IDIQ).
- Range of project types – roads and bridges
- Range of project size – typical small project to mega-project
- Range of project complexity – simple to highly complex
- Range of project location – regionally dispersed
- Range of solicitation type – Invitation for Bids (IFB) to sole source
- Range of payment provisions – lump sum (LS) to time and materials
- Use of incentive/disincentive (I/D) and bonus provisions” (Gransberg and Loulakis 2012)

Case Study Demographics
The study identified nine emergency procurement projects worth more than $290 million in nine states that represent the cross-section of variations on project types, sizes, and project delivery methods. Table 1 is a summary of the case study projects that were sampled for this research. One can see that the projects span from coast to coast and north to south. The case study projects represent the use of four different project delivery methods including a hybrid DBB project with a nested DB provision. The project types spanned the spectrum from the replacement of a washed out culvert to an emergency replacement of an eight lane interstate highway bridge over the Mississippi River.

Table 1: Emergency Procurement Case Study Projects. (adapted from Gransberg and Loulakis 2012).

<table>
<thead>
<tr>
<th>State (Agency acronym)</th>
<th>Case Study Project (Value)</th>
<th>Construction Type</th>
<th>Expedited Procurement Procedure</th>
<th>Project Delivery Method</th>
<th>Payment Provision</th>
</tr>
</thead>
<tbody>
<tr>
<td>California (Caltrans)</td>
<td>I-580/880 MacArthur Maze Replacement ($5.9 million)</td>
<td>Overpass bridge replacement after truck struck pier and burned</td>
<td>Invitation-only bids from 9 experienced contractors.</td>
<td>DBB</td>
<td>UP with time incentive</td>
</tr>
<tr>
<td>Florida (FDOT)</td>
<td>I-10 Escambia Bay Bridge Repair ($26.4 million)</td>
<td>Repair interstate bridge damaged in hurricane</td>
<td>Natural Disaster Emergency Contract - Invitation-only bids from 4 contractors.</td>
<td>DB</td>
<td>LS with time incentive</td>
</tr>
<tr>
<td>Maine (MDOT)</td>
<td>Route 27 Bridge Replacement ($2.89 million)</td>
<td>Replace two bridges destroyed by flooding</td>
<td>Use of CMGC by a DOT without routine CMGC authority.</td>
<td>CMGC</td>
<td>UP</td>
</tr>
<tr>
<td>Minnesota (MnDOT)</td>
<td>I-35W Bridge Replacement ($234 million-DB contract only)</td>
<td>Replace collapsed interstate bridge</td>
<td>Abbreviated DB procurement for mega-project and protest of award.</td>
<td>DB</td>
<td>LS + time incentive &amp; No Excuse Bonus</td>
</tr>
<tr>
<td>Missouri (MoDOT)</td>
<td>I-270 – St. Louis County Slide Repair ($550,000)</td>
<td>Emergency land slide remediation on interstate highway</td>
<td>Use of a &quot;nested&quot; DB contract provision in a DBB contract</td>
<td>DBB w/DB</td>
<td>Time &amp; Materials</td>
</tr>
<tr>
<td>Montana (MDT)</td>
<td>US-2 Rockfall Mitigation ($3.0 million)</td>
<td>Rockfall mitigation features</td>
<td>Use of a DB unit price provision without geotechnical investigation.</td>
<td>DB</td>
<td>LS with UP items</td>
</tr>
<tr>
<td>New York State (NYSDOT)</td>
<td>981G Ramapo River Bridge Replacement ($1.4 million)</td>
<td>Bridge replacement</td>
<td>Use of Statewide Emergency Bridge IDIQ Contract</td>
<td>IDIQ</td>
<td>Time &amp; Materials</td>
</tr>
<tr>
<td>Oklahoma (ODOT)</td>
<td>I-35 – Culvert Repair ($715,000)</td>
<td>Replace major box culvert washed out by flooding</td>
<td>Sole source cost plus contract for temporary shoring while expedited IFB developed</td>
<td>DBB</td>
<td>UP with hourly I/D</td>
</tr>
<tr>
<td>Utah (UDOT)</td>
<td>SR-14 Landslide Repair ($15 million)</td>
<td>Repair extensive landslide damage</td>
<td>Use of CMGC to expedite construction via 3 work packages</td>
<td>CMGC</td>
<td>GMP</td>
</tr>
</tbody>
</table>

*LS = Lump sum; GMP = Guaranteed maximum price; UP = Unit price; I/D = Incentive/disincentive clause
4 CASE STUDY ANALYSIS

Due to the page limitations for this paper, the salient details of the case studies have been synopsized in Table 2 to permit the reader the ability to easily compare any specific project against all other projects. The analysis of the case study projects shown in Tables 1 and 2 will focus on the comparison of the PDM rationale, procurement, permits, incentives, and tools used to expedite the emergency procurements. These elements are the factors that constitute the elements that must be addressed to allow the agency to expedite the procurement of an urgent or emergency project. Based on the protocol detailed in Section 3, a set of standardized categories was established for the procurement rationale information and the tools used to expedite the procurements. This permits the direct comparison of case study projects and the identification and classification of trends during cross-case analysis. Finally, it should be noted that three of the nine cases involve procurements that anticipated the emergency and put resources in place contractually to be able to rapidly react to an emergency if it occurred or to mitigate the risk that the emergency would be actualized. As can be seen in Table 2’s timeline column, this proactive approach not only provides the ability to immediately react without the need to process environmental permits or acquire right of way, but it also eliminates the risk that the award of the emergency contract will be protested on the grounds that the agency abrogated its responsibility to maintain free and open competition in all procurements.

Table 2: Case Study Project Details

<table>
<thead>
<tr>
<th>Agency</th>
<th>Scope</th>
<th>PDM Choice Rational – Procurement Procedures – Permits</th>
<th>Incentive Details</th>
<th>Expedited Procurement Tools</th>
<th>Time to Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caltrans</td>
<td>Replace I-580 overpass and I-880 deck</td>
<td>- DBB with I/D only authorized PDM</td>
<td>$200K/day capped at $5 million</td>
<td>Limited competition</td>
<td>Award: Demo – 1 day New – 2 days Complete: 27 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Invitation only prequalified contractors</td>
<td></td>
<td>Standing list</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Emergency permit waiver</td>
<td></td>
<td>Incentivize critical success factors</td>
<td></td>
</tr>
<tr>
<td>FDOT</td>
<td>Temporarily bridge</td>
<td>- Need single source of design and construction</td>
<td>$250K/day capped at $3 million</td>
<td>Limited competition</td>
<td>Award: 1 day Complete: 91 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Invitation only prequalified contractors</td>
<td></td>
<td>Co-locate design on site</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Used expedited award with hand-written scope</td>
<td></td>
<td>Use of available materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Emergency permit waiver</td>
<td></td>
<td>Contractor design involvement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Incentivize critical success factors</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Limited competition</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standing list</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Use of available materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Contractor design</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>involvement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Confidential ATCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Confidential one-on-one</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>meetings</td>
<td></td>
</tr>
<tr>
<td>MDOT</td>
<td>2 new bridges</td>
<td>- Need contractor input to design</td>
<td>None</td>
<td></td>
<td>Award: 2 days Complete: 82 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Invitation only prequalified contractors – negotiated GMP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Emergency permit waiver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Extensive agency DB experience; needed</td>
<td>$7 million &amp; $2 million/10 day period early capped at $20 million</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>sophisticated contractor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Minimized info req’d in proposals;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Categorical exclusion for 10 req’d permits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnDOT</td>
<td>Replace I-35W bridge</td>
<td></td>
<td></td>
<td></td>
<td>Award: 50 days Complete: 339 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 4.1 Case Study Procurement Analysis

Table 2 shows that the need to have the construction contractor’s input during design drives the selection of a project delivery method for an emergency project. Agencies favor CMGC and DB since these methods involve the contractor making substantive input to the design process and purport to improve constructability and construction phasing (West et al. 2012). Caltrans and ODOT did not have the statutory authority to use DB or CMGC, and therefore, both agencies turned to adding large incentives to their DBB contracts as a means of encouraging the contractor to focus on achieving an aggressive schedule (Bai et al. 2006). Maine had authority to use DB but wanted to use in-house design assets, which is functionally impossible in a DB contract. Thus, the agency sought emergency authority to use CMGC to replace the Route 27 bridges (Pulver 2012). New York’s emergency bridge replacement IDIQ was in place when Hurricane Irene washed out the bridges over the Ramapo River (NYSDOT 2007) and as such was able to marry up in-house design assets with the IDIQ contractor that delivered the projects in exactly the same fashion as a typical CMGC project with the contractor identifying immediately available structural steel sections around which the NYSDOT engineers designed (Rueda and Gransberg 2014). This leads to the conclusion that early contractor design involvement is key to not only achieving an expedited delivery but it also facilitates the schedule by designing a project that is highly constructable.

Table 2 also shows that when an agency is unable to obtain an emergency waiver of environmental permitting requirements, the contractor can be given the responsibility for obtaining the permits based on its actual means and methods. The Montana DOT assigned the permit responsibility to its contractor
because the permits would be specific to the means and methods that would be used in the field (MDT 2011). The Utah DOT shared the permitting responsibility with its contractor because of the need to build a temporary access road as quickly as possible to provide egress for the residents that were trapped by the landslide in the valley. A Stream Alteration Permit was required to restore the bed and banks of the creek that is located below the road as well as permits from the county, the US Fish and Wildlife Service and the Utah Department of Wildlife Resources. Lastly coordination was required with the local Native American tribe. To quantify the risk of delay due to permitting, UDOT had the contractor develop two schedules, naming them the “Fast Track” and “Slow Track” permitting packages. These planning packages included right-of-way, environmental documents, and the contractor’s site grading package, which is dependent on both. The Slow Track schedule was 60 days and the Fast Track schedule is 25 days. Permits were received in time to allow preliminary construction to start and accomplish the removal of excess material and to build the temporary access road (UDOT 2011).

Five of the case study projects limited competition to a standing list of prequalified contractors. While still limiting free and open competition, this approach provides more competition than a sole source award and essentially give all potential contractors the chance to qualify for inclusion on the prequalified list before the emergency. Thus, the risk of a protest of award based on restricting competition is reduced and the agency is encouraging as much competition as practical given the urgency of the emergency procurement.

Lastly, every case study project utilized some form of altered or streamlined version of procurement procedures to advertise, evaluate and award the contract. One end of the spectrum was the Florida project that was awarded using FDOT’s standard form modified with seven pages of hand-written “assumptions and clarifications” (Maxey 2006). Minnesota’s process reduced the size of the DB proposal for $240 million bridge project to a mere 20 pages by holding confidential one-on-one conferences to clarify issues in the solicitation and entertain alternative technical concepts (Heitpas 2008). Montana modified its routine lump sum DB contract by adding a unit price item as a means of sharing the geotechnical risk with its design-builder.

4.2 Case Study Incentives Analysis

A recent Strategic Highway Research 2 study found that on complex projects the agency should first identify critical success factors and then incentivize those aspects of project delivery that contribute to success (Gransberg et al. 2013). Table 2 shows that to be the case in only four of the nine projects included monetary incentives. To put this in perspective, three of the cases, Missouri, Montana and New York, were contracts awarded before the emergency occurred and therefore, the contracts were formed without the urgency inherent to contracts procured after an emergency event, reducing the need for incentives and quite frankly, making large incentives more difficult to justify. In these cases, the incentive is in winning the contract. Maine and Utah were other two cases without incentives and both were delivered using CMGC. In CMGC, the contractor is actively involved in forming the final design solution (West et al. 2012) and in both cases, the agency created an incentive for expeditious completion in its contractor selection scheme during procurement. Previous project delivery methods research found that contractors view the possibility of getting future work by satisfactorily completing a CMGC project as the most valuable incentive available in this method, or as stated by one author: “By far the most important incentive that an owner has is the promise of repeat work” (Thomsen 2006). Thus, one can infer that the agency can use the benefits inherent with winning new work as the incentive if it anticipates the emergency, and it can leverage the same incentive after the emergency by selecting CMGC project delivery.

4.3 Case Study Tools Analysis

Gray and Larson (2008) describe project management as “the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements” A recent study defines a procurement tool as “those things that project management practitioners use to ‘do the job’ to execute a process.” (Besner and Hobbs 2008). Thus, the term as used in this paper refers to a specific technique or approach used to expedite the procurement of either design and construction services on an urgent or emergency
basis. Table 3 consolidates the expedited procurement tools show in Table 2. One can see that involving the construction contractor in the design process is the most frequently used tool followed by the use of limited competition and incentives.

<table>
<thead>
<tr>
<th>Expedited Procurement Tool</th>
<th>Number of Agencies</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractor design involvement</td>
<td>6</td>
<td>None</td>
</tr>
<tr>
<td>Limited competition</td>
<td>4</td>
<td>Minnesota effectively limited competition by short-listing known entities</td>
</tr>
<tr>
<td>Incentivize critical success factors</td>
<td>4</td>
<td>None</td>
</tr>
<tr>
<td>Anticipated emergency with special provision</td>
<td>3</td>
<td>None</td>
</tr>
<tr>
<td>Standing list of prequalified contractors</td>
<td>3</td>
<td>None</td>
</tr>
<tr>
<td>Abbreviated contract documents</td>
<td>3</td>
<td>All cases altered their routine process in some fashion.</td>
</tr>
<tr>
<td>Use of immediately available materials</td>
<td>3</td>
<td>None</td>
</tr>
<tr>
<td>Co-locate design team on project site</td>
<td>2</td>
<td>None</td>
</tr>
<tr>
<td>Confidential Alternative Technical Concepts</td>
<td>2</td>
<td>None</td>
</tr>
<tr>
<td>Confidential one-on-one meetings</td>
<td>2</td>
<td>None</td>
</tr>
</tbody>
</table>

The Utah DOT found that design documents developed in nonemergency CMGC contracts were released for construction much earlier due to contractor involvement (Alder 2007). Additionally, as the contractor is already under contract, the designer no longer needs to produce a full set of biddable construction documents. The agency can direct it to develop its design documents on a feature by feature basis at a point in time where the contractor declares there is sufficient detail for it to release for the trade subcontract work package bids (Alder 2007; West et al. 2012). A previous study on early contractor design involvement (ECDI) found that it yields four specific benefits useful in an emergency procurement:

1. "ECDI permits the DOT to gain access to information regarding available construction means, methods, and materials. This permits the design to be tailored to the immediate need

2. ECDI adds a reality check to the design process via the designer getting immediate feedback on the consequences of design decisions from the entity that is tasked to construct the project. This results in a more constructable project.

3. The use of time-based incentives in emergency projects focuses the contractor on executing very aggressive schedule and to devote as much effort as possible to ECDI as a means to get design packages released for construction in a timely manner.

4. While ECDI does not transfer the design liability, it does produce a higher quality set of design documents with a lower probability of the need for delay due to changes for design errors and omissions." (Gransberg 2013).

Both Table 3 and the subsequent discussion lead one to the conclusion that the involving the construction contractor in the design process is the most effective procurement tool to expedite the completion of emergency project. Additionally, limiting competition reduces the procurement period to as little as one day and if limited to a standing list of prequalified contractors can reduce the risk of award protest. Finally, emergency projects should be recognized as inherently complex and as such, the case studies show that...
aligning thoughtfully developed incentives with critical project success factors also facilitate the expedited completion of the project.

5 CONCLUSIONS

Three major conclusions are reached in this study. The first is the most obvious. The best way to expedite the reaction to an emergency is to anticipate it. The study found two approaches to ensuring that the necessary resources were available to react to an unforeseen event: Missouri’s nested DB provision and NYSDOT’s IDIQ for emergency bridge replacement. It also identified Montana’s approach to nesting a unit price provision inside a lump sum DB contract to provide a means to mitigate the risk to the infrastructure from rock slides. In each case, actions were taken in advance of an emergency in a full and open competition environment and as such did not require emergency waiver of competition statutes.

Secondly, the study finds that selecting a project delivery method like CMGC, DB, or IDIQ which is structured to permit the construction contractor to make substantive input to the emergency project’s design was the most used expedited procurement tool among the case study agencies. The lesson learned here is that the separation of designer and contractor that exists in traditional DBB construction contracts, actually works against the expeditious resolution of an emergency loss of service. Bring the contractor into the emergency project design process, allows the repair and restoration of service to be tailored to that particular contractor’s preferred means and methods and enhances the constructability of the final design solution.

Lastly, maintaining a standing list of prequalified contractors willing to bid on an emergency basis permits the agency to provide as much competition as possible while avoiding the delays associated with running a full open competition solicitation. This conclusion speaks to the political environment rather than the technical aspects of emergency procurements. As with the first conclusion, the standing list acts as an insulator against delays due to protest of award founded on the idea that competition statutes were violated.

Acknowledgements

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References


EXPLAINING THE INFLUENCE OF CHANGE REASONS ON COST AND SCHEDULE PERFORMANCES

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Abstract: This research aimed at revealing and characterizing the influence of change events or reasons on cost and schedule performances. The specific objectives were to assess the frequencies of various change reasons with respect to cost and schedule deviations, and to assess the impact intensities of such change events or reasons on performance. Initially, a team of industry experts identified a total of 36 change types and grouped them in 9 major change categories. Then, change log information for 135 completed projects was statistically analyzed to quantify the intensity, frequency, and impact of changes on cost and schedule performances. The most recurrent types of change events for both cost and schedule were associated with issues related to construction productivity; planning; supplier and subcontractor; scope errors and omissions; design or engineering errors and omissions; or engineering productivity issues. In addition, this study quantified the specific impact on cost and/or schedule from a change event or reason. Specifically, this study provides evidence that fairly infrequent change events tend to cause large impacts on performance. The results from this study are likely generalizable, since the retrospective project data was representative of multiple project types, sectors, and organizational roles, among other project facets.

1 INTRODUCTION

Events can have a significant impact on cost and schedule deviations (Grau and Back 2013a; Grau and Back 2013b). As a result, cost overruns and schedule delays are very common in construction projects (Ibbs 2013, 2012; Mulva and Dai 2012). Various construction forecasting methods are used with the intention to ascertain cost and schedule deviations on time, but notably, such methods typically do not provide accurate forecasts (Grau and Back 2014a; Grau and Back 2014b). In reality, different events cause incremental impacts on cost and schedule performances, but those changes are difficult to foresee and their impacts to forecast. If change events could be detected early, such identification would help to minimize impact on performance and also to improve project outcome predictions. Thus, an early recognition of changes is critical to evaluate and implement changes in a proactive manner (Grau and Back 2013b). Importantly, this study tackled the issue of change reasons or events, understood as any unplanned event with a potential impact on cost and schedule.

In reality, the construction industry lacks evidence on the impact of changes on cost and schedule performances or deviations, and on the frequency of such changes. While a perception that the impact of changes vary with the nature of the change reason exists, the reality is that, to date, there is no data to
back up or reject such notion. The extent to which change events or reasons affect both cost and schedule deviations have not yet been documented (Grau and Back 2013a; Grau and Back 2013b; Ibbs 2005; Westersund 2008). As today, change events with high impacts are compensated with the use of large contingency reserves (Ibbs et al. 2008; McEniry 2007). However, we argue that the early recognition, communication, and proactive action to mitigate the impact of changes on performance are critical to minimize their impact. Reactive or late responses can only lead to significant negative impacts on performance, and increase the use of contingency reserves.

Indeed, questions such as: what are the major change reasons for cost and schedule deviations?; or, what are the types of changes that have the most influence on cost and schedule deviations?, have not yet been answered. This study aims at providing an answer to those and other similar questions with the overarching goal to enable construction industry organizations to be timely alert on the change reasons that can have a higher potential impact on performance, and to proactively manage such changes.

2 OBJECTIVES AND SCOPE

This research aimed to reveal the change events or reasons that have significant consequences on cost and schedule deviations. The specific objectives are listed below:

1. To assess the frequencies of various change reasons with respect to cost and schedule deviations; and
2. To assess the impact intensities of such change events or reasons on performance.

The scope of this study is defined as follows: 1) the sample for this study was randomly drawn from projects completed by CII member organizations; 2) the study was performed irrespective of the timing within the project timeline at which a changed occurred; and 3) the study considered the cumulative impacts of changes, regardless of their differences with respect to the controllability of each change.

3 LITERATURE REVIEW

A well-understood impact of change events on project performance should guide both owners and contractors to proactively manage changes. However, while the qualitative literature on changes is large, there is limited evidence on the frequency and impact of changes, as presented in the rest of this section. Those studies with a quantitative facet are mostly limited by the type of projects investigated or by the geographical location (e.g. Middle East) of the projects, and hence such results cannot be generalized.

Indeed, Hanna et al. (1999) quantified the impacts of change orders on craft labor productivity for mechanical trades. The authors collected data from 61 projects, and developed a statistical model to quantify labor productivity loss from change orders. Al-Momani (2000) studied 130 public projects in Jordan, representative of residential and commercial facilities, to examine the causes of delay. The study identified the key factors in delays for public projects as weather conditions, site conditions, economic conditions, delays in deliverables, increase in quantities, and inadequate design. Hsieh et al. (2004) conducted a statistical analysis to find the root causes of change orders, based on data collected from 90 completed metropolitan public works projects in Taipei. The study indicated that issues in planning and design are the key sources of change orders in such projects. In addition, the study identified thirty-five change-order causes within nine categories, and ranked those as per their impact effect. Ibbs (2005) studied the influence of the timing of actual change implementation in the project delivery process on performance. Importantly, the study results determined that changes implemented late in the project timeline have a more detrimental effect on project performance than changes implemented early in the project timeline. In addition, the study proved that changes have a negative effect on craft labor morale and productivity. Assaf and Al-Hejji (2006) investigated the causes of delay specific to large construction projects. The study identified seventy-three causes of project delay. Additionally, the study conducted a field survey among owners, contractors, and consultants to examine frequency, severity, and importance of identified delay causes. Ibbs et al. (2008) conducted a meta-analysis of previous research studies to
show that incremental project changes have significant impact on productivity. Ibbs developed a statistical model to evaluate the effect of changes on craft labor productivity. Sun and Meng (2009) conducted an extensive literature review on construction project change causes and effects, and developed two taxonomies to explain such causes and effects. Ibbs (2012) statistically analyzed change orders from 226 construction projects to identify change patterns, and quantify change impact on project cost, schedule, and productivity. The study found that the entire impacts of a change upon authorization are not well understood by both owners and contractors. As mentioned earlier, these successful studies have not yet provide a generalizable but specific answer to whether or not a relationship exists among change events and, project cost and, schedule deviation, and how frequently such events occur.

4 METHODOLOGY

The research method consisted of three key steps: categorization of change orders, data collection with a survey instrument, and data analysis. First, a detailed review of the existing literature in the topic resulted in a preliminary categorization of change types. The literature review was conducted through key word search, analysis of relevant articles, and further retrieving and analyzing meaningful references in the previously reviewed papers. This preliminary categorization of changes was also contrasted and improved with actual change log categories from 12 industry organizations, and resulted in a broad list of 310 potential change reasons. Through 4 face-to-face research charrettes with a group of 15 industry members over a period of half a year and additional phone call meetings, the list change reasons was sequentially reduced to 36 specific change reasons, and grouped into major 10 types of changes. Table 1 contains the classification of changes by type and category.

<table>
<thead>
<tr>
<th>Change Type</th>
<th>Change Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Scope Changes</td>
<td>A.1. Business Drivers Change</td>
</tr>
<tr>
<td></td>
<td>A.2. Budget/Finance Change</td>
</tr>
<tr>
<td></td>
<td>A.3. Plan Change</td>
</tr>
<tr>
<td></td>
<td>A.4. Scope Error/Omission</td>
</tr>
<tr>
<td></td>
<td>A.5. Other</td>
</tr>
<tr>
<td>Legal Requirements</td>
<td>B.7. Labor Dispute</td>
</tr>
<tr>
<td></td>
<td>B.8. Permitting</td>
</tr>
<tr>
<td></td>
<td>B.9. Other</td>
</tr>
<tr>
<td>C. Engineering Design</td>
<td>C.10. Design/Engineering Errors/Omission, Inclusive of</td>
</tr>
<tr>
<td></td>
<td>C.11. Engineering Productivity</td>
</tr>
<tr>
<td></td>
<td>C.12. Other</td>
</tr>
<tr>
<td>D. Work Planning and Execution</td>
<td>D.13. Construction Productivity</td>
</tr>
<tr>
<td></td>
<td>D.14. Construction Errors/Omissions</td>
</tr>
<tr>
<td></td>
<td>D.15. Construction Equipment</td>
</tr>
<tr>
<td></td>
<td>D.16. Infrastructure, Site, or Utilities Issues</td>
</tr>
<tr>
<td></td>
<td>D.17. Other</td>
</tr>
<tr>
<td>E. Commissioning and Start-up</td>
<td>E.18. Commissioning and Start-up Issues</td>
</tr>
</tbody>
</table>
Second, a survey instrument was designed to collect general project data on completed projects, their change log data, and also on the corresponding separate impact of changes on cost and schedule deviations, if any. General project data included multiple specific inquiries related to cost and schedule performance, project delivery method, use of incentives, project controls structure (e.g. field vs. home office), among many others. Survey respondents were selected through random sampling within experts on project management and controls affiliated with CII member companies. In total, we collected 135 responses with retrospective data on an equivalent number of completed projects. The aggregate equivalent installed costs for the 135 completed projects was $28.88 billion, with a combined project completion time of about 300 years. Median schedule deviation at completion was 7.91 percent, while the median cost deviation was 5.93 percent. The sample of projects was well distributed between contractors (52%) and owners (48%). Project sector affiliation was 49% for public, 47% for private, and 5% for both public and private sectors. The projects were also representative of multiple organizational roles, as Table 2 illustrates. Notice that respondents frequently selected several organizational roles, so that the sum of the percentages in Table 2 actually exceeds 100%. The projects were also representative of multiple industry sectors, as Table 3 illustrates.

<table>
<thead>
<tr>
<th>Role Function (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner / Client</td>
</tr>
<tr>
<td>Owner / Client</td>
</tr>
</tbody>
</table>
Table 3: Industry sectors.

<table>
<thead>
<tr>
<th>Industry Sector (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>General Building 7</td>
<td>Pharmaceutical 0</td>
</tr>
<tr>
<td>Pulp &amp; Paper 1</td>
<td>Heavy Industrial 7</td>
</tr>
<tr>
<td>Light Industrial Manufacturing 1</td>
<td>Chemical 30</td>
</tr>
<tr>
<td>Others 7</td>
<td>Highway &amp; Infrastructure 2</td>
</tr>
</tbody>
</table>

5 RESULTS AND DISCUSSION

Each survey respondent used a 10-point scale (from 1-low to 10-high) to assess the impact of changes in the project on cost and schedule deviations at completion. Respondents separately provided the assessment of change reason types according to the project change log. Table 4 contains the most occurring changes, by frequency of occurrence, with an impact on cost, while Table 5 contains the most occurring changes, by frequency of occurrence, with an impact on schedule. Indeed, order-of-magnitude differences in the frequency of individual change reasons exist. Most recurrent types of change events for both cost and schedule are associated with the following: construction productivity issues; planning; supplier and subcontractor issues; scope errors and omissions; design/engineering errors and omissions; and engineering productivity issues. Virtually any project is likely to face several of these change events. On the contrary, there are other types of change events that show a low recurrence, but, as explained below, tend to have a larger impact on performance.

Table 4: Frequency of Changes with an Impact on Cost.

<table>
<thead>
<tr>
<th>Order</th>
<th>Change Type</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C.10 Design/Engineering Errors/Omission,</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>Inclusive of Constructability Issues</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>D.13 Construction Productivity</td>
<td>41%</td>
</tr>
<tr>
<td>3</td>
<td>A.3 Plan Change</td>
<td>34%</td>
</tr>
<tr>
<td>4</td>
<td>A.4 Scope Error/Omission</td>
<td>33%</td>
</tr>
<tr>
<td>5</td>
<td>G.25 Supplier/Subcontractor</td>
<td>29%</td>
</tr>
<tr>
<td>6</td>
<td>C.11 Engineering Productivity</td>
<td>23%</td>
</tr>
</tbody>
</table>

In order to assess the importance or influence of changes on cost and schedule performance, we defined the metric of average impact effect, which was separately computed for each change reason with respect to cost and schedule performances. Indeed, the average impact effect for a particular change on cost or schedule responds to the sum of the product between impact value (on a 1–10 scale, from low to high) times the corresponding project cost or schedule deviation, divided by the number of project instances with such cost or schedule change (Back and Grau 2013). The average impact effect scores were then grouped by high, medium, and low intensity. Tables 6 and 7 represent the changes with top ten average impact effect for cost and schedule outcomes respectively and their corresponding frequencies.
Table 5: Frequency of Changes with an Impact on Schedule.

<table>
<thead>
<tr>
<th>Order</th>
<th>Change Type</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D.13 Construction Productivity</td>
<td>32%</td>
</tr>
<tr>
<td>2</td>
<td>A.3 Plan Change</td>
<td>29%</td>
</tr>
<tr>
<td>3</td>
<td>E.18 Commissioning and Start-up Issues</td>
<td>24%</td>
</tr>
<tr>
<td>4</td>
<td>G.25 Supplier/Subcontractor</td>
<td>23%</td>
</tr>
<tr>
<td>5</td>
<td>A.4 Scope Error/Omission</td>
<td>15%</td>
</tr>
<tr>
<td>6</td>
<td>C.10 Design/Engineering Errors/Omission, Inclusive of Constructability Issues</td>
<td>15%</td>
</tr>
</tbody>
</table>

Indeed, it is observed that the frequency of a change does often have an inverse relation with the severity of its impact on cost or schedule performance. Indeed, changes were observed to have a high frequency of occurrence often show a small impact on cost and/or schedule deviations, while those with a low frequency of occurrence often have a large, or severe impact on cost and/or schedule performances. Among the top 10 change events with them most impact on cost, only two of them occur in more than 10 percent of the projects. Change events with the most impact on cost were: standard, regulatory, and legal requirements; project team integration; procurement processes, natural threats; or project management issues. In addition a similar relationship observed between the low-probability change events and a large impact on schedule exists. Labor disputes, infrastructure or site issues, and permitting problems may seldom occur, but when they do, they are likely to have a high negative impact on project completion time. Among the most influential change events affecting schedule is the occurrence of scope changes. Indeed, scope changes have proven to be somewhat more frequent and observed in fifteen percent of sampled projects. Scope changes tend to have ripple effects on the project delivery process, and fundamentally affect core management functions, such as estimating, planning, and execution. The results indicate that the frequency of a change is inversely correlated to its impact on cost and/or schedule deviations, a notion that may have existed in industry but that had not been previously documented.

Table 6: Frequency and Intensity of Change Reasons on Cost.

<table>
<thead>
<tr>
<th>Order</th>
<th>Change Type</th>
<th>Impact Effect</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B.9 Other (Standard, Regulatory, and Legal Requirements)</td>
<td>High</td>
<td>5%</td>
</tr>
<tr>
<td>2</td>
<td>F.23 Project Team Integration</td>
<td>High</td>
<td>5%</td>
</tr>
<tr>
<td>3</td>
<td>G.28 Procurement Process</td>
<td>High</td>
<td>7%</td>
</tr>
<tr>
<td>4</td>
<td>J.36 Natural Threats</td>
<td>High</td>
<td>8%</td>
</tr>
<tr>
<td>5</td>
<td>F.22 Project Management</td>
<td>High</td>
<td>9%</td>
</tr>
<tr>
<td>6</td>
<td>H.30 Foreign Exchange</td>
<td>High</td>
<td>5%</td>
</tr>
</tbody>
</table>
A probable explanation for the inverse relationship between frequency and average impact effect is that highly recurrent change events are more easily expected, identified, and addressed by the project team. Infrequent events are not likely to be accounted for during the planning of a project and, hence, when they occur, they are not rapidly addressed and result in a significant negative impact (Back and Grau 2013, Ibbs 2013, Westersund, 2008). These types of infrequent events, though, prove to be the most influential on cost and schedule deviations. Ensuring that potential high-impact events are communicated and addressed as soon as they can be predicted or occur is critical to reduce their impact on performance. The information in this section is useful to industry teams so that they inform how to address underlying change reasons that are associated with revisions to cost and schedule performances and forecasts, and how frequently such reasons can be expected.

6 CONCLUSIONS

Change management plays a critical role in the effort to identify changes early, and evaluate and implement responses to changes in a proactive and effective manner. The later the recognition of a change, the more difficult it becomes to implement corrective actions, mitigate cost and schedule impacts, and accurately and timely forecast project performance at completion. As important as change management is to industry, to date there is a lack of concrete evidence of what the frequency of a change may be, and what its intensity on cost and schedule performances could be.

In order to fill such gap in the body of knowledge, we have statistically analyzed change log information for 135 completed projects to prove the long-held perception that the impact of change is inverse to their frequency, and thus help industry professionals to recognize change events early. Indeed, this study reveals that change events or reasons tend to have significant different consequences on cost and schedule deviations. We found that the frequency of a change does not necessarily directly correspond to the severity of its impact on cost or schedule performances. Specifically, fairly infrequent change events tend to cause large deviations. Also, we have learnt that different change reasons impact cost and schedule performances with different occurrences and intensity. Indeed, some changes were observed to have a high frequency of occurrence with a small impact on cost and/or schedule deviations, while others were observed to have a low frequency of occurrence with a large or severe impact on cost and/or schedule performances. For instance, permitting issues are rare, but, when they occur, tend to have a very significant impact on schedule, but a moderate impact on cost. In summary, we identified change types that are most frequent, and those which are most influential for both owners and contractors, for both cost and schedule.
Overall, this study provides a better understanding of the severity of impacts associated with various change events, and should be used to enhance risk, contingency, and change management practices. Above all, indications of potential changes should be continuously sought and communicated as early as possible. The early recognition, communication, and remediation of changes are critical to decrease their impact on performance. Changes and events will happen, but they must be recognized and proactively addressed by the project team in order to mitigate their impact.

Acknowledgements

The authors want to acknowledge the support from the Construction Industry Institute (CII) to all the facets of this study, including its funding. The authors also want to recognize the contribution of CII’s RT291 team members, and also of additional industry experts, to the completion of this study.

References


THE INTERFACE BETWEEN BUILDING INFORMATION MODELS AND THE PUBLIC

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Abstract: Almost all work to date in the field of Building Information Modelling (BIM) tools has developed software for building professionals: designers, constructors, and operators. However, another important group of potential users is the public. Use cases fall into two broad categories. Pre-construction applications span the design phase and all forms of public engagement during design development, from traditional user-feedback/community engagement processes to innovative applications such as crowd-source design. Post-construction applications include a variety of occupant-centric scenarios, including building dashboards, occupancy-assessments, etc. The relevant technology spans both BIM and social media. The Green 2.0 project aims to develop a middle-ware platform to support a range of BIM-to-public applications, with an emphasis on building energy performance and related “Green” applications. By analogy, if Facebook is conceived as a platform for a public-to-public interaction, and Google Maps as a platform for public-to-geospatial interaction, then the Green 2.0 project aims to provide a platform for public-to-building interactions. This paper describes the problem domain and preliminary work to develop the pre-construction and post-construction application areas for the Green 2.0, BIM-to-Public platform.

1 INTRODUCTION

Building Information Modeling (BIM) is a technology which has caused a paradigm shift in the Architecture, Engineering and Construction (AEC) industry, it has transformed the way buildings are designed, constructed and managed. BIM is moving the construction process from being “lonely” to “social”, in the sense that BIM is enabling professionals: designers, constructors and building managers to easily share information with each other. Another set of potential users is the general public and the occupants of buildings, who can contribute useful information to the building owners, designers and operators. The current performance gap in buildings is twofold. On one hand, the actual energy saving and resource usage like water usage are not as expected (Turner and Frankel 2008). On the other hand, occupants in green buildings have not been shown to exhibit a higher satisfaction compared to those in conventional buildings (Birt & Newsham, 2009; Altomonte & Schiavon, 2013). A building-to-end user interface can help in reducing the performance gap in buildings and can also create a more satisfying indoor environment for the end-users. In the design phase, end-users preferences and opinions can assist the designers and owners to come up with a user-driven design and innovation. Similar, in the post-occupancy phase, the user interactions with the BIM model can help in capturing occupant feedback about the indoor environment in buildings which can be useful for building operators.

In recent years, end user engagement in the product development industry has been gaining importance. Some social media tools like blogging, online forums, video sharing and social networking are turning out to be useful for facilitating this engagement. Crowdsourced design and rapid prototyping are some of the common methods being used in the product development industry. With recent advances in information
technology in the construction industry, 3D modelling and visualization tools like BIM are becoming commonplace. This has created a potential for developing applications that can bridge the gap between the buildings and end-users. In fact, the average North American spends about 87% of his time inside the built environment (Klepeis et al. 2001), hence it is imperative that the building end-users’ design preferences and indoor environment quality feedback should be considered.

The Green 2.0 project, being led by the University of Toronto, is aimed at adding user interaction in design and operation of facilities through using Web 2.0 and gaming technologies with BIM software. The objective of our study is to develop web-based or mobile applications built on the Green 2.0 middleware platform to provide end-users with an easy-to-use interaction interface with the building. These applications will then be tested on the existing and to-be-built buildings in the University of British Columbia (UBC) campus using the Living Lab methodology. This paper describes the problem domain and preliminary work to develop the pre-construction and post-construction application areas for the Green 2.0, BIM-to-Public platform. An outline of the Green 2.0 project is provided in the second section. The third section provides a brief overview of developments in the current building-to-end user interfaces. In the fourth section the conceptual use case scenarios in the design and operation phase of the buildings are discussed. The future work related to this study is presented in the final section of the paper.

2 GREEN 2.0

Achieving a sustainable built environment requires socio-technical solutions. Technology and hardware for green buildings have reached unprecedented levels of advancement, yet the decisions to achieve energy and water savings, ultimately, rests on end-users and other stakeholders. Given that modelling and analysis tools have been developed by engineers for use by engineers, the bottleneck over the life cycle of green building management now lies in the human interaction of end users with the facility during design and operation.

We must match the advanced technical tools with socially-savvy tools that engage people in the design stage to make sure that designers understand their needs and attitudes towards energy usage, and that involve larger communities in the visioning and design processes as expected by new net-native generations of home buyers and building occupants. We also need to fully inform users of green opportunities and their possible role in enhancing the energy profile of their facilities in operation phase.

Green 2.0: a middleware platform for enabling socio-technical analytics of green buildings is a collaborative research project led by the University of Toronto. The project aims at developing a web-based middleware platform to empower professionals from diverse background to create analysis applications while engaging users’ ideas. The platform brings together several core enabling technologies: open BIM for modeling buildings and related project information, social networks and social network analytics for supporting user interactions and investigating the results of this social interaction, energy analysis to model and provide feedback about the impact of various design alternatives, and business process modelling to model users’ activities. The Green 2.0 platform will be open source and free to use, not only open to professional engineers but also available to public users. The Green 2.0 platform provides a base for us to create applications which will give users access to building information and encourage user engagement in both the design and operations phase. The preliminary work on these applications is presented in the fourth section of the paper, Building-to-end user interface.

Research to explore if, when, and how to engage users in building design has been an ongoing subject of research and development. Some researchers have categorized four types of user engagement: unidirectional social research (USR) (information/education), USR (decision support), weak interactive social research (ISR) and strong ISR. Strong ISR, which engage users in all phases of research, is recommended, but studies on ISR projects show that changes are needed in institutional arrangements and organizational settings for ISR (Talwar et al. 2011). Another research project, where novice users were asked to create Business Intelligence information dashboards, found some drawbacks in novice users’ design, such as lack of concepts on categories, lack of consideration in coordinated view, and less consideration on data filtering (Elias and Bezerianos 2011). Therefore, we will collect users’ opinions
when developing the interface but not let the users to design any applications in our research. In this paper, the user engagement refers to using the building-to-end user interface.

To better achieve user engagement, an easy-to-understand building-to-end user interface should be useful (functionally), usable (it is easy to do things), and used (attractive and available) (Glawischning et al. 2011). A number of previous research projects have explored this issue, such as the following two projects:

Robert Zach, et al. developed a Monitoring System Toolkit, MOST, an open-source, vendor and technology independent toolkit for building monitoring, data processing, and visualization (Zach et al. 2012). The toolkit is based on five components: Connectors, Database-Core, Java-Framework, GWT based web interface, Matlab-Framework and thus supports use of building data from various resources. MOST provides a web-based visualization framework to support some use cases such as 3D building browsing. The platform is similar to Green 2.0 platform but the user interaction in MOST focuses on drag and drop and highlighting. One thing that may be valuable is that with the claimed powerful data preprocessing function, the toolkit is allows access to salient and dynamic building information such as zone temperature and energy use, which are the main concerns of building stakeholders including occupants. Although no user applications for presenting such building data were developed, the MOST research team conducted user survey and focus group sessions to investigate the importance of different kinds of information (Chien et al. 2011). The results offer some guidance to the development of our use cases, which will be specifically discussed in Chapter 4.

VIC-MET is a tool developed at Aalborg University in Denmark to involve end-users in the building design process. It offers four different design spaces to enable user-involvement throughout the design process from the mapping of the context to the final solution. Various ICT tools like IHMC CmapTools for conceptual modelling and Ramboll VR Wii for interactive visualization are described in the VIC-MET handbook to support VIC-MET activities in these four different spaces (Christiansson et al. 2011).

The use of social media to present the user with 3D virtual models of the building is another useful method to capture user opinions. In the Finnoo-Kaitaa project, a web portal was used to share project information with end-users and an online forum where registered users can freely propose new ideas and like comment of others. The Nissola Street and railway plan made use of an Internet application that enabled citizens to place comments on different parts of the 3D model while flying through it (Jäväjä et al. 2013). GreenNetwork, developed at UC Berkley, is another social media prototype application integrated in the work environment aimed at promoting a “green work style” amongst the people. It allows people to track their energy use, share this information through social media platforms like Facebook and LinkedIn, and comment on the energy use of their peers (Lehrer et al. 2014). POE 2.0 is a new bottom-up approach towards Post-Occupancy Evaluation (Daltona et al. 2013), it involves analysis of user reviews and comments on social media websites like Yelp, TripAdvisor and ArchDaily. The Smart Campus project being undertaken on four European Universities uses the Living Lab methodology. Their applications are aimed at influencing and transforming the user energy consumption behavior by enabling user interactions with the building. The project expects energy savings of about 20% and 15% of which will be due to user behavior transformation (Nina et al. 2014). These tools and methods have proven to be effective in terms of engaging the users. However, currently there are no applications available that can connect the general public to the BIM model of the facility.

3 CONCEPTUAL FRAMEWORK OF BUILDING-TO-END USER APPLICATIONS

The conceptual framework to develop the building-to-end user applications consists of four steps. First, develop a conceptual process model or algorithm of the application. Use cases will be used to illustrate the requirements and processes that the application will have in this phase. Second, use the use case processes to drive the development of a conceptual data model. This stage will be used to determine how to collect required data and how the application interacts with the data. Flowcharts, process models, and pseudo-code are used to show the processing procedures. Third, programmers will turn the conceptual data model into a detailed implementation-level data models. Fourth, the implementation-level processes
will be programmed around the data model. Our research efforts will be focused on the first two steps. The remainder of this chapter will introduce the work done to date in the first stage.

The focus of the “SocioBIM” applications being developed in our research is on the three different targets areas as depicted in Figure 1. The social net positive target area is aimed at incorporating sustainable values in occupants which results in green behavior amongst occupants. Green and regenerative buildings often focus on achieving a net zero or net positive energy, for example the CIRS building on UBC campus has a net positive energy performance. However, there is not much emphasis on social net positive performance for buildings where occupant’s satisfaction, health and productivity are enhanced by the building environment. The performance gap in buildings often exits due to inappropriate use of the buildings systems by the occupants. These applications will aim at minimizing this performance gap by creating a competing environment amongst the building occupants. In the design and operations phase, these applications will enable occupant feedback and opinions, which will provide useful information for designers, owners and operators.

![SocioBIM Applications](image)

**Figure 1 Target areas for SocioBIM applications**

The applications will be linked to the middleware interface being developed in the Green 2.0 project. The use of these applications is limited to the design and the operations phase. In the next two subsections the conceptual ideas for two of the SocioBIM applications will be discussed.

### 3.1 Use Case in the Design Phase

For the design phase, the primary focus of the SocioBIM application is to present the users with a curated BIM model of the facility extracted from the Green 2.0 middleware. The end-users of the facility are able to easily navigate and walk through in this curated BIM model, similar to the Google Maps street view interface. In addition to navigation, the users have the option of commenting, like/dislike certain parts of the model and can propose some design changes as well. As shown in the use case scenario in Figure 2, users create a profile, access the model and they also enter their design requirements. The data collected is then analyzed by the designers and buildings owners to make appropriate changes to building design. These different user entries will ultimately result in a design evolution of the facility. This application can be used in buildings where end-users are known at the time of design of the facility which is possible in case of high-rise residence, office buildings and academic buildings.
3.2 Use Case in the Operations Phase

A typical post-construction application is a building dashboard. Autodesk is conducting a research named Project Dasher, which is aimed at collecting and displaying occupancy information, but it is not for end users’ involvement in any phase of construction. Real-time building dashboards will visualize information collected from sensors distributed throughout a building. Specifically, occupancy, power usage, heat sources, airflow, and temperature are presented (Autodeskresearch.com, 2015). We will develop a dashboard to present building data for occupants.

3.2.1 What information to present

The results from the MOST research (survey and focus groups) (Chien et al. 2011) demonstrated that users are more interested in knowing about heating/cooling system, electricity, temperature, humidity, illuminance, the number of occupants, and ambient lighting. Users prefer to use laptop and smart phones to get building information. They wish the user interface be simple and clear, easier to interact with. One feedback mentioned the value of “comparison” function of “Oberlin”, which is in accordance with one of our ideas to incorporate a type of “competition pattern” to motivate occupants to reduce energy consumption.

To summarize, our goals are to provide the information that users care most about, illustrate the sustainability of the building and encourage green behaviors. As a protocol to illustrate the ideas above, the dashboards will be presenting these four types of data:

- Electricity usage: This will be divided into Lighting, Devices and Heating/cooling systems;
- Thermal Comport: Temperature and Relative Humidity with votes;
- Health credit: Individual health credit and Average health credit of all the people in the building;
- Energy credit: The energy credit of the working station (room or floor) will be displayed with the average energy credit of all the working stations in the building.
### 3.2.2 How to collect and present data

The building dashboard will use data from building operating system, and Green 2.0 Middleware. The dashboard is web-based. Occupants can get access to it from their own laptop. Each office, each floor, and the whole building can have a big screen showing the dashboards at every entrance. This use case is applicable mainly to office buildings and academic buildings.

### 3.2.3 Functions

The dashboard shows the real-time electricity usage with a pie chart and compares each division with the expected levels. When the usage is over expectation, the usage column and number will turn red to alarm the users. In reverse, it assigns energy credits to spaces where energy usage is below expected levels. A vivid 3D building model with energy usage or room credits of all the rooms in the building is accessible from the dashboard. This provides an intuitive sense of competition. Moreover, occupants can vote on their preferred temperature levels through the dashboard website. Therefore, the building manager or the office manager can adjust the temperature according to people’s needs. With granted rights to vote on temperature, people are encouraged to interact with the building. In addition, people can enter their mode of commute to building, use of stair v/s elevators, etc., in order to earn individual health credits. This is to encourage green behaviors among occupants.

![Diagram of user interactions](image)

**Figure 3.** Use case for end-user interaction during building operations.

### 4 FUTURE WORK

In the following research, the aforementioned conceptual ideas of the SocioBIM applications will be further developed into detailed process maps specifying their requirements and functioning. These process maps will then be used to rapidly prototype these applications in buildings on UBC campus using the Living Lab methodology.

In terms of future work in building-to-end user applications, researches can focus on developing more use cases that are tailored to occupants’ need and trying to connect with big data in social media which can...
make the application not only open to the public but also automatically provide scientific suggestions to
designers and building operators.

5 ACKNOWLEDGEMENTS

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References

A RELATIVE ENERGY PREDICTION METHODOLOGY TO SUPPORT DECISION MAKING IN DEEP RETROFITS

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Abstract: Various energy prediction tools and methods are widely used in the design process to reduce the energy consumption of buildings. It is also well known that not only the system selection but also the synergies of these critical system selection decisions have impact on building energy performance. However, these decisions are incorporated into simulations without synergies are considered early in design process. These late evaluations cannot go beyond the projection of energy performance that is already selected for design. Thus, this is a need for a decision support system that stimulates the integration of decisions to achieve higher levels of energy efficiency compared to considering individual measures. In the light of these indicators, this paper presents a critical review of energy conservation measures (ECM) used in retrofit project case studies. The individual impact of changes to these critical ECMs is modeled in EnergyPlus and eQuest. A simplified energy prediction methodology fed by a process model, and the possible synergies are presented. The prediction range is tested in three case studies with different energy performance levels. The calculation algorithm relies on determining individual system performance relative to the ASHRAE standard. This relative system performance evaluation is also useful in defining the scope of system retrofit by comparing options with the standard baseline. It assists collaborative design teams to evaluate the individual impact of system decisions and overall energy saving prediction rate earlier in the design of a variety of deep retrofit projects.

1 INTRODUCTION

Approaches to support decision making prediction in energy performance include checklists, databases, and forward and inverse modeling. It is well known that integrated system upgrades result in significantly more energy reduction rates than standard approaches. However, these synergies between decisions are not communicated to all team members in order to be able make energy-efficiency decisions early in the design process. In a typical energy efficient retrofit design, decisions are entered into simulations without collaboration to document and predict the energy performance of design. These late evaluations cannot go beyond the projection of energy performance of what has already been selected for design. Thus, there is a need for a simplified energy analysis methodology to provide instant comparative performance evaluations and to improve decision making by interdisciplinary design teams.
This paper reviews energy efficiency initiatives and measures in retrofit projects and then presents three case study projects that informed the development of a new approach to comparative energy outcome analysis in deep retrofit projects. The key features of the new approach are presented and the benefits over conventional approaches highlighted.

2 ENERGY EFFICIENCY INITIATIVES

2.1 Energy Efficiency Metrics

The energy performance target of a retrofit design affects the criteria used for system selection. These selections are usually based on energy conservation measures (ECMs). An ECM is intended to improve the energy efficiency of building infrastructure, including heating, cooling, and ventilation systems, utility systems, roof, and windows. This is achieved by an engineering investigation to identify potential replacements of, or upgrades to, existing systems that enhance energy efficiency (Kunselman 2013).

In order to evaluate the performance of ECMs, it is important to quantify their impact on building performance. One of the most common quantitative energy comparison measures is energy (Btu) per square foot, energy (Btu) per occupant, and cost per square foot (PNNL 2012). Designers usually make comparisons by using the Btu/sqf per year. These comparisons generally rely on various energy simulation tools, databases and checklists. According to a study done in 2007, there are 330 energy performance evaluation initiatives available using different measures of performance outputs (WBDG 2014). These initiatives include websites, technical publications, software, databases, checklists and matrices. From the literature review on performance evaluation metrics of energy efficient buildings, the most common units of analysis for energy efficiency are as follows:

- LEED Scorecard: Certified, Silver, Gold, Platinum (USGBC 2005),
- Normalized Annual Energy Consumption and Energy Use for heating in kWh/m2 (Rey 2004; Zhu 2006), Annual Electricity Use in kWh/m2 (Rey 2004),
- Energy and Time consumption Index (ETI) (Chen et al. 2006),
- Energy Saving by Retrofitting expressed by (1- Energy/ Energy Baseline) % (Gholap and Khan, 2007).

For the purposes of this paper, the energy percentage reduction output measure defined by Gholap and Khan (2007) for energy performance comparisons was used.

2.2 Energy Efficiency Initiatives

As mentioned before in the scope of building performance evaluations; checklists, technical publications/standards, and software are the most popular initiatives. These initiatives carry different levels of information and are more beneficial to a certain design phase than others. With the use of different units of analysis, the performance evaluation methodology also varies.

2.2.1 Checklists

Checklists and rating systems provide a holistic performance evaluation in addition to energy performance. One of the most common green building rating systems is the Leadership in Energy and Environmental Design (LEED™) program that was developed by the United States Green Building Council (USGBC). This program aims to provide third-party verification that a building or community was designed and built using strategies aimed at improving performance across all the metrics that matter most: energy savings, water efficiency, CO₂ emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts (USGBC: What LEED™ is 2010). 10 bonus credits are available, four of which address regionally specific environmental issues. This individual type of approach provides more flexible and reliable results for green building performance. There are also
different types of certifications for different types of buildings, such as Core and Shell, and Commercial Interiors.

### 2.2.2 Technical publications and Standards

**Technical publications and standards** prepared by professional societies, national laboratories, and academicians are also used in the design process as a benchmark and recommendations. The outcomes of these studies are improved on year by year to improve the energy efficiency of buildings. American Society of Heating and Air-Conditioning Engineers (ASHRAE) has developed the ASHRAE 90.1 standard to provide minimum requirements for the energy-efficient design of buildings except low-rise residential buildings (ASHRAE 2007). Various versions of this standard are widely used in the building industry. As seen in an analysis done by a national laboratory (PNNL 2011), ASHRAE 90.1-2010 standard targets a minimum requirement of 19% lower energy use than ASHRAE 90.1-2007, and 24% lower than ASHRAE 90.1-2004. In this research, ASHRAE 90.1-2007 is used as a common baseline to compare case studies. It is on continuous upgrades every three years. The current version is ASHRAE 90.1-2013.

In addition to providing minimum requirement standards, ASHRAE is delivering performance and process related recommendations. ASHRAE 189.1 is targeting higher energy efficiency levels for the design of High-Performance, Green Buildings except Low-Rise Residential Buildings. In addition to these efforts, ASHRAE delivered Advanced Energy Design Guide 30% to 50% to explain and show a way and recommendations to achieve 30% and 50% savings relative to ASHRAE 90.1. Briefly, this guide provides critical ECMs under four main categories: optimize orientation and glazing, use efficient building systems, use efficient energy producing systems, and engage occupants (ASHRAE 2011). These ECMs include energy measures for envelope, lighting, HVAC water and air side, renewable sources, and plug and process loads. This specific technical publication is designed to provide recommendations to achieve 50% energy savings when compared with the minimum code requirements of ASHRAE Standard 90.1-2004. It also gives hints on an efficient process with key design activities as organized below (Table 1).

<table>
<thead>
<tr>
<th>ASHRAE AEDG</th>
<th>Key Design Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Kick-off and Conceptual Design</strong></td>
<td>Set Design Goal (OPR)</td>
</tr>
<tr>
<td></td>
<td>Perform Site Brainstorm Session</td>
</tr>
<tr>
<td></td>
<td>Analyze Floor Plate Zoning</td>
</tr>
<tr>
<td><strong>Schematic Design</strong></td>
<td>Exercise Test Fit</td>
</tr>
<tr>
<td></td>
<td>Study Glazing</td>
</tr>
<tr>
<td></td>
<td>Study Climate/ Natural Resource</td>
</tr>
<tr>
<td></td>
<td>Define Behavioral Analysis Unit (BAU) Case</td>
</tr>
<tr>
<td></td>
<td>Compare ECM energy use to BAU</td>
</tr>
<tr>
<td></td>
<td><strong>Find ECMs</strong></td>
</tr>
<tr>
<td><strong>Design Development</strong></td>
<td>Write Basis of Design (BOD) Document</td>
</tr>
<tr>
<td></td>
<td>Perform Life Cycle Cost (LCC) Analysis of ECMs</td>
</tr>
<tr>
<td></td>
<td>Confirm Design Cost</td>
</tr>
<tr>
<td></td>
<td>Compare BOD to OPR by Commissioning Authority (CxA)</td>
</tr>
<tr>
<td><strong>Construction Documents</strong></td>
<td>Perform Constructability Review/ Waste Reduction</td>
</tr>
<tr>
<td></td>
<td>Review Material Sourcing</td>
</tr>
<tr>
<td></td>
<td>Control Strategy Review by Project Programmer</td>
</tr>
<tr>
<td></td>
<td>Update Design Changes</td>
</tr>
<tr>
<td></td>
<td>Check back Design against OPR by CxA</td>
</tr>
</tbody>
</table>

Table 1: ASHRAE AEDG key design activities
2.2.3 Modeling Techniques

The use of modeling techniques has increased year by year in order to predict a relative energy efficiency rate to building performance standards. There are four times more building performance simulation (BPS) tools than nearly 15 years ago. However, the increase in tools used by architects in early design is not as high as the increase in the engineering tools used for system design later in the design process (Attia et al. 2012). In particular, the ECMs and user interfaces are specialized according to certain systems and disciplines. In this paper, the aim is to provide a list of ECMs that are meaningful for architects, engineers, and project managers in a collaborative decision making environment.

With regard to energy consumption analysis techniques, there are two types of prediction methods. First, inverse modeling is commonly used more in academia, which is used to predict building parameters such as ECMs by energy use and drivers with statistical models. Secondly, forward modelling is commonly used more in industry to predict energy use by building parameters and environmental drivers such as weather using energy models. There is a need for more case studies to provide valid statistical models rather than energy models. Thus, the forward modeling technique was used due to a limited number of case studies. Also, one of the objectives of this research was to understand the practical context and approaches for the decision making environment of the deep retrofit design process. In-depth process evaluation was prioritized over energy evaluation, which is defined as comparative performance of alternatives rather than precise energy consumption prediction.

Since there are around 400 energy modeling tools (DOE Website 2013), designers are willing to use the most realistic prediction tools. However, these tools are not only specialized based on expertise and experience, but also on specific design phases. A study shows that only 1% of BPS tools carry pre-design information (Attia et al. 2012). This shows that the aim of using the tools is to predict the performance of already selected design alternatives. Another study shows that starting energy simulation at the conceptual design phase has greater impact ability on the level of energy efficiency performance than schematics and starting even later at design development phase provided significantly lower level of green performance outcomes (Gultekin et al. 2013).

Figure 1: Pearson's correlation analysis results showing the effect of starting to use energy simulations at various phases of design on high-performance green index (Source: Gultekin et al. 2013)

Since the goal of this paper is on improving the collaborative design decision making environment, the focus was placed on the early phases of design. Performance analysis was undertaken with a simplified comparative energy comparison rather than energy prediction.

There is still room for improvement in terms of the energy predictions of forward modeling tools. A study compared three widely used energy simulation tools; DOE-2, DeST, and EnergyPlus (Zhu et al. 2013) by using three case studies (simulated cases). Figure 2 shows the discrepancy of annual heating and cooling loads (kWh) with the use of the same building parameters, environmental drivers, and occupancy behavior.
Figure 2: Prediction comparison of DOE-2, DeST, and EnergyPlus in annual heating and cooling load of same building (Source: Zhu et al. 2013)

Even though these there still discrepancies in the performance prediction of these three tools, they are pretty detailed in terms of ECM parameters and calculation algorithms. Since the focus of this study is on a comparative analysis of ECMs, the impact of particular ECMs was tested by simulation using EnergyPlus. For this analysis, DOE Commercial Reference Building’s EnergyPlus data was used to simulate certain technical criteria (NREL 2010). For retrofit comparison basecase, a medium sized office building in Zone 5A (RefBldgMediumOfficePre1980_v1.4) climate region by using State College typical meteorological year TMY weather data. ASHRAE 90.1 Prototype Building Specifications was used as as base case (PNNL 2014). For the selection of critical technical criteria, simplified energy simulation tools that use the most critical ECMs to predict energy were reviewed. Energy-10, developed by National Renewable Energy Laboratory (NREL), was one of the rare early design tools that provides annual energy use information, cost breakdown, and ranking of energy efficiency strategies (Deru et al. 2010). Another simplified energy model is Design Advisor, developed by MIT (2007), which also provides ECM inputs such as: zone configuration, building orientation, room, window, wall, thermal mass, occupancy, and ventilation rates. Its aim is also to improve the understanding of ECMs for various disciplines with a simplified user-interface.

These tools still require the input of form, zone, orientation, occupancy, and internal loads. This study is limited to a specific region, form and building type, and excludes orientation and zoning impacts in energy performance analysis.

3 RETROFIT CASE STUDIES

In this research, case studies have been found appropriate to gain first-hand experience of the current approaches being adopted and to understand the practical context for decision making in retrofit projects. Three case study projects in Pennsylvania were investigated. Two of the projects were superior examples in terms of the collaborative design process and new technologies used, while one was a typical project that represents the traditional retrofit process.

Two of the case studies, Energy Innovation Center (EIC) Retrofit Project and Energy Efficient Buildings Hub (EEB Hub) Retrofit Project in Pittsburgh and Philadelphia respectively are deep retrofit projects. Both projects are best practice examples regarding the collaborative project delivery process and energy efficiency technologies used. The decision making is transparent due to the aim of delivering showcase projects in terms of energy efficiency technologies and techniques used as well as the process followed. The third case study was of an academic building (HHD) on a university campus, which provided an example of a traditional retrofit process; this enabled the identification of differences from the more modern approaches in the other two case studies through the cross-case analysis.

Case studies are selected purposefully to reflect the various levels of energy efficiency, process followed, and tools used. For the energy performance data, the case studies represented different levels of ASHRAE 90.1 and LEED targets. The two showcase projects represented an integrated project delivery approach based on contractual and informal project processes. The EIC followed a typical design-build approach with the early involvement of the contactor in the design process, while the EEB Hub project was an example of an integrated design process as part of an informal integrated project delivery (IPD) process. On the other hand, the HHD building represented a fragmented design process with a lower
energy efficiency target as a result of a design-bid-build delivery process. Additionally, the use of various simulation tools in different projects with different efficiency levels is beneficial for our simplified energy performance prediction test comparisons (Table 2). The multiple source calculation algorithms improve the validity of our energy performance range prediction.

Table 2: The use of various simulation tools in case studies

<table>
<thead>
<tr>
<th>Energy Modelling Tool</th>
<th>Lighting Modelling Tool</th>
<th>Modeled by</th>
<th>LEED Documentation and Target</th>
<th>ASHRAE Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIC</td>
<td>TraneTrace</td>
<td>AGI32</td>
<td>3rd Party Platinum</td>
<td>90.1 2007 53%</td>
</tr>
<tr>
<td>EEB</td>
<td>eQuest</td>
<td>Radiance</td>
<td>3rd Party Gold</td>
<td>90.1 2007 38%</td>
</tr>
<tr>
<td>HHD</td>
<td>HAP</td>
<td>AGI32</td>
<td>In-house</td>
<td>90.1.2004 28%</td>
</tr>
</tbody>
</table>

3.1 Case Study Data Source

Case studies are the main data source of this research. Since the number of case studies is limited, construction projects were selected purposefully and compared with literature. The decision making environment and decision scope in the case studies were tracked by attendance in the project team meetings. The variety of energy simulation tools provided us to range our predictions with different algorithms. The simulation tools that are used for case study predictions are TraneTrace, Hourly Analysis Program (HAP), and eQuest.

4 CALCULATION ALGORITHM

After the key decision points were sequenced into a process model, certain steps that required decision support were refined. The refinement criteria were defined as energy efficiency performance and available technical criteria tracked in project participant interviews and documents.

4.1 System Algorithm

Related critical technical criteria from the key decisions point of view were collected from project documents and reports for all the case studies as follows.

ECM1. Natural Lighting Hours
ECM2. Interior Lighting Power Density
ECM3. Window-Wall Fraction
ECM4. Wall R-Value (assembly)
ECM5. Roof R-Value
ECM6. Window U-Value
ECM7. Shading
ECM8. Daylighting controls
ECM9. Ventilation Rate
ECM10. Chiller Efficiency
ECM11. Boiler/Furnace Efficiency
ECM12. Heat Recovery
ECM13. AHU Fan Type
ECM14. Pump Type
These ECMs were individually tested on Commercial Reference Building model (NREL 2010) as a baseline by using EnergyPlus v8.1 and the energy reports of EEB Hub Project that were created by eQuest. ECMs are taken from energy reports and created after the discussions in expert workshops. Input parameters such as u-value, COP, cfm/sqf are tested in EnergyPlus, and the output parameters such as natural lighting hours %, daylighting controls are taken from eQuest reports.

Finally, the individual system parameter efficiency represents the individual system efficiency (1- Energy/Energy Baseline)% (Gholap and Khan 2007) is used as a proportion of change in the case study and test options at certain key decision point as in Table 3.

Table 3: Individual system efficiency based on test option ECM

<table>
<thead>
<tr>
<th>ECM</th>
<th>Unit</th>
<th>Baseline</th>
<th>Test Option</th>
<th>Individual System Parameter Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM1</td>
<td>Natural Lighting Hours</td>
<td>% daylight hours</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>ECM2</td>
<td>Interior Lighting Power Density</td>
<td>W/sqf</td>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>ECM3</td>
<td>Window-Wall Fraction</td>
<td>% (&lt;50)</td>
<td>33</td>
<td>20</td>
</tr>
<tr>
<td>ECM4</td>
<td>Wall R-Value (assembly)</td>
<td>ft2fh/BTU</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>ECM5</td>
<td>Roof R-Value</td>
<td>ft2fh/BTU</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>ECM6</td>
<td>Window U-Value</td>
<td>BTU/ft2fh</td>
<td>0.62</td>
<td>0.4</td>
</tr>
<tr>
<td>ECM7</td>
<td>Shading</td>
<td>Y/N</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ECM8</td>
<td>Daylighting controls</td>
<td>Y/N</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ECM9</td>
<td>Ventilation Rate</td>
<td>cfm/sqf</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>ECM10</td>
<td>Chiller Efficiency</td>
<td>COP</td>
<td>2.638</td>
<td>3.517</td>
</tr>
<tr>
<td>ECM11</td>
<td>Boiler/Furnace Efficiency</td>
<td>%</td>
<td>78</td>
<td>88</td>
</tr>
<tr>
<td>ECM12</td>
<td>Heat Recovery</td>
<td>Y/N</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ECM13</td>
<td>AHU Fan Type</td>
<td>kw/cfm</td>
<td>0.000702</td>
<td>0.0005</td>
</tr>
<tr>
<td>ECM14</td>
<td>Pump Type</td>
<td>%</td>
<td>85</td>
<td>95</td>
</tr>
</tbody>
</table>

4.2 Algorithm Testing for Defining Range

Since the focus is on comparative energy performance rather than predicting energy consumption amounts, precision was not of prime concern. Based on the energy simulation, the results of EEB HUB, EIC and HHD (38%, 53%, 23%) are tracked in project reports submitted by project team members and compared with energy predictions by adding up individual system parameter efficiency ratings (e.g. 33%, 44%, 19%) The proposed prediction deviates 5%, 9%, 4% from the energy efficiency rates documented in reports, respectively. The precise average of deviation of three projects is 5.82% lower than the reported numbers. The prediction range was rounded to 10% more or less than the DSS prediction, which covers both the average and largest deviations that can result from the impact of interdependent measures.

In EEB HUB prediction calculation, the deviation is 5% which is lower than the average. The calculated prediction and reported performance gap is lower than the average performance deviation. There are two main reasons for such close prediction. First, all baselines and proposed performance criteria of ECMs were captured and documented well during the design of the project. Secondly, there are commonalities between the list of critical ECMs and test project ECMs while setting up the calculation algorithm. The list of tested case study parameters is documented in Table 4.
Table 4: EEB HUB ECM comparison of baseline vs proposed design

<table>
<thead>
<tr>
<th>ECM</th>
<th>Unit</th>
<th>Baseline</th>
<th>Proposed</th>
<th>Individual System Parameter Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM1</td>
<td>Natural Lighting Hours</td>
<td>% daylight hours</td>
<td>100*</td>
<td>10</td>
</tr>
<tr>
<td>ECM2</td>
<td>Interior Lighting Power Density</td>
<td>W/sqf</td>
<td>1.1</td>
<td>2.48</td>
</tr>
<tr>
<td>ECM3</td>
<td>Window-Wall Fraction</td>
<td>% (&lt;50)</td>
<td>13</td>
<td>17.5</td>
</tr>
<tr>
<td>ECM4</td>
<td>Wall R-Value (assembly)</td>
<td>ft²/ft²/BTU</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>ECM5</td>
<td>Roof R-Value</td>
<td>ft²/ft²/BTU</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>ECM6</td>
<td>Window U-Value</td>
<td>BTU/ft²/ft²</td>
<td>0.67</td>
<td>0.32</td>
</tr>
<tr>
<td>ECM7</td>
<td>Shading</td>
<td>Y/N</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>ECM8</td>
<td>Daylighting controls</td>
<td>Y/N</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ECM9</td>
<td>Ventilation Rate</td>
<td>cfm/sqf</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>ECM10</td>
<td>Chiller Efficiency</td>
<td>COP</td>
<td>2.726</td>
<td>3.517</td>
</tr>
<tr>
<td>ECM11</td>
<td>Boiler/Furnace Efficiency</td>
<td>%</td>
<td>80</td>
<td>96</td>
</tr>
<tr>
<td>ECM12</td>
<td>Heat Recovery</td>
<td>Y/N</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>ECM13</td>
<td>AHU Fan Type</td>
<td>kw/ft²/ft²</td>
<td>0.000702</td>
<td>0.000661</td>
</tr>
<tr>
<td>ECM14</td>
<td>Pump Type</td>
<td>%</td>
<td>85</td>
<td>90</td>
</tr>
</tbody>
</table>

In the EIC prediction calculation, the deviation is 9% which is higher than the average. The prediction and reported performance gap is higher than the average performance deviation, but still in the range of 10% projected energy performance range. The prediction gap can be resulted from the uncertainty of baseline assumptions, which is mark as (*). These baseline criteria were not precisely documented due to inaccessibility of energy model, and flexibility of the project goal and system selections. Since the project is a green demonstration showcase, the interdependencies of the flexible system schedule enabled much higher efficiency than individual system performance. The list of tested case study parameters is documented in Table 5.

Table 5: EIC ECM comparison of baseline vs proposed design

<table>
<thead>
<tr>
<th>ECM</th>
<th>Unit</th>
<th>Baseline</th>
<th>Proposed</th>
<th>Individual System Parameter Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM1</td>
<td>Natural Lighting Hours</td>
<td>% daylight hours</td>
<td>100*</td>
<td>10</td>
</tr>
<tr>
<td>ECM2</td>
<td>Interior Lighting Power Density</td>
<td>W/sqf</td>
<td>1.1</td>
<td>2.1</td>
</tr>
<tr>
<td>ECM3</td>
<td>Window-Wall Fraction</td>
<td>% (&lt;50)</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>ECM4</td>
<td>Wall R-Value (assembly)</td>
<td>ft²/ft²/BTU</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>ECM5</td>
<td>Roof R-Value</td>
<td>ft²/ft²/BTU</td>
<td>20*</td>
<td>30</td>
</tr>
<tr>
<td>ECM6</td>
<td>Window U-Value</td>
<td>BTU/ft²/ft²</td>
<td>1.2</td>
<td>0.43</td>
</tr>
<tr>
<td>ECM7</td>
<td>Shading</td>
<td>Y/N</td>
<td>0*</td>
<td>0.8</td>
</tr>
<tr>
<td>ECM8</td>
<td>Daylighting controls</td>
<td>Y/N</td>
<td>0*</td>
<td>1</td>
</tr>
<tr>
<td>ECM9</td>
<td>Ventilation Rate</td>
<td>cfm/sqf</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>ECM10</td>
<td>Chiller Efficiency</td>
<td>COP</td>
<td>2.93</td>
<td>4.4</td>
</tr>
<tr>
<td>ECM11</td>
<td>Boiler/Furnace Efficiency</td>
<td>%</td>
<td>80*</td>
<td>98</td>
</tr>
<tr>
<td>ECM12</td>
<td>Heat Recovery</td>
<td>Y/N</td>
<td>0*</td>
<td>1</td>
</tr>
</tbody>
</table>
In the HHD prediction calculation, the deviation is 4%, which is lower than the average. The prediction and reported performance gap is lower than the average performance deviation. The prediction gap can be caused by the assumptions (*) made for baseline comparison. The preciseness of the baseline criteria is interrupted with inaccessibility of energy model, and unavailable proposed model parameter. Additionally, 5% ASHRAE 90.1 conversion difference is subtracted from 2004 version 2007 of ASHRAE according PNNL’s recommendation. The list of tested case study parameters is documented in Table 6.

Table 6: HHD ECM comparison of baseline vs proposed design

<table>
<thead>
<tr>
<th>ECM</th>
<th>Unit</th>
<th>Baseline</th>
<th>Proposed</th>
<th>Individual System Parameter Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECM1 Natural Lighting Hours</td>
<td>% daylight hours</td>
<td>100*</td>
<td>60</td>
<td>0.4</td>
</tr>
<tr>
<td>ECM2 Interior Lighting Power Density</td>
<td>W/sqf</td>
<td>1.03</td>
<td>0.93</td>
<td>0.8</td>
</tr>
<tr>
<td>ECM3 Window-Wall Fraction</td>
<td>% (&lt;50)</td>
<td>22.9</td>
<td>23.1</td>
<td>-0.01385</td>
</tr>
<tr>
<td>ECM4 Wall R-Value (assembly)</td>
<td>ft2fh/BTU</td>
<td>15.38</td>
<td>15.62</td>
<td>0.0544</td>
</tr>
<tr>
<td>ECM5 Roof R-Value</td>
<td>ft2fh/BTU</td>
<td>20.82</td>
<td>21.28</td>
<td>0.0598</td>
</tr>
<tr>
<td>ECM6 Window U-Value</td>
<td>BTU/ft2fh</td>
<td>0.45</td>
<td>0.4</td>
<td>0.727273</td>
</tr>
<tr>
<td>ECM7 Shading</td>
<td>Y/N</td>
<td>0*</td>
<td>0.4</td>
<td>0.16</td>
</tr>
<tr>
<td>ECM8 Daylighting controls</td>
<td>Y/N</td>
<td>0*</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ECM9 Ventilation Rate</td>
<td>cfm/sqf</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>ECM10 Chiller Efficiency</td>
<td>COP</td>
<td>2.93</td>
<td>4.11</td>
<td>5.101251</td>
</tr>
<tr>
<td>ECM11 Boiler/Furnace Efficiency</td>
<td>%</td>
<td>80*</td>
<td>100</td>
<td>12.2</td>
</tr>
<tr>
<td>ECM12 Heat Recovery</td>
<td>Y/N</td>
<td>0*</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ECM13 AHU Fan Type</td>
<td>kw/cfm</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>ECM14 Pump Type</td>
<td>%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

A simplified comparative energy performance analysis methodology for deep retrofit designs has been presented. This study contributes to an integrated design process by providing critical decision stages with regard to energy performance, and describing the resolution of system decision conflicts by adding criteria impact. This relative system performance evaluation is also useful in defining the scope of system retrofit by presenting a comparison of options relative to a standard baseline. It assists collaborative design teams to evaluate the individual impact of sub-system decisions earlier by identifying potential synergies between sub-systems in the design of deep retrofit projects. The limitations of this research are as follows:

- Synergies are tracked for the future step, but not calculated.
- ECM impacts are calculated with a single energy model single tool and an energy analysis report with single set of decisions.
- Modeling level of detail is accepted as it is in Commercial Reference Building model. Zoning, occupancy, building type measures are accepted as constant. The prediction will improve with the reflection of these variables impact.
• The number of deep retrofit case studies is limited to create a complete list of all technical criteria. This study focused on tracking the critical technical criteria which are defined by project team members of three projects and literature review.

• Load calculation is analyzed based on final building energy load, not based on sub-systems such as heating, cooling, and lighting. Even though the impact of system on load type varies, the source of energy is accepted as electricity.

The future step of this study is developing a decision support system that provides guidance to interdisciplinary teams to analyze their decisions during retrofit design process. This tool will enhance system-based decision making process by comparing their proposed decision alternative individually and energy consumption reduction rate relative to a certain baseline.

References


ELECTRONIC DOCUMENT MANAGEMENT SYSTEMS FOR TRANSPORTATION CONSTRUCTION INDUSTRY

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Abstract: The concept of Civil Integrated Management (CIM) was developed to facilitate better utilization of data and information that would enable effective decisions for transportation agencies. It is important to select appropriate intelligent technologies or tools and use them efficiently. Moreover, data needs to be collected, stored, and managed wisely so that it could be used throughout the life cycle of a transportation facility and even for the next reconstruction cycle. This makes it necessary for agencies to have electronic document management (EDM) systems, so that they can manage and share their data with other stakeholders in an efficient manner. Though EDM systems have been implemented and their benefits are well understood in the building construction industry, they are not as common in the transportation design and construction industry, and there are only a few leader state DOTs implementing EDM at agency wide level. Since there are differences between the building and the transportation industry, it is desirable to analyze early examples of implementation from the transportation industry in order to achieve further progress. The purpose of this paper is to present and analyze current state of the EDM systems within the state DOTs that lead with regard to EDM implementation. During a United States National Cooperative Highway Research Project Domestic Scan effort, seven state DOTs and their contractors collaborated to present their extensive experience on CIM related practices and tools. Of these seven, four distinguished themselves with leadership in the area of EDM systems implementation while others were leaders in other areas. In this paper, those four agencies who are leaders with regard to the EDM systems implementation are analyzed and their practices are documented in detail.

1 INTRODUCTION

Electronic Document Management (EDM) systems have become more crucial to the transportation industry as more advanced tools and automated process have been adopted. Prior to the adoption of EDM systems, piles of paper plans or other documents had to be handed back and forth within agencies and/or between various parties. Considerable time and cost were spent on printing out and shipping hard copy documents during the duration of a typical project. Nowadays, with the adoption of EDM systems, personnel form various stakeholders can easily submit documents to the same platform, and other users involved with the project or a particular task can view the submitted documents and provide comments, concurrence and approvals. Furthermore, certain engineering products, such as 3D models must be delivered electronically, because they cannot be easily converted to hard copies. EDM systems eliminate the need for printing and shipping documents among various parties (Sulankivi et al. 2002). Moreover, the
documents or models might be stored in the system as permanent record if necessary, so that stakeholders can extract and use them in the future.

Especially after the release of Moving Ahead for Progress in the 21st Century (MAP 21) legislation, many leading transportation agencies started using various advanced tools such as EDM system, 3D modeling, GPS, GIS, automatic machine guidance and others. Also, programs such as Every Day Count (EDC), which is facilitated by Federal Highway Administration (FHWA) in the United States, is meant to encourage the adoption of various innovative methods and tools. E-construction, one of the topics under EDC-3, specifically addresses the importance and benefits of using EDM systems (FHWA 2015).

This paper presents the results associated with the EDM system obtained from the National Highway Cooperative Research Program (NCHRP) Domestic scan project 13-02 Advances in Civil Integrated Management (CIM). The final report of this project is expected to be released during the second or third quarter of 2015. During this scan study, panel members visited seven leading states to explore current practices related to CIM. Content analysis method was adopted to analyze the EDM system related presentations and documents provided by host agencies. It is found that EDM systems, as one of the major components of CIM, are helpful in increasing communication efficiency among various parties and retaining data integrity and transparency during the project duration. EDM systems adopted by four transportation agencies and their functionalities are analyzed in this paper.

2 BACKGROUND

Common tools used by agencies or companies to support electronic collaboration include document management, file sharing, emails, calendars, discussions, polling, and instant messaging (Munkvold and Zigurs 2005). Study results from 2003 indicated that about half of the larger contractors were already using project collaboration technologies to some extents in the US (Issa, Flood, and Caglasin 2003).

During the project duration, a large number of documents are usually produced, such as design drawings, schedules and estimates, meeting minutes, bill of quantities, and others. There has been several attempts at the standardization of those documents involved various industrial organizations in various countries. As word and CAD applications became more commonly adopted in the industry, traditional hard copies began to be replaced with digital forms of documents which can be distributed out by email or other tools. Subsequently, the EDM systems evolved with the capability to retain all of the latest documents that were generated during a project on the same web server (Björk 2006). Such systems could be created by an agency or company’s in-house staff, project participants, or a third party (Bjork 2003), and these systems were either developed at project/team level or at enterprise level (Munkvold and Zigurs 2005).

The role of metadata in EDM systems is important, as the directory structures embedded within the metadata could help mitigate potential damage that would result from loss of data or documents. Also, document searches become easier and more precise with the directory structure that can be devised from metadata (Tough and Moss 2003). The standardization of metadata and data storage is very important, as it could provide considerable convenience for downstream users (Bjork 2003).

Based on the case studies conducted by Sulankivi et al. (2002), the use of EDM systems resulted in 29 work days’ savings and avoided 1700 days of delay in information distribution, which together saved 17,300 USD for one single project in Finland. Major qualitative benefits of using EDM systems include easier document distribution and publishing, easy access to the latest updated versions of documents, and easy access to real-time information (Sulankivi et al. 2002). On the other hand, there are some challenges associated with the use of EDM systems. In a study conducted by Mohamed and Stewart (2003), it was indicated that considerable training and support related to the EDM system would be necessary for users. Becerik (2004) indicated that lack of studies on illustrating the EDM systems’ benefits resulted in the slow development and popularization of the EDM systems. In addition, Munkvold and Zigurs (2005) recommended that the EDM systems should be developed in a way that users can easily adapt to them. Otherwise, users might tend to select the older ways of performing work tasks. Also, guidelines and support should be developed to instruct new users about how to implement such systems.
3 METHODOLOGY

A content analysis approach was adopted as the major methodology to establish a better understanding of current practices on the implementation of EDM systems. The analyses were conducted as part of US Domestic Scan Project 13-02 that was entitled Advances in CIM which is managed under the auspices of the NCHRP 20-68A U.S. Domestic Scan Program. Scan team members were chosen from among leading state DOTs who have interest in adopting CIM related practices and tools in addition to the FHWA representatives. Scan team members, along with a subject matter expert (SME, the second author) and his assistants (the first and third authors), developed a set of amplifying questions relevant to the topics of interest including EDM system. These questions were then sent to the target agencies and their contractors and consultants. When scan team members visited the leading state DOTs, presentations were provided by the host agencies in response to the questions. Detailed notes were recorded during the presentations and interactions between scan panel members and host agencies. In addition, supplemental documents were also provided by the host agencies to assist panel members in better understanding their usage of certain tools. These notes and supplemental documents were systematically analyzed to provide the findings.

As previously mentioned, EDM is one of the major components of CIM. Various agencies or companies are using various EDM systems produced either by their in-house employees, project partners or commercial software developers. Four state DOTs who served as host agencies in this study were selected for detailed analysis, as they have relatively mature EDM systems and extensive experience in using such systems. Presentations and documents related to EDM were reviewed using the content analysis method (Elo and Kyngäs 2008, Neuendorf 2002). For Iowa DOT case study, additional documents obtained from Iowa DOT’s official website were also analyzed. In Section 4, the content analysis results associated with the EDM systems used in four target agencies are summarized and presented.

4 FINDINGS

4.1 Utah DOT

Utah DOT is currently using an application called Interchange which was developed using a Microsoft SharePoint platform. This program contains segments that were developed for different groups of users and also for different phases of projects. Additional segments are still under development. The program can not only be used by DOT personnel, but also can be used by their local contractors. This construction portal is adopted for 18 construction projects so far, and Utah DOT is planning to have all construction projects use this portal by the end of 2015. Some of the major capabilities provided by this program include document submission, task management, meeting minutes, and design review.

Through this program, various groups are able to submit their documents or design models to the same platform. When documents are being submitted, users can make selections with regard to the document filter, type, and subtype. This initial setup selection allows documents to be better organized within the system, making it easier and faster to search and manage documents. Users can assign other attributes to documents such as document event date and due date, phase, and others, and they can also specify which personnel within which group can receive the submitted document. Thus, when the documents are submitted successfully to the system, recipients are notified immediately.

Task management is another important function of this program. The schedule of various project-related tasks will be shown on a task calendar, which reminds users to perform the required tasks within the expected due dates. Tasks that are not completed yet are marked as open tasks, and users can view task status, due date, and responsible personnel for each open task. Users can not only view their own tasks, but also view tasks assigned to their group. Each open task is closed once it is finished.

Meeting minutes can also be tracked by this program. Meeting minutes can be recorded including other related information such as creator, meeting organizer, time, location, type, and attendees. At the same time, tasks can be assigned through meeting minutes if necessary. Utah DOT also tried to integrate this
meeting minutes stored in this program with other applications such as the agency’s email platform, however their attempt was unsuccessful due to data integration issues.

More importantly, this application allows for better tracking comments and responses, which makes design review process more effective. Usually in Utah, design reviews occur at 15%, 30%, 60%, and 90% of design. Design packet that needs to be reviewed can be uploaded to the system based on the planned milestones. When uploading the design documents, the system provides various options such as which disciplines are supposed to review the submitted materials and by which date the review is expected to be completed. Then, reviewers can provide their comments before the designated due dates, and subsequent responses will be created by design documents creators to address those comments. Each review document will be coded by different colors based on each division’s review status (e.g. not needed, no response, in progress, complete, etc.). When changes are made to the design documents, the responsible disciplines will also be notified to review the changes. Usually, solutions to proposed comments will be addressed in the next design review meeting. Between each design review meeting, project managers will also have intermediate meetings to track the design progress. Exceptions might occur when design-builders ask for reduction of the number of submittals or meetings, and decisions for approving such requests will be made based on actual cases. Compared to the traditional design review process where piles of paper need to be handed back and forth, this digital communication method increases work efficiency and flexibility as well as maintaining a digital record of comments and responses occurred during design reviews.

4.2 Michigan DOT

Michigan DOT requires all electronic documents submitted through ProjectWise platform (Bentley Inc. 2014) and kept up to date. The only exceptions are delivery tickets for hot mix asphalt (HMA), concrete, and aggregates, which are stored as hard copy documents. Contractors are responsible to coordinate electronic document submittals by their subcontractors, suppliers, fabricators, and others that are involved in the construction process. Failure to upload documents to the system will result in delayed payment.

In order to better manage all submitted electronic documents, there are rules developed for document format, folder structures, and user authorizations. For example, contractors need to sort and place their files into the following folders: correspondence, materials, payrolls, shop drawings, and sub-contractor in box. Michigan DOT also provided training courses on the use of their EDM system for their contractors. In general, by using this electronic document management system, all information could be stored in one place and stakeholders have easy access to the most up to date project-related data.

The level of authorization is determined and monitored to ensure that personnel can access files when necessary while maintaining the security. For example, the project team cannot view information in contractors’ inbox until the documents are submitted to the system. After contractors submit their documents, an audit trail will be attached to each file to achieve transparency. At the same time, restrictions are in place to prevent consultants or contractors who have competitive relationships from seeing each other’s proprietary information or intellectual property.

Additionally, Michigan DOT uses and accepts digitally encrypted electronic signatures. Digitally encrypted electronic signatures are not scanned copies of handwritten ones, but rather electronic “objects” containing unique identities, password, and date/time. Most commonly adopted software for placing digital signatures for Michigan DOT EDM system is Adobe Acrobat. Each user will have a unique digital identification (ID) and password. Before placing an electronic signature, the user is required to provide his or her password. After the signature is placed digitally, the electronic document will become a signed original file which has the same legal effect as a paper document with a handwritten signature. In terms of signature validation, document recipient can check whether the electronic signature is placed by an expected signer and whether the document is sent from an agency/company’s email account. If the signer has previously been verified by the system, there will be a green mark besides his or her signature. If the signer is new or cannot be verified, there will be a grey question mark besides his or her signature.
Michigan DOT developed a detailed instruction document for placing and verifying digitally encrypted electronic signatures.

4.3 New York State DOT

New York State DOT requires all project related electronic documents to be stored in its EDM System which is built on a ProjectWise platform (Bentley Inc. 2014). Project related electronic documents to be stored normally included studies, permits, mapping, plan sheets, digital terrain models, reports, control, calculations, photos, correspondence, and other items. Emails involving project-related decisions are also expected to be stored in the system. DOT personnel, consultants, or contractors are required to follow specific instructions for document naming conventions, categories, and formats to ensure that the documents can be better organized, managed and retrieved.

This system contains DOT’s DataSource and archive DataSource. DataSource is composed of various documents, folders, and their supporting database. Documents for active projects will be submitted to DOT’s DataSource (NYSDOT 2006). There are specific rules developed for folder and subfolder structures within the DataSource. Official project records will be created based on electronic documents that reside in DOT’s data source. After projects are completed, documents in DOT’s DataSource will be moved to archive DataSource by a data manager, so that they become permanent records.

In order to ensure system security, access is limited to stakeholders who have proper authority based on work groups’ responsibilities in various phases of a project. Read and write access will be given only to work groups that have active roles in a particular phase of a project. The rest of work groups without active duties will only have read access to a project. A regional data manager will be responsible for providing and changing each work group’s access as the project moves forward. For non-department personnel such as consultants, contractors, and partners, only the minimum access required for their work will be provided. Employees of an outside company will only have read and write access to their company’s designated folders.

All documents retained in the system are kept up to date. When a document is checked out, it means someone has downloaded the file for revision work and other personnel cannot make changes to this file at this stage. When the revision work is completed, this document will be checked back into the system. Alternatively, users can select update server copy option to upload the most recent version to the server and keep the document checked out for further work.

Attributes assigned for each document are important for organizing and searching information. When searching for a document, documents with attributes matching the search criteria will be displayed for users. Thus, when uploading a document, all appropriate attributes applicable to a document should be assigned by the document creator. In addition, information could be automatically generated in MicroStation based on the document attributes resided in predefined tags.

The archiving process is another important part of data management. Documents that are used to create officially approved project records should be included in the archiving process. Data owners are expected to determine which documents should be kept and which documents can be deleted and then convey their decisions to the data manager. At each stage of a project (e.g. scoping, design, and construction), there are rules developed for key data that must be stored in the archive. When project is completed, all project data should be moved to the archive DataSource.

4.4 Iowa DOT

Iowa DOT’s EDM system was developed using a Doc Express platform (Info Tech, Inc. 2015). Iowa DOT offers instructions for contractors and suppliers about how to use this system for electronic file storage and sharing (Iowa DOT 2015). Through this system, contractors can manage their contracts and associated documents systematically. They can view and sort their contracts based on their own preference, and they can choose to receive real-time notifications (e.g. ready to be processed, rejected, etc.) or request a summary report for all of their contracts and/or ones added in their favorite lists. Under each contract, they can select various virtual “(file cabinet) drawers” named based on document
categories for managing their documents, including Contract Documents, Pay Items, Payrolls, Contract Modifications, Working, Shop Drawings, and Signatures.

Documents are submitted to their appropriate drawers. DOT and prime contractors can open the submitted documents in the drawers to which they have access. Subcontractors and suppliers can only open documents submitted by their own companies, though they can see a larger list of documents. Documents will be electronically signed when submitters check the electronic signature box. Once documents are submitted to the system, no changes can be made to the documents’ contents. Comments can be added to those documents by other personnel or document creators.

The Contract Documents drawer is the place for storing documents related to a particular contract. This drawer is mostly used by DOT personnel, but there are also cases where the prime contractor needs to submit documents to this drawer. DOT users or the prime contractor can make comments on the submittals in this drawer. Likewise, the Pay Items drawer is used for storing pay item documents associated with a particular contract. DOT personnel mark the submittals as received or audited. The status of audited indicates that the materials users have audited the item and no further checking is needed.

Contract modifications (or change orders) are made in the FieldManager application (Info Tech, Inc. 2015) and then submitted to the Contract Manager drawer. Once contract modifications are submitted to the system, users who have access to this drawer will receive notifications immediately. The prime contractor needs to review the submitted documents and provide signatures if they approve those submittals. All associated activities could be tracked down through the system. The time, date, and personnel’s role associated with each transaction are visible to users with access. After all signatures have been collected, contract modification will be approved in FieldManager.

Payrolls sent from subcontractors can be certified by the prime contractor and then submitted to the Payrolls drawer by the prime contractor. The submitter can open and view the submitted payroll documents, but users associated with the prime contractor can only view the list of submittals. Also, only selected DOT personnel involved with the contract are given the access to those payrolls.

The Working drawer is designed for sharing documents that are produced during working process and should be continuously updated until the final version is completed. Once a document is finalized in the Working drawer, it will be published by a DOT user to its appropriate location (a specific drawer). As for the Shop Drawings drawer, it is the place to which shop drawings should be submitted. The prime contractor is the only user authorized to submit drawings to this drawer. Personnel who are supposed to review the documents can either open or download the drawings in this drawer and make comments if necessary. The Signature drawer is mostly used by DOT personnel and contains documents that need to be signed by one or more people.

4.5 Discussion and Comparisons

Generally, the EDM products described above are designed with three different approaches which could be categorized as:

- General purpose workflow and file storage solution (e.g. Microsoft SharePoint Platform)
- Document access solution originally developed to meet the needs of design groups (e.g. ProjectWise)
- Document management solution designed mainly for transportation construction agencies (e.g. Doc Express)

The original purpose and approach for the development of these products were somewhat different, so they all come with their own unique capabilities, characteristics, and IT support demands. However, there are common functionalities shared, such as:

- Document submission
- Electronic signatures
- Document access based on the predesignated level of authority
• Document sharing
• Document format and structure standardization
• Document searching based on the assigned attributes
• Creation and modification tracking
• Instant notice to related users

These functionalities appear to be adequate for supporting most transportation agency needs for electronic document management. Moreover, the communication process between various stakeholders becomes easier and faster when an EDM system is implemented. Despite the differences of these EDM implementation approaches, they have proven to be efficient in organizing and managing electronic documents within the same agency and exchanging documents amongst the agency, designers and contractors. In cases where current products could not support an agency's needs, modifications were made by collaborating with software developers or assigning in house or consultant programmers to produce a solution addressing agency needs. Overall, stakeholders provided positive feedback on the adoption of EDM tools for the purpose of data storage and exchange. In one case, a contractor trade association proactively encouraged the use of the EDM tool for file exchange.

During the application of these EDM tools, some challenges were also identified as below: (1) interoperability issues between various software applications and hardware are always challenging; (2) An insufficient budget is often initially allocated for purchasing and updating hardware and software applications; (3) It is difficult for agencies to decide whether to use an existing commercial product or to develop a customized in-house product; (4) Stakeholders outside the agency, such as contractors, might have difficulty accessing the system due to stringent protocols required to penetrate agency firewalls; and (5) It is often be difficult to obtain quick and effective specialized IT assistance within the unit that needs help, especially if IT support has been highly centralized (for example provided on a state wide basis).

5 CONCLUSIONS AND RECOMMENDATIONS

The EDM systems have become more commonly used in the transportation construction industry, as they help to better manage and share documents produced throughout the project life cycle. Currently, various companies or agencies are using various EDM systems which might be produced by their in-house staff, project partners, or third parties such as a software vendor. All these products are designed to help improve the digital communication process and increase work efficiency by reducing the time spent in handing hard copies of documents among various parties. Each product might have its unique characteristics and ways to support its users during the project duration or daily company operations. The intention of this study is not to conclude which product is better than the others but rather to present the functionality and real practice of EDM systems adopted within some leading transportation agencies.

It is important for agencies and companies to determine which product might fit their demand better or if they need to develop their own unique product. No matter which product they are using or planning to use, critical issues need to be considered include standardization of document submission and sharing, proper level of user authorizations, long term storage, training programs, IT support, and others. Essentially, the EDM systems are tools that can make the work process easier and faster. Discussions with host agencies indicated that as employees become more familiar with the systems, their work efficiency increases and they come to greatly prefer the EDM systems to the traditional work process.

Nowadays, technologies are evolving quickly. The transportation design and construction industry, which has not adopted EDM systems as fast as the building design and construction industry, can review these case studies and select the tools that will increase their productivity and quality of work. The EDM systems are basic tools that should be used not only at project level, but can also be useful at enterprise level. Feedback from using current EDM systems should be kept and sent to program developers for further improvement. Furthermore, more communication should occur among agencies or companies, software developers, and researchers to share lessons learned and exchange ideas. Collaboration between researchers, developers and industry practitioners to deliver more useful products and
disseminate best practices can be helpful. Together, with everyone’s efforts, technologies can continue to be improved and become more beneficial for the entire transportation design and construction industry.

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References


A PROCESS FOR THE ASSESSMENT OF INFRASTRUCTURE RELATED RISK DUE TO NATURAL HAZARDS

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Abstract: The determination of network related risks for transport infrastructure systems, such as road or railway networks, is a challenging task. Due to such complex systems, it is generally impossible to abstract the global behavior from the analysis of single components, especially under conditions such as failures or damages. People who manage infrastructure have to handle these risks. The proposed overarching risk assessment process is constructed in a way so that computational support can be constructed in modules. This allows to couple the process with detailed sub-processes to achieve varying levels of detail in the risk assessment. The use of the overarching risk assessment process is demonstrated by using it to evaluate infrastructure related risk due to natural hazards for an example region in Switzerland.

1 INTRODUCTION

Transport infrastructure is a key element for the economic growth and development and it plays a fundamental role in the modern world. Over the past decades it has become obvious that the analysis and understanding of large-scale infrastructure networks is important for research, engineering and society. The failure or damage of an infrastructure system could cause huge social disruption. It could be out of all proportion to the actual physical damage (Vespignani 2010). Thus, understanding the phenomenon of failure is critical for evaluating the systems risk and vulnerability and for designing robust infrastructure (Schneider et al. 2011). People who manage infrastructure, herein referred to as infrastructure managers, have to handle these risks. Each infrastructure manager relies on his own risk management processes. These processes are systematic, timely and structured processes that when followed will provide the infrastructure manager with a better understanding of what may go wrong with the system in which the infrastructure is embedded, the probability of this happening and the associated consequences. This risk assessment process is particularly challenging for managers of infrastructure networks, due to the large number of scenarios that need to be analysed in order to assess the risks appropriately, the spatial and temporal correlations between these events (MOVE 2011), and the correlation between event occurrences, or so called cascading events (Garcia-Aristizabal & Marzocchi 2011).

In addition to the challenges in the physical world, the process is made even more complex because the risk assessment process requires that persons work together from many different disciplines who each
has their own discipline based approaches to risk assessment that are not always harmonious with those in other disciplines. This makes it so that independent risk assessments from different persons are not always easy to aggregate to a level that is useful for the infrastructure manager.

The overarching process presented in this article is meant to be helpful to infrastructure managers who want to assess the infrastructure related risks due to natural hazards. It is to be used to help bring together people from many different disciplines so that they can provide information in a way that will be useful to an infrastructure manager. It has been specifically developed to deal with road and rail infrastructure networks but it is believed to be generally applicable to all types of infrastructure networks. The proposed overarching process is meant to fit within the risk management process of any infrastructure owner. This process is developed so that it can be coupled with detailed sub-processes to achieve varying levels of detail in risk assessment. This flexibility ensures that the overarching process is applicable for different types of infrastructure, different types of hazards, different levels of detail in the assessment, different sizes of regions, different types of regions and different levels of abstraction. It is also developed to ensure that the temporal and spatial correlation of events can be considered.

The work was carried out in the scope of the European project INFRARISK, with the aim to develop reliable stress tests to establish the resilience of European road and rail network infrastructure to rare low frequency extreme events and to aid decision making in the long term regarding robust infrastructure development and protection of existing infrastructure. This article is a summary of Hackl et al. (2014). Additional information also can be found in the report Adey et al. (2014) which was submitted as a deliverable in the INFRARISK project. The work builds on that done for the Swiss Federal Roads Authority in 2005 (Adey et al. 2009; Adey et al. 2010).

2 METHODOLOGY

The overarching risk assessment process is based on ISO 31000 (2009), including different principle activities: communicating and consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk. Beside the basic concepts of ISO 31000, the proposed framework has been extended to allow explicit consideration of the spatial and temporal correlation between hazards as well as the modelling of the functional interdependencies between multiple objects in the infrastructure networks, including physical dependencies, cybernetic dependencies, geographical dependencies and the modelling of impacts. The process is described using generic definitions of sources, hazards, objects of the network and the network itself, which eases the application to different decision-making situations. It is constructed keeping in mind that for many decision-making situations it will be desired to have the process be computer supported, for example to model specific parts of the system. It has also been constructed keeping in mind that different decision situations will require the use of different types of models and models that will provide different levels of detail. In the following, a brief overview of the different sub-processes of the overarching risk assessment is given.

2.1 Problem Identification

The first step is to identify the question to be answered. This step includes the generation of preliminary thoughts on the area to be investigated. It is only once this question is identified that a meaningful risk assessment can be conducted. It will affect the system definition, the requirements of the assessment in terms of both input, e.g. man-power, and output, e.g. the accuracy of the results or the number and types of scenarios to be investigated. It will also affect the scope of the assessment and the level of detail.

2.2 System Definition

The system representation is a model of the relevant part of reality used for the evaluation and consists of all relevant realizations of stochastic processes within the investigated time period. It includes sufficiently good representations of the hazards, infrastructure, and consequences, as well as the interaction between them so that it can be reasonably certain that there is an appropriate understanding of the system and that the risks and the effectiveness of the strategies can be determined.
The system to be modelled includes all things required to assess risk, including the natural environment, e.g. amount of rain, amount of water in rivers, the physical infrastructure, e.g. the behaviour of a bridge when subjected to high water levels, and human behaviour, e.g. traffic patterns when a road bridge is no longer functioning. As it is necessary to model the system over time, it is necessary to also model the spatial and temporal correlation between events and activities within the investigated time period. This includes the consideration of assumptions, agreements as to how the system will react in specific situations, and drawing fixed system boundaries where it is clear that the things outside the considered system are not being modelled. It also includes the consideration of cascading events.

2.2.1 Boundaries

By establishing spatial boundaries, the part of the natural and man-made environment to be specifically modelled is determined. In addition to the definition of the geographical space, this includes specification of where the objects are located, where the events and hazards can occur and where the consequences could take place. It is usually easy to specify the possible locations of the events, hazards and objects. It is more difficult to, however, determine how they are related, e.g. heavy rain causes a flood hazard. This becomes even more difficult when the location of possible consequences is to be specified. Consequences can be far away from the location of the events, hazards, and infrastructure, and may be outside the direct area of responsibility of the infrastructure manager (e.g. the collapse of a highway bridge on a trans-European highway network can have consequences on the free flow of goods in many countries). By establishing temporal boundaries, the time period over which risk is to be assessed is fixed, as well as how this time period is to be subdivided for analysis purposes. With respect to time, the system representation can be made either: static or dynamic. In the case of a dynamic representation, the model evolves over time whereas in the case of a static representation time is not explicitly modelled.

2.2.2 Elements

It is proposed to group the system elements from initiating events to the events that are considered to be quantifiable and no further analysis is required. It is considered that the element types can be further grouped as either elements to which no value can be directly assigned or elements to which a value can be assigned. In the assessment of risk related to infrastructure due to natural hazards, one can label these further as “hazard elements” and “consequence elements”. Although the number of element types to be considered vary depending on the type of problem and the desired level of detail. Each element type is considered to correspond with events, which can be considered to have a probability of occurrence. Five basic element types, or event types, that should be regularly considered are:

Source events, or initiating events, are events, such as rainfall, tectonic plates movements, ground movement etc. The occurrence of such an event does not necessarily mean that a hazard will be triggered.

Hazard events, or loading events, are events related to any earlier event that may lead to consequences. A hazard always has a source event. It may also trigger another one (e.g. earthquake triggers landslide). Most hazards evolve through space and time and interact with their environment. The time frame can vary from a few seconds (e.g. earthquake) to over a few days (e.g. flood) to several months (e.g. drought). The area that is affected can range from very local, to global. In defining the hazards to be considered it is important to define the intensities of the hazards to be considered. This should include consideration of the return period of the hazards to be used, e.g. 1/500 year flood or earthquake, and the loads to which the infrastructure will be subjected, e.g. the amount of water in the river during a flood, the magnitude of ground motions during an earthquake, the amount of displaced soil during a landslide.

Infrastructure events include all the objects and the condition states of these objects to be considered, e.g. a bridge collapse is an infrastructure event. How the infrastructure networks to be modelled are subdivided into infrastructure objects depends on the specific problem and the level of detail desired in the risk assessment. For example, a 10 km road link may be modelled as one element, although it consists of 3 bridges, 4 road sections and a tunnel, or it may be subdivided to explicitly consist of all eight of these objects. If more detail is required then each object could be subdivided. For example, one of the bridges could be seen as being composed of columns, bearings, decks, etc. In the development of the
system representation it is important to consider which infrastructure objects are affected by which hazard and how the states of these objects may change over time. This is a difficult task as in many cases many objects could be affected but the effect might range from very small, e.g. yielding of a reinforcement bar in a bridge during an earthquake, to very large, e.g. collapse of the bridge. An example of a value that could be assigned to this element type may be the cost of reconstruction of the infrastructure object if damaged. This value depends on the level of damage that might happen and how the infrastructure manager plans to intervene on the object if it is damaged. Sometimes these are referred to as direct consequences, although this terminology is not used consistently. For more in-depth analysis, one might decide to not assign values directly to infrastructure elements and to model the human activities involved in restoring the infrastructure, which would allow a substantially higher level of detail in terms of the costs related to multiple objects in a network being affected simultaneously.

*Network use events* include the states of use of the infrastructure network that might occur. For example, due to a tunnel collapse the freight corridor between Rotterdam and Genoa is closed and no vehicles can travel on it. The probabilities of these events occurring are particularly difficult to estimate as their occurrence depends on spatial and temporal correlation, and physical relationships between initiating events, hazard events and infrastructure events. Network use events can lead to cascading events, as can the other events. To be clear on the distinction between infrastructure and network use events, an example of a value that can be assigned to a infrastructure use event is the cost of deviating traffic around a closed road, whereas an example of a value to be assigned to a network use event is the cost lost travel time due to the closed link. Of course, the value assigned is highly dependent on the flow of traffic if the road is closed which in turn depends on the decisions of many persons in society. For more in-depth analysis, one might decide to not assign values directly to network use events and to model the human activities involved in redirecting traffic, which would allow a substantially higher level of detail, i.e. societal events.

*Societal events* include the actions of persons or groups of persons. For example, due the freight corridor between Rotterdam and Genoa being closed 50% of goods is put onto trucks, 40% of goods is diverted over other train routes and 10% is not delivered. In order to model the actions of persons or groups of persons it is often beneficial to group them into categories based on their general behavior, which in turn is coupled with how their behavior is to be modelled. Societal events may lead to other societal events. If a societal event is not an intermediate event then no value needs to be assigned to it. If they are, however, a terminal societal event, then a value needs to be assigned to the event.

![Network Use Events Diagram](image_url)

**Figure 1:** Example of a simple event tree for risk assessment of infrastructure networks

As the events from the initiating event to the event upon which a value is placed forms a causal chain it is convenient to think of them in the form of an event tree, where each chain of events is represented by a path in the event tree. To build the tree it is necessary to determine the intensity measures to be used to
define the events to be investigated, e.g. the water height above which a flood event is considered to have occurred. At each branch in the event tree a decision is required to determine the value of the intensity measures, which allow classification of the event. The number of intensity measures used to describe the events depends on the problem being investigated and the level of detail required in the analysis. A very simple example is given in Figure 1.

As can be deduced from this simple example, there is an infinite number of ways to represent reality. Due to this, particular care needs to be used in the development of an appropriate system representation. The necessary detail to be used depends on the specific problem and the level of detail desired. If events at any level, or complete ranges of the values of intensity measures are excluded, it should be explicitly explained and documented why, because in the following risk assessment, the risk coming from those hazards cannot be taken into account.

### 2.2.3 Relationships

In order to estimate the likelihood of each subsequent event in the causal chain of events appropriate models of the relationship between them are to be developed. For example, in order to determine the amount of water coming in contact with a bridge during a flood, it is necessary to model how the water which falls as rain reaches the river, taking into consideration, for example, the amount of water that seeps into the ground or evaporates, or is held in temporary retention ponds.

The amount of effort to be invested in this depends on the exact problem and the level of detail desired. For example, in some cases it may be sufficient to use one dimensional vulnerability curves based on expert opinion to estimate the amount of damage that a single object might incur during an earthquake. In other cases, it may be desirable to use multidimensional vulnerability curves based on detailed finite element models to estimate the amount of damage a large dam might incur during an earthquake. In general, extra effort should be spent to achieve more detail when it is suspected that the results will add additional clarity for decision-making. If additional clarity is not provided the extra effort is not worth it.

Although specific examples are given here, the general thoughts apply to all system elements, i.e. initiating events, hazard events, infrastructure events, network use events and societal events. If possible the availability of data to be used to model the relationships should be taken into consideration in determining the level of detail to be used.

### 2.3 Risk Identification

In the previous step emphasis is made on identifying the correct system elements to be used in the risk assessment and how to model the relationships between these. In its most extensive form the definition of these elements and relationships will provide all possible scenarios, or risks. As it is unrealistic to attempt to quantify all of these it is necessary to identify the specific scenarios that are to be part of the risk assessment. Each branch in Figure 1 is a scenario which has an associated risk.

The identification of the scenarios should be done in this step without an explicit estimation of their probability of occurrence or putting a value on the consequences. The starting point for the development of this set of scenarios is all combinations of the system elements in the system representation. It is useful in the identification of scenarios to first determine for who the risk assessment is to be done, and then to:

- start with the initiating events and think through how the infrastructure will be affected and then how humans will react to this,
- to start with the consequences and think through how the infrastructure would have to behave to something to cause these consequences, and
- to start with infrastructure behaviour and think in the other two directions.

Comprehensive identification of relevant scenarios is critical, because scenarios excluded in this step will not be included in further analysis and may result in an underestimation of risk. To minimize the possibility of this happening it is important that experts in each area are involved.
2.4 Risk Analysis

The analysis of risk has to do with estimating the probability of occurrence of the scenarios and the value of the consequences of the scenario if it occurs. It is only through doing this that an infrastructure manager can decide if action needs to be taken and if multiple options are available, which one is the best. It can be done using a qualitative or a quantitative approach. In both cases, however, the goal is to gain a better understanding of the probability of occurrence of a scenario and the consequence of that scenario.

Risk analysis, as with risk identification, can be undertaken with varying degrees of detail, depending on the specific problem, the information, data and resources available. Analysis can be qualitative, semi-quantitative or quantitative, or a combination of these, depending on the circumstances. The certainty with which both the probabilities of occurrence of each of the scenarios and the consequences can be estimated, as well as the sensitivity of these values to the modelling assumptions, need to be given appropriate consideration in interpreting the results. Indicators of the sensitivity of these values are the divergence of opinion among experts, the availability of information, the quality of information, the level of knowledge of the persons conducting the risk analysis, and the limitation of the models used.

2.5 Risk Evaluation

Risk evaluation has to do with verifying the meaning of the estimated risk to persons that may be affected, i.e. stakeholders. This is true regardless if a qualitative or a quantitative approach is used. A large part of this evaluation is the consideration of how people perceive risks and the consideration of this over- or under-valuation with respect to the analyst’s point of view used in the risk analysis step of the risk assessment. Through the risk evaluation there is the possibility to bring into the risk assessment aspects that have not been explicitly modelled in the risk analysis step. The risk evaluation step help to bring decision makers closer to finding a solution that is more acceptable to all stakeholders.

One possible result of this step is that the risk analysis needs to be redone with more detailed system representations, improved models and different values. Another possible result is that it is decided that the risks are acceptable and no exploration of possible interventions are required (ISO 31000 2009).

3 EXAMPLE

In this section, the use of the overarching process is demonstrated by using it to evaluate infrastructure related risk due to natural hazards for an example region. For the sake of simplicity, the example is presented in a sequential manner, although the process itself is highly iterative. The results of this example should be treated with care since only very simple physical models are used to evaluate the risk.

3.1 Problem Identification

The target area is located around the city of Chur, the local capital of the easternmost Canton of Switzerland, Graubünden. Chur is located in a valley between several mountains with many watercourses draining into the main river Rhine. The addressee of this risk assessment is the city administration being interested in damage, cost and other consequences resulting from a rare flood event. It is here important to note that this example was made using public data and was not done in collaboration with, or for, the city of Chur. The results, although they are realistic and serve to demonstrate how the methodology works, are not to be used for other purposes.

3.2 System Definition

3.2.1 Boundaries

The spatial boundary of the system has been selected to be that shown in Figure 2. The risk assessment is done for a flood hazard with a return period of 500 years. The occurrence of this hazard takes three
days. To compare the risk with other cities and regions, the losses resulting from this analysis are converted into an average annualized loss.

![Figure 2: Overview of the area of interest.](image)

### 3.2.2 Elements

**Source event precipitation**: The model of precipitation was constructed using the precipitation data from a historical event which occurred in year 2007 and is scaled in such a way that it corresponds to a precipitation event resulting in a flood with a return period of 500 years. **Hazard event flood**: The model of the amount of water on each land surface area and in the rivers was developed using a set of interrelated tools. **Infrastructure event hospitals**: In the area of interest, only one institution is present for ambulant care, the hospital of the Canton of Graubünden. **Infrastructure event road segments**: Since road geometries for the target area can have lengths up to several hundred metres, these are partitioned in such a way that a spatial analysis can be undertaken on a feasible resolution. **Network use events**: The road network for the target area is extracted from the VECTOR25 dataset. Each road is represented by a linear geometry with assigned attributes on their type (swisstopo 2014).

**Societal events**: Societal events are how the traffic behaves on the network when it is not fully operational. It is estimated using traffic simulations to estimate how much additional time is required to travel from anywhere in the hospital catchment area to the hospital.

### 3.2.3 Relationships

**Source-Hazard-Interaction**: For reasons of simplicity and efficiency only a simple hydrological model for the runoff calculation is used. The ModClark model (Kull & Feldman 1998) is used to estimate the discharge during the precipitation event. **Hazard-Infrastructure-Interaction**: To estimate damage resulting from inundation, simple damage curves are used from Deckers, et al. (2010). **Infrastructure-Society-Interaction**: It is assumed that if infrastructure is damaged that it would be restored to the condition it had prior to being damaged. The unit values used are taken from Kutschera (2008). **Infrastructure-Network-Interaction**: Since this connectivity changes during the scenario due to node failure, for each time step a distinct network had to be created. **Network-Society-Interaction**: The quantification of consequences related to travelling across the network resulting from the failure of infrastructure network nodes was undertaken in terms of the following non-exhaustive list of examples: travel time costs (e.g. man hours of work time lost), vehicle operating costs (e.g. increase of fuel needed), accident costs (e.g. number and type of injuries/deaths), environmental costs (amount of additional nose/pollution) (Adey et al. 2012).

### 3.3 Risk Identification

The target area has been historically prone to the mentioned natural hazards flooding and landslides. Information on past events are stored in the database "Unwetterschadens-Datenbank" (Hilker et al. 2009) In addition, two more recent projects, AquaProtect and SilvaProtect (Losey & Wehrli 2013) provide model based information on regions vulnerable to floods and landslides. For the sake of simplicity, only one scenario is considered. This scenario is comprised of the following events: Source event is rainfall, the hazard events are floods, defined as being more severe as the largest volume of water expected in the main river expected in 500 years. The infrastructure events are derived from the road sections and
hospitals being in specified damage states. The network use events are derived from the different combinations of damage states of the different infrastructure objects. The societal events are derived from modelling the traffic flow results from the different network condition states.

3.4 Risk Analysis

For the risk analysis of the considered scenario a quantitative approach is used. In order to aggregate risk that has been estimated based on the specific scenario, it is necessary to ensure that they are directly comparable and that they are not double counted. The value associated directly to the condition of the infrastructure objects, are added. It is assumed that the maximum damage predicted throughout the three-day period is the amount of damage that needs to be repaired. Based on the cost associated with the single objects for each time step, the development of the total losses for the whole region of interest can be calculated. The costs related to the disruption of traffic on the road network are estimated by counting the number of additional hours of travel time that is required on the network while the network is not fully operational. In this case study it is also assumed that all road sections are restored to normal immediately following the three-day period.

![GIS results of the example for the time steps 20 and 38.](image)

Figure 3: GIS results of the example for the time steps 20 and 38.

Figure 3 exemplarily illustrates the results of this process. Here, for each type of event a pair of maps illustrates one stage of the overarching process in left-to-right order. To illustrate the change of the system, the upper maps represent the state of the system for time step 20 and the lower maps for time step 38. The source maps show heavy rainfall over the region of interest, which decreases towards the end of the simulation period. The hazard maps show the maximum inundation depths of the resulting flood for each surface area until the respective time step. It becomes apparent that the maximum inundation depths increase with time, which therefore leads to increasing damages of affected infrastructure objects. This causes rising reconstruction costs, which is shown in the element maps for the Haldenstein region. The road networks functionality is reduced as shown in the network maps. Here, red road segments indicate that they are isolated from the green main network. Impassable road segments are not shown. This reduced network state results for some regions, in particular in the northern and south-western parts, to be cut off from important infrastructure objects. For example, it is impossible for people in these areas to get to the hospital in Chur as indicated by the society maps.
3.5 Risk Evaluation

In this paper, risk evaluation is not performed. If a complete risk management process is being conducted this work would need to be done in conjunction with the city administration of Chur. The results coming from the risk analysis would support this task in order to plan further analyses, safety measures or risk treatments.

4 DISCUSSION

The example demonstrates that the proposed overarching risk assessment process is useful to assess infrastructure related risk due to natural hazards. Computer systems can highly accelerate its distinct steps so that the results can be delivered to infrastructure managers in a timely manner. However, in order to refine the results, the methodology needs to be applied to a greater number of scenarios. The process can be used for a wide range of different problems at different levels of detail. In addition, the changes over time and interactions between different events can be modeled as shown in the example. Although the proposed overarching risk assessment process can be used conceptually for all kinds of different problems, its usefulness depends on the quality of available models and data. Often the physical models do not take into account interaction with their environment. For example, if a bridge collapses, the cross-section of the river will be changed, too.

In the presented example a relatively deterministic point of view was chosen. In order to take the numerous uncertainties into account a probabilistic approach seems more suitable, especially when dealing with natural hazards. If one associates a probability of occurrence with the occurrence of the particular precipitation then one could quantify the risk. A more sophisticated example will require the consideration of the not only the probability of occurrence of different rain patterns, but also given the rain fall patterns, the probability of different water run-off events, different levels of water in different parts of the rivers, different behavior of the infrastructure objects in the network, and different behavior of the vehicles on the network. It would also require consideration of larger periods of time, in which multiple rain events occur and perhaps even different types of source events that may result in consequences.

In the expansion of the example to do this there are substantial hurdles with respect to the infinite number of scenarios possible, the uncertainties associated with many different models to be used to make approximations and the temporal changes in the probabilities of event occurrences.

5 CONCLUSIONS

This article describes a generic overarching risk assessment process as well as an example of how it can be used and how it can be implemented using a GIS framework. Even in its current form it is believed that this process would be useful to infrastructure managers in the assessment of their infrastructure related risks due to natural hazards. It is applicable for different types of infrastructure, different types of hazards and different types of consequences and can take into consideration both simple and complex system representations. The overarching risk assessment process will be further improved by taking into account multiple scenarios, including multiple initiating events, multiple hazards, multiple infrastructure events, multiple network use events and multiple societal events. It will also be expanded to deal properly with the spatial and temporal consideration in the estimation of the probability of occurrence of scenarios and the establishment of the scenarios. More work is required to emphasis the human interaction in conducting the risk assessment.

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THE EFFECT OF SHADING DESIGN AND MATERIALS ON BUILDING ENERGY DEMAND

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Abstract: Building sector in most countries around the world requires large amounts of heating and cooling energy. Indeed, building cooling loads due to solar gains are responsible for approximately half of global cooling load. In addition, windows are considered as one of the important sources of energy loss in buildings. In order to minimize this loss, shading devices can be installed in the exterior part of the window to reduce solar heat. The objective of this study is to investigate the simultaneous effect of glazing, shading materials, and configuration of shading devices on total building energy consumption in different climate regions in the United States. To achieve this objective, a typical residential building was selected to assess the effect of the aforementioned parameters on total energy consumption in five main climate regions. A series of simulations were conducted using EnergyPlus simulation program to quantify energy consumption in each scenario and determine the most energy efficient glazing and shading materials as well as configuration of the shading device. Different types of window glazing (including clear, Low-Iron, Ref-B tint, Low-E clear and Low-E tint with 6 mm thickness) as well as different materials for shading devices (including PVC, aluminum and wood) were considered in this study. Moreover, the effect of five different shading device configurations, including horizontal and oriented overhang, vertical fin and combination of them were investigated. Results showed installing vertical fins and horizontal overhang shading devices in buildings located in Miami and Atlanta do not have a significant effect on annual energy consumption. However, combining these two overhang shading configurations will reduce energy consumption. In addition to shading configurations, it was found that Ref-B tint glazing material along with wood shading material reduced annual energy consumption by approximately 11.6% in Miami. However in Atlanta, total energy consumption was reduced by approximately 7% in the case of using Low-E tint glazing material along with wood shading material. No significant decrease in energy consumption was observed in cold climates.

1 INTRODUCTION

The total energy consumption in U.S. buildings has increased in recent years. Building energy consumption had increased by 48% for the period between 1980 and 2009. In 2009, residential buildings consumed 20.99 quadrillion Btu energy which is equivalent to 54% of building sector energy consumption as well as 22% of total primary energy consumption in the United States (Kelso 2012). One of the major sources of energy consumption in buildings is associated with space cooling and heating systems. In the United States, heating and cooling energy consumption is equal to 43% and 52% of the total energy consumption in residential and commercial sector, respectively. Building sector in most countries around
the world requires large amount of heating and cooling energy demand. Indeed, cooling load due to solar gains is responsible for approximately half of the global cooling load in both residential and commercial buildings. According to Residential Energy Consumption Survey (RECS), heating and cooling energy consumption was reduced by 10% in the U.S. residential buildings from 1993 to 2009 (2009). To continue this reduction trend, different parameters such as more efficient equipment, better insulation materials and more efficient windows can be used in buildings.

Windows are considered as one of the main sources of energy loss in buildings. Windows are mostly used as the architectural devices that connect the interior space to outdoors. Therefore, they absorb solar radiation and transfer the captivated heat inside the buildings. The three sources of solar radiation on exterior surface result from sun direct radiation, sky diffuse radiation as well as buildings and adjacent surface reflected radiation. Exterior shading devices are one of the building elements that can restrict the direct solar radiation and decrease the effect of the reflected and diffuse radiation (Stack, Goulding, and Lewis 2000). The main advantage of using shading devices is to restrict solar radiation (Stack, Goulding, and Lewis 2000). Effective shading devices should control solar radiation before heating up the fenestration and should provide large shading area for summer, while allow for maximum solar radiation absorption in winter.

Recently, it has been found exterior shading devices can reduce energy consumption and improve thermal comfort of buildings. Moreover, they provide a great view for the occupants by reducing glare (Norbert Lechner 2008). Several studies have been investigated the relation between shading devices and energy consumption. Peebles (Peebles 1940) conducted one of the very first works to investigate the effect of shading devices on energy consumption through an experimental study. It was found that shading devices with different colors can reduce building energy consumption. The results of the study showed that light color shading devices decrease heat gain by about 55% and 40% in the summer and winter, respectively. In another study conducted by Emery et al. (Emery et al. 1981), they found that the performance of shading systems in reducing building energy consumption significantly depends on climate condition. According to this study, the effect of climate on the performance of shading device systems was investigated for three cities in the United States and it was found that fixed overhangs and fins had the most reduction in energy consumption. In a similar study, Harkness (Harkness 1988) investigated the effects of various parameters including window areas and sunscreen projection on cooling energy reduction in Australian buildings. He found that use of single pane clear glass with exterior precast concrete overhangs and fins decreased the cooling energy loads by 50%. In another study conducted by Tzempelikos and Roy (Tzempelikos and Roy 2004), the effect of fixed and movable shading devices on thermal comfort and visualization was investigated. An office building with a large glass area in Montreal was selected as a case study in this work. It was found shading properties and location have significant effects on heating and cooling loads as well as thermal comfort. The simulation results indicated that exterior shading devices with small transmittance and high reflectance can reduce cooling loads by 60%. Kim and Kim (J. Kim and Kim 2010) conducted a series of simulation to compare exterior and interior shading devices in terms of energy performance and view. It was found that exterior shading devices reduce cooling and heating loads by 20% and 12%, respectively, and provide a better view compared to interior shading devices. Kim et al. (G. Kim et al. 2012) compared various exterior shading devices in terms of heating and cooling energy saving for residential building in South Korea. According to this study, the great impact on energy reduction occurred by changing the slat angle of shading devices. The slat angle range was between 0° to 60°. Smaller window area was covered with shading devices when the slat angle was reduced. Therefore, the occupant’s view and energy consumption were improved.

The objective of this study is to investigate simultaneous effects of glazing and shading materials in addition to the configuration of the shading devices on total building energy consumption in different climate regions in the United States. To achieve this objective, a typical residential building was selected in this study to assess the effect of these parameters on total energy consumption in five climate regions in the United States. A series of simulations were conducted using EnergyPlus simulation software to quantify energy consumption in each scenario and determine the most energy efficient glazing and shading materials besides configurations of the shading devices. Different types of window glazing materials (including clear, Low-Iron, Ref-B tint, Low-E clear and Low-E tint with 6 mm thickness) along
with different materials for shading devices (including PVC, aluminum and wood) were considered in this study. Moreover, the effect of five different configurations of shading devices, including horizontal and oriented overhang, vertical fin and combination of these configurations were studied in this paper.

2 METHODOLOGY

The objective of this study is to investigate the effect of various shading devices and glazing materials on residential building energy consumption in five climatic zones in the United States. Five different types of shading devices, three different shading materials and five glazing types were studied. Different scenarios were compared together to find out the most efficient combination for each studied climate zone. A detailed flowchart for simulation steps is shown in Figure 1.

Figure 1: Framework of the simulation model.

2.1 Selection of Representative Locations

Energy consumption varies significantly from building to building located in different climate regions. Climate is one of the most important factors in selecting effective exterior shading devices in terms of energy savings (Khezri 2012). According to Energy Information Administration (2005), the climate regions in the United States categorized into 5 main categories (see Figure 2) based on the last 30-year average heating degree-days (HDD) and cooling degree-days (CDD). The geographical information of the representative cities are summarized in Table 1.

Figure 2: Energy Information Administration climate zones with cities (EIA 2005).
Table 1: Building location and geometry

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Cities</th>
<th>Weather Condition</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Summer Altitude (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>FL-Miami</td>
<td>Hot-Humid</td>
<td>25.78</td>
<td>80.3</td>
<td>69.25</td>
</tr>
<tr>
<td>4</td>
<td>GA-Atlanta</td>
<td>Mixed-Humid</td>
<td>33.66</td>
<td>84.42</td>
<td>63.18</td>
</tr>
<tr>
<td>3</td>
<td>WA-Seattle</td>
<td>Marine</td>
<td>47.43</td>
<td>121.8</td>
<td>51.13</td>
</tr>
<tr>
<td>2</td>
<td>IL-Chicago</td>
<td>Cold</td>
<td>41.97</td>
<td>87.89</td>
<td>56.03</td>
</tr>
<tr>
<td>1</td>
<td>MN-Duluth</td>
<td>Very cold</td>
<td>46.82</td>
<td>92.18</td>
<td>51.66</td>
</tr>
</tbody>
</table>

2.2 Building model

A typical residential building (see Figure 3) was selected in this study to evaluate the effect of various shading designs and materials on total energy consumption in different climate regions in the U.S. The studied building was a one-story detached house with a height of 3.2 m and a total floor area of 130 m². The total window to wall ratio is 18.87 where the height and width of the windows are equal to 1.4 m and 1.2 m. The Ecotect (version 5.6) was used to build the building’s geometry and then it was imported in EnergyPlus for energy consumption simulation. All envelop properties, schedules and equipment (lighting system, HVAC system, etc.) were defined in EnergyPlus. The inside temperature was set to 20 and 24°C in winter and summer, respectively.

Figure 3: Typical Residential Building, (a) Floor Plan; (b) and (c) 3D model.

2.3 Glazing type

Building energy consumption can be affected greatly by glazing properties and shading configurations. In this study, the effect of five different types of glazing as well as five shading configurations considering shading depth and shading materials on building energy consumption were studied. The five studied glazing systems were Low Iron, Ref-B tint, Low-E clear, and Low-E tint with 6 mm thickness. To evaluate the performance of these glazing systems, a control case with no shading devices was simulated for each climate zone to identify the best-performing glazing type which served as the control case to evaluate shading performance.

2.4 Exterior solar shading devices

2.4.1 Shading depth

The depths of shading devices are different in each climate regions depending on the solar altitude angle. Solar altitude is the angle between the sun’s ray and the projection of that ray on a horizontal surface. It is a function of a location’s longitude and latitude. One important design principle for exterior shading
systems is that they can block out direct sunlight for most of the time in a year. In winter, the sun is low in the sky and its ray is considered as a source of heating while in summer the sun position is comparatively higher. Therefore, solar altitude in summer was used to calculate shading depth according to Equation 1 (Rungta and Singh 2011). The results of shading depth are shown in Table 2 below.

\[ \text{Shading depth} = \frac{\text{window height} \times \cos (\text{solar azimuth-window azimuth})}{\tan (\text{solar altitude})} \]

<table>
<thead>
<tr>
<th>Cities</th>
<th>Miami</th>
<th>Atlanta</th>
<th>Seattle</th>
<th>Chicago</th>
<th>Duluth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shading Depth (m)</td>
<td>0.5</td>
<td>0.7</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

2.4.2 Exterior Shading Types and Materials

In this study, the effects of five different types of exterior shading systems (Figure 4) on total building heating and cooling energy load were investigated. The shading depths for each type except shading Type 1 were calculated in previous section. The shading depth of Type 1 was considered the same depth as other types in each climate regions. By comparing the results of various exterior shading configurations, the more efficient configuration that is able to reduce energy consumption was determined for each climate region. In addition, the effect of different shading materials including PVC, aluminum, and wood on building energy consumption were investigated.

![Various exterior shading configurations](image)

Figure 4: Various exterior shading configurations

2.5 Parametric study

A parametric study was conducted to compare the performance of different exterior shading designs and materials and also glazing materials in a typical residential building in five major climate regions in the United States. A typical residential building with no shading device was considered as a control house. Energy simulation was conducted for each scenario to calculate annual heating and cooling loads. The results were then compared to the base case energy consumption to determine the most efficient glazing material in each climate region (see Figure 5). Then, the effect of different types of shading devices and materials on annual energy consumption was investigated for each scenario. The results were compared with the control case energy consumption to determine the efficient scenario for each climate region. The simulation process is illustrated in Figure 6.
3 RESULTS AND DISCUSSION

3.1 Efficient Glazing Materials

To identify the optimal glazing type in terms of energy consumption, a building with clear glass windows was first modeled for each climatic region and the results were compared with other types of glasses as mentioned above. Figure 7 shows the total energy consumption of all studied glazing types. It should be mentioned that clear glazing was considered as the control case. Results showed that the studied glazing types do not have significant impact on total energy consumption in different climatic regions. This is explained by the fact that glazing materials with different coating basically have the same amount of U-value and the window to wall ratio is small. In Miami, the best performing glazing type was Ref-B tint which reduced the annual cooling energy demand by 1.14 MWh. Comparing to the control case with clear glazing, Ref-B tint saved 7.6% in total energy consumption. In Atlanta, Low-E tint reduced total energy consumption by about 4.1%. For all other studied locations, the reduction in energy consumption was not significant.
3.2 Efficient Shading Properties in Each Climatic Region

Installing shading devices on windows will reduce the amount of beam solar radiation passing through and, hence, reduce the amount of heat gain. As it can be seen in Figure 8, in all selected cities, shading 4 and shading 2 with best performance glazing material and wood as a shading material, respectively, have the most and the least window heat gain reduction compared to the clear glass case without shading. The window heat gain and loss for each climate with best performance glazing material, various shading device types, and wood as a shading material are shown in Figure 8. In all locations, window heat gain was affected by installing different shading devices, but the window heat loss did not change significantly because shading devices reject window solar gain effectively depending on shading configuration.

3.2.1 Hot-Humid climate zone

Miami was selected as the representative city of hot-humid climate zone. Energy consumption on heating and cooling between the 15 investigated cases for Miami were compared and the results are shown in Figure 9. By adding exterior shading devices on top of the windows in building in Miami, the maximum reduction in solar radiation absorbed by windows was decreased. In Miami, the great energy consumption reduction was achieved by placing shading 4 while the total energy consumption for clear glass case without shading was 14.8 MWh.
The energy consumption with shading 4 along with wood material and Ref-B tint as an efficient glazing material was 13 MWh, which was a reduction in the annual energy consumption by about 11.6%. Shading device 4 increases the shade area of window and restricted excessive solar beams and consequently the cooling energy consumption was reduced. In addition, heating energy demand in Miami is not too much due to weather condition, so it did not have a significant impact on the annual energy consumption.

![Graph showing energy consumption comparison](image)

**Figure 9: Annual energy consumption of various variables in Miami**

### 3.2.2 Mixed-humid climate zone

Atlanta was selected to simulate the effect of exterior shading devices in mixed-humid climate zone. As Figure 10 shows, the total annual energy consumption in a building having shading device 4 along with wood as a shading material and Low-E tint as a glazing material is 11.95 MWh which reduced the annual total energy consumption by about 7.1% in comparison with clear glass case with no shading.

![Graph showing energy consumption comparison](image)

**Figure 10: Annual energy consumption of various variables in Atlanta**

### 3.2.3 Marine climate zone

For marine climate zone, Seattle was selected as a representative location. According to Figure 11, the total annual heating and cooling energy loads in a building with shading 3 and Low-E clear as a glazing material is 10.1 and 2.1 MWh, respectively and for clear glass case with no shading is 9.98 and 2.77 MWh. Therefore, it was found that replacing clear glass with Low-E clear glass result in 4.2% reduction in energy consumption in Seattle. Also, the energy consumption is not affected much by shading materials in this climate zone.

![Graph showing energy consumption comparison](image)
3.2.4 Cold and very cold climate zone

As Figure 12 shows, in Chicago and Duluth (climate zone cold and very cold), the best performance was achieved in Duluth for a building having shading 2 along with Low-E clear as a glazing material. For a building with Low-E clear glass in Duluth, heating and cooling energy consumption were 21.6 and 2.1 MWh, respectively and for the control case were 21.88 and 2.55 MWh. In Chicago for shadings 3 and 4 with Low-E tint as glazing material, heating and cooling energy consumption respectively were 13.93 and 4.3 MWh and for clear glass case with no shading were 13.85 and 5.08 MWh. In comparison with control case, total energy consumption was reduced by about 3.69%. As shown in Figure 12, shading device does not have a significant impact on energy consumption in cold climates.

3.3 Shading properties guideline

A numerical simulation was conducted to study the impact of exterior shading types, shading and glazing materials on annual energy consumption. After identifying the best performing glazing types for all locations, a series of simulations were conducted to study the impact of different shading types and shading materials. Table 3 summarizes best scenarios among 15 cases with different combinations of shading devices and shading materials in each climate zone.
Table 3: Efficient scenarios and total energy consumption in each climate region

<table>
<thead>
<tr>
<th>City</th>
<th>Energy consumption (MWh)</th>
<th>%Decrease in energy</th>
<th>Glazing Material</th>
<th>Shading Type</th>
<th>Shading Material</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miami</td>
<td>13.06</td>
<td>11.6%</td>
<td>Ref B Tint</td>
<td>Shading 4</td>
<td>Wood</td>
<td>All Side</td>
</tr>
<tr>
<td>Atlanta</td>
<td>11.95</td>
<td>7.1%</td>
<td>Low E Tint</td>
<td>Shading 4</td>
<td>Wood</td>
<td>All Side</td>
</tr>
<tr>
<td>Seattle</td>
<td>12.21</td>
<td>4.2%</td>
<td>Low E Clear</td>
<td>Shading 3</td>
<td>N/A</td>
<td>All Side</td>
</tr>
<tr>
<td>Chicago</td>
<td>18.23</td>
<td>3.7%</td>
<td>Low E Tint</td>
<td>Shadings 3 and 4</td>
<td>N/A</td>
<td>All Side</td>
</tr>
<tr>
<td>Duluth</td>
<td>23.82</td>
<td>2.5%</td>
<td>Low E Clear</td>
<td>Shading 2</td>
<td>N/A</td>
<td>All Side</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

This study investigated the impact of various shading devices and glazing materials on total energy consumption of a typical residential building in different U.S. climate regions. In this study, five different shading devices (horizontal and oriented overhang, vertical fins, and combination of these two), five glazing materials (clear, low-iron, Ref-B tint, Low-E clear, and Low-E tint with 6 mm thickness) and three different shading materials (PVC, aluminum and wood) were considered as potential fenestration elements. In all climate regions, exterior shading devices reduced cooling energy consumption compared to the buildings without shading. The results of this study can be used as a guideline to select the most efficient shading types for various U.S. climate zones. It was concluded in hot climate zones, shading properties and materials play a key role in cooling energy consumption due to restricting the solar beams. In cold and very cold climate regions, installing exterior shading devices can reduce the cooling demand in summer and increase heating demand in winter. Therefore, no significant reduction in total energy consumption may be resulted.

References

ONE RELATION TO RULE THEM ALL: THE POINT-TO-POINT PRECEDENCE RELATION THAT SUBSTITUTES THE EXISTING ONES

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Abstract: Precedence Diagram Method (PDM) has gained the widest acceptance in the scheduling practice in the last decades due to its modeling flexibility over other existing techniques, and to the relative simplicity of its mathematical background. The four basic precedence relationships have been serving planners for more than half a century. However, even this model is not flexible enough; proper modeling of overlapped activities seems to be a never-ending debate. Different practical and theoretical solutions have been proposed during the years for better modeling overlapped activities. The most promising among them is the development of a new type of relation that can connect any two arbitrary points of the related activities. These relations can be called point-to-point relations. Different authors in various ways have proposed similar solutions. To the best of our knowledge, the literature on the mathematical model of PDM using this new relation is lacking. Main results of the paper are: 1) standardized discussion of the different approaches to point-to-point relations; 2) proper mathematical model of PDM with point-to-point relations; 3) introduction of the algorithm that can handle point-to-point relations with both minimal and maximal lag to define the earliest and latest feasible time policy.

1 INTRODUCTION AND LITERATURE REVIEW

Widely used network techniques are more than half a century old. The results of Fondahl, (Fondahl 1961), Roy (Roy 1959), (Roy 1960), IBM (IBM 1964) and many others have led to the present form of the Precedence Diagram Method, the prevailing network technique of our times. PDM has hardly changed during the decades in spite of the critiques it has received about its modeling capabilities. Proper modeling of overlapping activities seems to be a never-ending debate when traditional precedence relations are used, (Douglas et al. 2006) because traditional endpoint relations are simply not suitable for describing this kind of logic. Different solutions have been proposed using the traditional precedence relations; but fragmentation of activities and developments based on this idea (Tarek & Menesi 2010) seem to be the best theoretical solution despite the arising practical problems, namely the multiplication of the number of activities and precedence relations. Probably the fragmentation technique has given the idea of connecting the inner points of the activities, which will be discussed in this paper. These point-to-point relations connecting the internal points of the activities seem to be theoretically more suitable for modeling overlapping activities – especially if continuous activities are assumed - as multiple relations are allowed between the activities. To the best of our knowledge four partly parallel works regarding point-to-point relations can be found: Kim (Kim 2010, 2012) calls his new relations bee-line relations and the graphical representation Bee-line Diagram (BDM), while Francis and Miresco (Francis & Mireco 2000, 2002) call their new relations temporal functions and they call their graphical representation method
chronographic approach. Plotnick (Plotnick 2004) calls his method Relationship Diagramming method (RDM) using the term of ‘event’ for the internal points. Ponce de Leon (Ponce de Leon 2010) uses the term Graphical Diagramming Method (GDM) and connected internal points are called embedded nodes. Despite the differences in terminology and definitions, e.g. bee-line and RDM relation does not allow a lag between the connected inner points, maximal lags are defined only in the work of Francis and Miresco, the concept behind all these works is the same. All these improvements regarding the relationships can be seen as a new type of precedence relation that can substitute all traditional precedence relations, as it will be shown later. The goal of this paper is twofold: firstly, to remedy a common shortcoming of these works (authors have failed to present the mathematical model); secondly, to show that traditional precedence relationships can be derived from the general point-to-point relations discussed in this paper. A proper mathematical model and the algorithm will be introduced using standardized technical terminology. The new point-to-point relation can be seen as a generalization of traditional precedence relations. It will be shown that the existing traditional precedence relations are special cases of the point-to-point relations; they connect the endpoints of the activities instead of the internal points.

2 THE MATHEMATICAL MODEL

2.1 Notations

Let a directed acyclic graph be given with one start (s) and one finish node (f). Let \( N = \{1,2,\ldots,i\ldots,j\ldots,n\} \) stand for the set of nodes also called activities. \( A \) will define the set of arcs, also called precedence relations. The ‘super’ relation defined later can have minimal or maximal lags, therefore \( A_{\text{min}} \) and \( A_{\text{max}} \) subsets are introduced for differentiating relations with minimal and maximal lags. In the algorithm, relations with maximal lags will be transformed into relations with minimal lags. In this case \( A^* \) denotes the set of relations. An activity \( i \) is defined by its start and finish points \( P^i_s, P^i_f \), shortly \( S^i \) or \( F^i \), or by any of the two aforementioned points and its duration \( d^i \). Additional points of the activities can also be defined. \( P^i_k \) stands for the \( k^{th} \) point of activity \( i \). The relative place of the \( k^{th} \) point of activity \( i \) is defined by the time span \( (t^i_k) \) from the start point of activity \( i \) \( (P^i_s) \). A relation can be defined between any \( l^{th} \) internal point of activity \( j \) and any \( k^{th} \) internal point of activity \( i \) by defining the time that must elapse between the two points \( (z^i_k j_l) \). Therefore this ‘super’ precedence relation can be defined either by the points and the lag as \( (P^i_k; P^j_l, z^i_k j_l) \) or by the relative positions of the points and the lag \( (t^i_k; t^j_l, z^i_k j_l) \). Explanation can be seen in Fig. 1. Lags can be defined using production volumes as well.

![Figure 1: Explanation of notations and the the 'super' precedence relation. \((t^i_k; t^j_l, z^i_k j_l)\)](image-url)
Let the time when a point is accomplished be called point or event time and denoted by $T_i$. This way $T_i^S$ stands for the start, and $T_i^F$ stands for the finish of activity $i$. Table 1 shows how the traditional relations and bee-line relations can be derived from the new ‘super’ relation. Transformation of temporal functions (Francis & Miresco 2002) and RDM relations is obvious so this is not presented here. If instead of time, the names of the points of the activities are used for describing the relation, then even the same notation can be used. (e.g. instead of SS100 days (S; S; 100 days) can be used.) Based on the above notations the following model can be defined.

Table 1: ‘Super’ relation can be used instead of traditional and bee-line precedence relations

<table>
<thead>
<tr>
<th>Known precedence relations</th>
<th>Equivalent point-to-point relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDM</td>
<td>$z_i^j$</td>
</tr>
<tr>
<td>Start-to-Start $z_i^j$</td>
<td>$(0; 0; z_i^j S)$ or $(S; S; z_i^j S)$</td>
</tr>
<tr>
<td>Finish-to-Start $z_i^j$</td>
<td>$(d_i; 0; z_i^j F)$ or $(F; S; z_i^j F)$</td>
</tr>
<tr>
<td>Finish-to-Finish $z_i^j$</td>
<td>$(d_i; d_i; z_i^j F)$ or $(F; F; z_i^j F)$</td>
</tr>
<tr>
<td>Start-to-Finish $z_i^j$</td>
<td>$(0; d_i; z_i^j S)$ or $(S; F; z_i^j S)$</td>
</tr>
</tbody>
</table>

2.2 The model

The first two conditions tell that all precedence relations must be satisfied. [1] describes the precedence relations with minimal lags, while [2] describes the precedence relations with maximal lags.

$$[1] \quad T_j^l - T_k^i \geq z_k^j l, \quad \forall (P_k^i; P_j^l) \in A_{min}$$
$$[2] \quad T_j^l - T_k^i \leq z_k^j l, \quad \forall (P_k^i; P_j^l) \in A_{max}$$

By definition $T_k^i = T_k^S + t_k^i$ and $T_j^l = T_j^S + t_j^l$, therefore [1] and [2] can be modified as:

$$[1^*] \quad T_j^S - T_k^i \geq z_k^j i - t_k^i + t_j^l, \quad \forall (P_k^i; P_j^l) \in A_{min}$$
$$[2^*] \quad T_j^S - T_k^i \leq z_k^j i - t_k^i + t_j^l, \quad \forall (P_k^i; P_j^l) \in A_{max}$$

The finish of the activities can be calculated according to [3]. Activities are assumed to be continuous [4]. Let’s set the start of the project to zero. [5]

$$[3] \quad T_i^S + d_i = T_i^F, \quad \forall i \in N$$
$$[4] \quad T_k^i - t_k^i = T_k^S, \quad \forall i \in N \quad \text{and} \quad \exists P_k^i \quad (P_k^i \text{ exist})$$
$$[5] \quad T_0^S = 0$$

The $T$ policy that satisfies $[1^*], [2^*], [3], [4], \text{and} [5]$ is called a feasible time policy. An infinite number of feasible time policies exist, but the objective of the model is to find that/those time policy/policies where the project duration is the minimum, that is

$$[6] \quad T_F^i - T_S^i \rightarrow \min \quad \text{that is} \quad T_F^i - 0 \rightarrow \min \quad \text{that is} \quad T_F^i \rightarrow \min$$

This model is an LP model, so any LP solver can be used for solving it, furthermore, based on the simplistic structure of this LP problem different efficient primal dual algorithms can be developed. The solution shown below is based on the modification of the simplistic and widely used CPM/PDM time analysis. This approach is probably the easiest to digest for planning engineers.
3 ALGORITHMS

3.1 Point-to-point relations with minimal lag

The goal of the algorithm is to find the optimal time policy, the earliest and the latest out of the existing – sometimes millions of – optimal time policies. The earliest optimal time policy is denoted by \( E_i^S \) and \( E_i^F \). The latest optimal policy is denoted by \( L_i^S \) and \( L_i^F \). The applied algorithm has two phases. The result of the first phase is the earliest optimal time policy, while the result of the second phase is the latest optimal time policy.

Let’s suppose for the sake of simplicity that only relations with minimal lags are allowed in the network. In this case, the earliest start and finish of an activity \( j \) can only be calculated, if the earliest start dates for all its predecessors are known. As all precedence relations must be satisfied, the early start of a given \( j \) can be defined by the maximum of the shifts caused by the preceding relations of activity \( j \), that is:

\[
E_j^S = \max \{ E_i^S + t_{ik} + z_{kj} - t_{jl} \mid \forall (P_i^k;P_j^l) \in A_{\text{min}} \} \tag{7}
\]

To start, an activity with known predecessors has to be found. In the beginning, only the start activity satisfies this condition: all of its predecessors are known because it does not have any. After these introductory thoughts, the steps of the first phase, that is the steps aiming to find the earliest time policy, can be summarized as follows:

**Step 1**
- Let \( E_i^S = -\infty \) and \( E_i^F = -\infty \) \( \forall i \in N \); Let \( E_S^S = 0 \); Let \( g := 1 \).

**Step 2**
- **REPEAT**
  - \( g := g + 1 \)
  - Choose an activity \( j \) from the unknowns \( (E_i^S = -\infty) \) with known predecessors only.
  - **IF** there is no such activity then **GO TO** Step 3
  - \( E_j^S = \max \{ E_i^S + t_{ik} + z_{kj} - t_{jl} \mid \forall (P_i^k;P_j^l) \in A_{\text{min}} \} \); \( E_j^F = E_j^S + d_i^j \)

**UNTIL** \( g = n \)

**Step 3**
- **IF** \( g < n \)
  - **THEN**
  - STOP (There is a loop in the network.)
  - **ELSE**
  - \( p = E_F^F \) (Project duration is the same as the early finish of the finish activity.)

During the backward pass, the latest optimal time policy will be defined. It is completed by working from the terminal activity to the initial activity in reverse direction of the arrows. It is based on the observation that the late activity times of an activity can only be calculated, if these dates are known for all of its successors. As all successor relations must be satisfied, the late start of a given \( i \) can be defined by the maximum of the shifts caused by the succeeding relations of activity \( i \), that is:

\[
L_i^S = \min \{ L_j^S + t_{jk} - z_{kj} - t_{jl} \mid \forall (P_j^k;P_i^l) \in A_{\text{min}} \} \tag{8}
\]

The rules of the backward pass can be summarized as follows:

**Step 1**
- Let \( L_i^S = \infty \) and \( L_i^F = \infty \) \( \forall i \in N \); Let \( L_S^F = p - d_f \); Let \( g := 1 \).

**Step 2**
- **REPEAT**
  - \( g := g + 1 \)
  - Choose an activity \( i \) from the unknowns \( (L_i^S = \infty) \) with known successors only.
  - \( L_i^S = \min \{ L_j^S + t_{jk} - z_{kj} - t_{jl} \mid \forall (P_j^k;P_i^l) \in A_{\text{min}} \} \); \( L_i^F = L_i^S + d_i^j \)

**UNTIL** \( g = n \)

(Note: Loop detection is not necessary during the backward pass.)
3.2 Point-to-point relations with mixed lags

Calculations with mixed lags require more computational steps. Maximal relations have to be transformed into minimal relations first. Comparing conditions [1] and [2], it can be seen that the difference between a relation with minimal or maximal lags lies in the direction of the operand. Transforming a relation with maximal lag into a relation with minimal lag requires a simple multiplication by -1.

\[ T^l_j - T^l_k \leq z^l_j \quad \forall (P^l_k;P^l_j) \in A_{\text{max}} \quad \cdot (-1) \]

\[ T^l_j - T^l_k \leq - z^l_j \quad \forall (P^l_k;P^l_j) \in A_{\text{max}} \]

This is nothing else but a relation from \( j \) to \( i \) with a negative minimal lag (see Fig. 2).

![Figure 2: Point-to-point relation with maximal lag a) and its minimal equivalent b)](image)

Traditional precedence relations with maximal lags, and their transformed equivalent minimal lags can be found in Table 2.

<table>
<thead>
<tr>
<th>Traditional precedence relations with maximal lag</th>
<th>Equivalent point-to-point relation with maximal lag</th>
<th>Transformed equivalent precedence relations with minimal lag*</th>
<th>Transformed equivalent point-to-point relation with minimal lag*</th>
</tr>
</thead>
<tbody>
<tr>
<td>maxSSz</td>
<td>max(0; 0; z)</td>
<td>SS-z</td>
<td>(0; 0; -z)</td>
</tr>
<tr>
<td>maxFSz</td>
<td>max(d^f; 0; z)</td>
<td>SF-z</td>
<td>(0; d^f; -z)</td>
</tr>
<tr>
<td>maxFFz</td>
<td>max(d^f; d^f; z)</td>
<td>FF-z</td>
<td>(d^f; d^f; -z)</td>
</tr>
<tr>
<td>maxSFz</td>
<td>max(0; d^f; z)</td>
<td>FS-z</td>
<td>(d^f; 0; -z)</td>
</tr>
</tbody>
</table>

* Transformed equivalents go in the opposite direction

However, converting relations with maximal lags into their equivalent minimal relations can result in so-called transformation loops. In Fig. 3 it can be seen that there is a loop between B and C.

The simple time analysis presented in 3.1 cannot be used in case of loops. One can easily check it by selecting the activities. E.g. during the forward pass activity A has to be chosen first. After that none of the activities can be selected, B has two predecessors but only A is known and C is not; C has two predecessors but only A is known and B is not, so the algorithm will stop here.

In case of loops, different algorithms exist to find the longest path. We will use the modified version of the algorithm developed by Bellman (Bellman, 1958) and Ford (1956) for finding the shortest path between any two points of a cyclic graph. The algorithm is based on the idea that during the forward pass all activities are calculated using the dates of their predecessors even if those have not taken their final dates yet. When all activities have been calculated this way, it has to be checked whether there have been changes in activity dates or not. If the answer is yes, then the entire calculation must be repeated again and again, until we come to the results we had in the previous iteration. In every iteration, at least
one activity takes its final value, so after maximum \( n \) iterations we get the results. Usually much fewer iterations are necessary. If the \( n^{th} \) iteration still brings changes, then the network cannot be solved due to the maximal relations that probably impose logic on the network, which contradicts the minimal or other maximal lags. E.g. imagine that \( B \) can start minimum five days after the finish of \( A \) (\( F;S;5 \)) point-to-point relation but another relation describes that \( B \) should start maximum 4 days after the finish of \( A \) (\( F;S;\text{max}4 \)).

Figure 3: Transformation of relations with maximal lag into their minimal equivalent can result in loops.

This definite contradiction cannot be solved. In this case, the value of the transformation loop will be positive, and the result for the project duration will increase by at least this value in every iteration even after the \( n^{th} \) iteration. The steps below summarize the forward pass:

**Step 1**
- \( E_i^{s} = -\infty \) and \( OLD_E_i^{s} = -\infty \) \( \forall \; i \in \mathbb{N} \); Let \( E_i^{i=0} = 0 \) and \( OLD_E_i^{i=0} = 0 \); Let \( h=0 \); Let \( No_of_Iter=0 \)

**Step 2**
- \( REPEAT \)
  - \( There\_were\_changes:=\text{FALSE}; \; No\_of\_Iter:=\; No\_of\_Iter+1 \)
  - \( REPEAT \)
    - \( h:=h+1 \)
    - Select any \( j \) activity that has not been selected in this iteration yet
    - \( E_j^{s} = \max \{ OLD_E_j^{s}; (E_i^{s} + t_{ik} + z_{kl} - t_{jl}) \; \forall \; (P_i^k;P_j^l) \in A^* \}; \; E_j^{f}=E_j^{s}+d_j \)
    - IF \( E_j^{s}> OLD_E_j^{s} \) THEN \( There\_were\_changes:=\text{TRUE} \)
  - UNTIL \( h=n \)
- \( Let \; OLD_E_i^{s}=E_i^{s} \; \forall \; i \in \mathbb{N} \)
- \( UNTIL \; No\_of\_Iter>n \; or \; There\_were\_changes:=\text{FALSE} \)

**Step 3**
- IF \( No\_of\_Iter>n \) THEN There is no solution. (There is a loop with positive value.)
- IF \( There\_were\_changes:=\text{FALSE} \) THEN we arrived to a feasible optimal time policy (All activity dates remained unchanged after two iterations.)

The rules of backward pass can be summarized as follows:

**Step 1**
- \( L_i^{i}= -\infty \) and \( OLD_L_i^{i}= -\infty \) \( \forall \; i \in \mathbb{N} \); Let \( L_i^{i=0} = E_i^{i=0} \) and \( OLD_L_i^{i=0} = L_i^{i=0} \); Let \( h=n \);

**Step 2**
- \( REPEAT \)
  - \( There\_were\_changes:=\text{FALSE}; \)
  - \( REPEAT \)
Select any \(i\) activity that has not been selected in this iteration yet
\[
L_i^S = \min \{ OLD_L_i^S; (L_i^S + t_{i-k} - z_{i-k} - t_{i-l} \land (P_{i-k},P_{i-l}) \in A^*) \}; L_i^F=L_i^S+d_i
\]
IF \(L_i^S > OLD_L_i^S\) THEN \(There\_were\_changes:=TRUE\)
\(h:=h-1\)
UNTIL \(h=0\)

Let \(OLD_L_i^S=L_i^S \land i \in N\)
UNTIL \(There\_were\_changes:=FALSE\)

Notes to the algorithm:
- Loop detection was done during the forward pass, so there is no need for that during the backward pass.
- Any order of activities can be used during the algorithm, which can largely modify the number of iterations. Here we used the ascending order of activities during the forward pass and the descending order during the backward pass. In the optimal case, the first iteration presents the results and the second iteration will validate this, in the pessimistic case, \(n+1\) iterations are necessary.
- Following the optimal order of the forward pass will be the worst during the backward pass, and vice versa.

4 SAMPLE PROJECT

4.1 Sample project: only minimal lags are allowed

A small sample project is shown in Fig. 4 a) consisting only of relations with minimal lags. Results can be seen in Figure 4b), calculations can be tracked below.

Forward pass:
Only activity A can be selected. \(E_A^S=0\); \(E_A^F=E_A^S+d_A=0+6=6\)
Only activity B can be selected. \(E_B^S = \{(E_A^S + t_A^A + Z_A^A - t_B^B)\} = \{(0+3+0-0)\} = 3\); \(E_B^F=E_B^S+d_B=3+6=9\)
Only activity C can be selected. \(E_C^S=max\{(E_A^S + t_A^A + Z_A^A - t_C^C);(E_B^S + t_B^B + Z_B^B - t_C^C)\} = \{(0+6+4-0);(3+2+2-0)\} = 10\); \(E_C^F=E_C^S+d_C=15\)
Only activity D can be selected. \(E_D^S=max\{(E_B^S + t_B^B + Z_B^B - t_D^D);(E_C^S + t_C^C + Z_C^C - t_D^D);(E_C^S + t_C^C + Z_C^C - t_D^D)\} = \{(3+6+3-0);(10+3+0-0);(10+4+0-1);(10+5+0-2)\} = \{12;13;13;13\} = 13\);
\(E_D^F=E_D^S+d_D=17\)

Early dates for all activities have been calculated, the forward pass is finished. (See Fig. 4)
Figure 4a) Sample project with minimal lags.  
Figure 4b) Results of the calculations.

Backward pass:

Only activity D can be selected. \( L_D^F = 17; L_D^S = L_D^F - d^D = 17 - 4 = 13 \)

Only activity C can be selected. \( L_C^S = \min((L_D^S + t^D_2 - z_{C0}^D - t^C_0); (L_C^S + t^C_1 - z_{C1}^D - t^C_1); (L_D^S + t^D_0 - z_{C3}^D - t^C_3)) = \min((13 + 2 - 0 - 5); (13 + 1 - 0 - 4); (13 + 0 - 0 - 3)) = \min((10; 10; 10)) = 10 \)

\( L_C^F = L_C^S + d^C = 10 + 5 = 15 \)

Only activity B can be selected. \( L_B^S = \min((L_D^S + t^D_0 - z_{B0}^D - t^B_0); (L_C^S + t^C_0 - z_{B2}^C - t^B_2)) = \min((13 + 0 - 3 - 6); (10 + 0 - 2 - 2)) = \min((4; 6)) = 4 \)

\( L_B^F = L_B^S + d^B = 4 + 6 = 10 \)

Only activity A can be selected. \( L_A^S = \min((L_B^S + t^B_0 - z_{A3}^B - t^A_3); (L_C^S + t^C_0 - z_{A6}^C - t^A_6)) = \min((4 + 0 - 3); (10 + 0 - 4 - 6)) = \min((1; 0)) = 0 \)

\( L_A^F = L_A^S + d^A = 0 + 6 = 6 \)

Late dates for all activities have been calculated, the backward pass is finished. (See Fig. 4)

4.2 Sample project: both minimal and maximal lags are allowed

A small sample project is shown on Fig. 5a) consisting of relations with minimal and maximal lags. The network with the transformed maximal relation and with the results is shown in Fig. 5b). Due to the transformation loop, the iterative algorithm has to be used.

Any order of the activities can be used. Here we use the A;B;D;C order for the forward pass. The calculations can be followed in Figure 6. Boxes of those activities that have been changed during the iteration are filled with grey.

Iteration #1

\( E_A^S = \max \{ \text{OLD}_E^A_s \} = 0; E_A^F = E_A^S + d^A = 0 + 6 = 6 \)

\( E_B^S = \max(\text{OLD}_E^B_s; (E_A^S + t^A_3 + z_{A3}^B - t^B_0); (E_C^S + t^C_0 + z_{C0}^B - t^B_2)) = \{-\infty; (0 + 3 + 0 - 0); (\infty + 0 - 2 - 2)\} = 3 \)

\( E_B^F = E_B^S + d^B = 9 \)

\( E_D^S = \max(\text{OLD}_E^D_s; (E_A^S + t^A_0 + t^B_6 + z_{B0}^D - t^B_0); (E_C^S + t^C_0 + z_{C0}^B - t^B_2); (E_A^S + t^A_6 + z_{A0}^B + t^B_0); (E_C^S + t^C_0 + z_{C0}^B - t^B_2); (E_A^S + t^A_7 + z_{A0}^B - t^B_0)) = \{-\infty; (3 + 6 + 3 - 0); (-\infty + 3 + 0 - 0); (-\infty + 4 + 0 - 1); (-\infty + 5 + 0 - 2)\} = 12 \)

\( E_B^F = E_B^S + d^D = 16 \)

\( E_C^S = \max(\text{OLD}_E^C_s; (E_B^S + t^B_0 + z_{B0}^C - t^C_0); (E_A^S + t^A_3 + z_{A0}^C - t^C_0)) = \{-\infty; (3 + 2 + 2 - 0); (0 + 6 + 4 - 0)\} = 10 \)

\( E_C^F = E_C^S + d^C = 15 \)

Figure 5a) Sample project with mixed lags.  
Figure 5b) Transformed network with the results
Iteration #2

\[ E^A_S = \max \{\text{OLD}_E E^A_s\}; E^A_F = E^A_S + \Delta T = 0 + 6 = 6 \]

\[ E^B_S = \max(\text{OLD}_E E^B_S; (E^B_S + t^A_S + z^B_S)t^A_S; (E^C_S + t^C_S + z^C_S)t^C_S) = \{3; (6 + 0 - 0); (10 + 0 - 2 - 2)\} = 6 \]

\[ E^B_F = E^B_S + d^B = 12 \]

\[ E^D_S = \max(\text{OLD}_E E^D_S; (E^B_S + t^A_S + z^B_S)t^A_S; (E^C_S + t^C_S + z^C_S)t^C_S) = \{12; (6 + 6 + 3 - 0); (10 + 3 - 0); (10 + 4 - 0); (10 + 5 - 0)\} = 15 \]

\[ E^D_F = E^D_S + \Delta T = 19 \]

\[ E^C_S = \max(\text{OLD}_E E^C_S; (E^B_S + t^A_S + z^B_S)t^A_S; (E^C_S + t^C_S + z^C_S)t^C_S) = \{10; (6 + 2 - 0); (6 + 4 - 0)\} = 10 \]

\[ E^C_F = E^C_S + d^C = 15 \]

### Initial State

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<table>
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<tr>
<td>3</td>
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### End of iteration #1

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<td>F; S; 4</td>
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### End of iteration #2

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### End of iteration #3

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<tr>
<td>10</td>
<td>15</td>
<td>F; S; 4</td>
</tr>
<tr>
<td>3</td>
<td>S; 0</td>
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</table>

No activity dates have changed in the course of iteration #3; therefore the forward pass is finished. For the backward pass the D; B; C; A sequence is selected. Calculations can be followed below.

### Iteration #1

\[ L^D_S = \min(\text{OLD}_L L^D_S); (\text{nil}) = 15; \quad L^D_F = L^D_S + \Delta T = 19 \]

\[ L^B_S = \min(\text{OLD}_L L^B_S; (L^D_S + t^D_0 + z^B_S + t^B_0); (L^C_S + t^C_0 + z^C_S + t^C_0)) = \text{min}(\infty; (15 + 0 - 3 - 6); (\infty + 0 - 2 - 2)) = 6 \]

\[ L^B_F = L^B_S + t^B = 12 \]

\[ L^C_S = \min(\text{OLD}_L L^C_S; (L^B_S + t^B_0 + z^C_S + t^C_0); (L^D_S + t^D_0 + z^C_S + t^C_0); (L^D_S + t^D_0 + z^D_0 + t^D_3); (L^D_S + t^D_0 + z^D_0 + t^D_3); (L^D_S + t^D_0 + z^D_0 + t^D_3)) = \text{min}(\infty; (6 + 2 - 2 - 2); (15 + 0 - 0 - 3); (15 + 1 - 0 - 4); (15 + 2 - 0 - 5)) = 10 \]

\[ L^C_F = L^C_S + t^C = 15 \]

\[ L^A_S = \min(\text{OLD}_L L^A_S; (L^C_S + t^C_0 + z^A_S + t^A_0); (L^B_S + t^B_0 + z^A_S + t^A_0)) = \text{min}(\infty; (10 + 0 - 4 - 6); (6 + 0 - 0 - 3)) = 0 \]

\[ L^A_F = L^A_S + t^A = 6 \]
Activity dates have not changed during the iteration. Calculations are finished. Results of the backward pass (and the forward’s as well) can be seen in Fig. 5b.

5 DISCUSSIONS AND FURTHER RESEARCH

A new ‘super’ precedence relationship based on the results of Francis & Mireco and Kim has been discussed in the paper. It has been shown that the traditional precedence relations (SS, SF, FS and FF with either minimal or maximal lags) could be derived from the new relation. It has also been shown that different results of parallel works e.g. bee-line relations can also be derived from this new ‘super’ relation; therefore claiming these results as a new technique is a wrong approach. This new relation forms a connection between two arbitrary points of two activities; therefore the name point-to-point relation fully describes the nature of this new relation. Following this logic, the traditional precedence relations, which could be called endpoint relations, form a subset of point-to-point relations as they connect the endpoints of the activities. Point-to-point relations affect the very fundamentals of network techniques, therefore all definitions, generalizations, problems based on the ‘old’ precedence relations must be checked and modified accordingly, if necessary, including the definitions and calculations of floats, the definition of the critical path, the classification of critical activities (Weist 1981) (Hajdu 1996) (Walls & Lino 2001), the algorithms for resource optimization etc. To our best knowledge, this work has not been done yet.

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INVESTIGATING THE BARRIERS AND POTENTIALS OF APPLYING LEAN PRINCIPLES IN THE EGYPTIAN CONSTRUCTION INDUSTRY: AN ACTION RESEARCH APPROACH FOR APPLYING VALUE STREAM MAPPING

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Abstract: Lean construction principles are not yet well known to the Egyptian construction industry. Introducing lean principles is often reported to be faced with considerable resistance to change. In this research, the authors follow the action research methodology to apply some lean construction tools on an ongoing construction operation in Giza, Egypt. The operation at hand is the manufacturing and installation of steel fences and gates in a new residential complex. The operation involves material procurement, off-site manufacturing, off-site finishing, transportation, installation and on-site finishing activities. The investigated sample includes four steel workshops, two painting workshops, and an on-site installation crew. The lean construction tool applied is value stream mapping. The main challenges faced by this operation are customer’s demand fluctuation and a resisting craftsmen culture. The customer demand unforeseeable fluctuations (1) affect the subcontractors’ ability to order large quantities of materials from the suppliers with sufficient lead-time; (2) results in an unstable cash flow to the subcontractors; and (3) generates an unbalanced workload distribution among the on-site and off-site crews. The supervisors of the workshops and on-site crews attempted to adopt some operation plans that according to their experience is best suited for mass production. These plans incorporated many wastes and needed significant modifications to respond in time to the fluctuation of the customer’s demands. Hence, value stream mapping is investigated as a possible solution to the aforementioned challenges. The authors succeeded to change and improve the operations of some participants, cutting the response time to customer demands by half in some cases. However, the authors failed with other participants, mainly because the craftsmen and their supervisors showed a significant resistance to change their operations design. This paper describes the lean construction initiatives, their results, and the main barriers and potentials identified through this research project.

1 INTRODUCTION

Lean construction seeks to maximize the generation of customer value by driving out all forms of waste, ensuring ‘right first time’ quality, reducing timescales and minimizing cost (Koskela 2004). Lean thinking offers an alternative method of project management to the construction industry. Lean construction is more efficient on complex projects with high uncertainties as well as fast track projects. There are several differences between the lean construction management approach and traditional project management. Following are some of these differences (Sicat 2012):

- The role of control in lean construction is to maintain a reliable flow, in contrary to the traditional after-the-fact variance detection,
Lean management focuses on the whole process to maximize value rather than optimizing each activity in isolation,

- Lean construction utilizes a pull planning approach, and
- Lean construction focuses on reducing variations at an early stage.

A key principle of lean thinking is the identification and systematic elimination of process waste at every stage of the value chain (Koskela 2004). Generally, the work done in any process to provide a product or service is classified as one of three activity types: (1) value adding; (2) essential but non-value adding, which is only needed because of current practice constraints; and (3) non-value adding, which is pure waste and should be eliminated immediately.

To identify the level and type of waste within a process, eight categories of waste can be defined, as follows (Koskela 2004):

1. **Transportation**, unnecessary movement and handling of goods,
2. **Inventory**, poor planning and control of inventory leading to excessive stocks,
3. **Motion**, excessive or unnecessary movement of people, and poor layout of tools,
4. **Waiting**, idle resources (people and/or plant) waiting for information or other resources,
5. **Over-production**, producing more than is required and/or ahead of time,
6. **Over-processing**, double handling of items, materials, etc.,
7. **Defects**, non-'right first time' quality requiring rework, and introducing extra time, and
8. **Skill misuse**, wasting or not effectively tapping into available skills, expertise, and knowledge.

Lean construction principles and applications are new to the Egyptian construction industry. A recent survey conducted in Egypt showed a current lack of awareness of lean construction, where 55% of the respondents are almost not aware of lean construction and 40% were at best only moderately aware (Gamal 2013). On the other hand, there is a great potential for adopting lean principles, where 55% of the respondents reported high potentials to use new management techniques.

Value stream mapping (VSM) is one of the essential lean practices, which has resulted in significant improvements in the manufacturing, military, and healthcare sectors, and has recently attracted interest in the software engineering community (Khurum 2014). VSM visualizes the entire production process throughout the enterprise. It represents both the materials and information flows. As defined by Rother (1999), value stream is the collection of all the activities required to bring a group of products through the main flow from raw materials to the end user. Furthermore, VSM enables documenting the relations between the activities and controls.

There are a number of reported attempts to leverage value stream mapping to improve construction processes. For instance, Roberto Arbulu et al. (2003) presented a case study within which VSM was used to re-engineer the construction supply chain for pipe supports used in power plants. Haitao Yu et al. (2009) developed a systematic approach that is based on VSM to analyze and formulate a lean production model for the home building industry. Chein-Ho Ko, and Shun-Chi Li (2014) used VSM to enhance submittal reviews for public construction projects by proposing a pull system instead of the traditional push system. Rosenbaum et al. (2014) used VSM to simultaneously assess production and environmental wastes over the execution stage of construction projects, and presented a case study of a reinforced concrete hospital in order to improve its production and environmental performance. Banawi and Belic (2014) used VSM as part of their delay analysis framework, in order to improve exterior construction processes. They applied their model to a case study of 53 residential units. Frandson et al. (2012) used VSM as one of the documentation tools in their study to analyze the workflow of complex projects.

In this paper, we attempt to use VSM to model and improve a number of processes in steel and painting workshops for manufacturing and painting steel products, including metal fences and gates. The studied construction operation involves material procurement, off-site manufacturing, off-site finishing, transportation, and on-site installation and finishing activities. The motivation to apply VSM to this operation was the reported long response times to the customer needs. Due the nature of the case study project, the customer demand was unpredictable and fluctuating. This unpredictable demand affected the
subcontractors’ ability to order large quantities of materials from the suppliers with sufficient lead-time, while the subcontractor’s mass production approach required large batches of materials to reduce the products unit costs. The demand fluctuations also resulted in an unstable cash flow to the subcontractor and generated an unbalanced workload distribution among the on-site and off-site crews. The following section describes the adopted research methodology to address this challenge.

2 RESEARCH METHODOLOGY

The studied project in this paper is a residential compound developed in Giza, Egypt. This paper focuses on the operation of manufacturing and painting steel products, which include side chain linked fence panels, back fence panels, and metal gates. The subcontractor responsible for this operation is Rawasy. The objective of this study is to propose and implement operational improvements that would reduce the subcontractor’s response time to meet the developer’s needs.

In order to achieve this objective, this research project adopted a four-phased action research methodology, which starts by developing a current state VSM for these processes that depicts the supply of raw materials, manufacturing processes in steel workshops, painting processes in painting workshops, and assembly on site. Second, the wastes within these processes are identified, and the process performance in terms of response time, cycle time, and inventory is reported. Third, a future state VSM is proposed and applied in order to eliminate processes wastes. Finally, the research findings are analyzed and discussed.

Table 1 shows the components and symbols of the VSM models developed to analyze this operation. The following subsections present the developed current and future state maps.

3 CURRENT STATE VSM

The objective of the current state VSM is to represent the actual state of the studied operation. This includes identifying and assessing the constituent processes/task, inventories between these tasks, crews and equipment, raw and manufactured materials transportation, and information flows. As shown in Figure 1, the current state VSM represents three lines of production, which are required to produce three product families; fencing side chain linked panels, fencing back panels, and pairs of steel gates. The production of each product family is sequentially conducted at three sites; the steel workshops, painting workshops, and on-site assembly locations. The production is distributed among four steel workshops, two painting workshops, and one on-site assembly team. Further, there are four suppliers and vendors providing the needed materials to the workshops and the on-site team. These materials include steel, wire mesh, accessories, and painting materials.

The customer sends monthly installation schedules to the subcontractor, who in turn uses these schedules to determine the required response time to meet the client’s needs. Accordingly, the subcontractor translates those schedules into weekly manufacturing schedules to the suppliers, workshops, and on-site assembly team. The steel workshops start the operation by conducting the three tasks of cutting, assembling, and mesh finishing, as shown in Figure 1.

These products are then shipped to the painting workshops, which conduct five tasks, including stocking, sanding, first coat application, second coat application, and wrapping. The finished products are then shipped to the work site for installation, finishing, and inspection. The current state map shows the cycle times of each task and the inventory durations as well as the response time as the key performance indicator for each of the three product families. For example, the batch size for the side chain linked panels (the first product family) is 100 panels and manufacturing response time is 8.1 working days. These achieved response times could not meet the customer’s needs. Accordingly, process improvements were required to the current state (for instance, as represented by the two Kaizen Bursts in the first product family). The proposed and implemented improvements are reported in the following subsection; the future state VSM.
Table 1: VSM Operation Components and Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td><img src="image" alt="Customer/Supplier Icon" /></td>
<td>Customer/Supplier icon: The customer for this operation is the developer of the residential compound. Suppliers are the steel suppliers, wire mesh vendors, steel accessories vendor and paint vendor.</td>
</tr>
<tr>
<td><img src="image" alt="Dedicated Process Icon" /></td>
<td>Dedicated Process flow Icon: Represents a process/task conducted by (Rawasy) with a continuous, internal fixed flow.</td>
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<tr>
<td><img src="image" alt="Work Cell Icon" /></td>
<td>Work cell Icon: indicates that multiple processes are integrated in a manufacturing work cell.</td>
</tr>
<tr>
<td><img src="image" alt="Inventory Icon" /></td>
<td>Inventory Icons: Represents inventory between two processes/tasks.</td>
</tr>
<tr>
<td><img src="image" alt="Shipment Icon" /></td>
<td>Shipments Icon: Represents movement of raw materials from suppliers to the receiving dock/s of the subcontractor workshops, or the movement of finished goods from the shipping dock/s of the workshops to the customer.</td>
</tr>
<tr>
<td><img src="image" alt="Connector Icon" /></td>
<td>Connector: Represents non-electronic information a flow.</td>
</tr>
<tr>
<td><img src="image" alt="Push Arrow Icon" /></td>
<td>Push Arrow Icon: Represents the “pushing” of material from one process to the next.</td>
</tr>
<tr>
<td><img src="image" alt="Spark Connector Icon" /></td>
<td>Spark Connector: Electronic information flow</td>
</tr>
<tr>
<td><img src="image" alt="Supermarket Icon" /></td>
<td>Supermarket Icon: an inventory “supermarket” (Kanban stock point)</td>
</tr>
<tr>
<td><img src="image" alt="Material Pull Icon" /></td>
<td>Material Pull Icon: Supermarkets connect to downstream processes with this “Pull” icon that indicates physical removal.</td>
</tr>
<tr>
<td><img src="image" alt="Kaizen Burst Icon" /></td>
<td>Kaizen Burst Icon: Highlight improvement needs and planned kaizen workshops for specific processes that are critical to achieving the operation Future State Map.</td>
</tr>
<tr>
<td><img src="image" alt="Timeline Icon" /></td>
<td>Timeline Icon: Shows the value added times (cycle times) and non-value added (wait) times.</td>
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</table>
Figure 1: Current State VSM
4 FUTURE STATE VSM

The use of value stream mapping enables visualizing the materials and information flows and identifying sources of wastes. Accordingly, a series of process improvements were proposed and implemented in the three product families, as shown in the future state VSM in Figure 2. The developed future state VSM was proposed to half of the workshops (i.e. two steel workshops and one paint workshop), whereas the remaining workshops continued to adopt the current state VSM. All the changes in the manufacturing process were implemented and tested in two consecutive batches in these workshops.

For space considerations, this subsection will discuss the details of the improvements implemented for the side chain linked panel (the first product family), whereas the improvements in all product families are demonstrated in the future state VSM in Figure 2. For improving the response time for producing the side chain linked panel, five improvements were made based on analyzing the shortcomings of the current state VSM, as follows:

- Decrease the batch size of the side panels from 100 to 35 panels,
- Combine assembly and mesh production processes in the steel workshops into one work cell,
- Combine the stocking and sanding processes in the painting workshops into one work cell,
- Combine the two coating processes in the painting workshops into one work cell, and
- Eliminate the wrapping process in the painting workshops.

Current processes adopt a mass production approach characterized by production wastes, such as large work-in-progress inventories, which in turn result in long response times. The first change is designed to gradually move from the current mass production approach as close as possible to a one-piece flow approach in order to minimize the production wastes associated with mass production. To this end, the production batch size was reduced from 100 panels to 35 panels, which is the minimum batch size that assures no waste in both material and transportation.

In the current state, each process in the steel workshop used to process the 100 panels before moving them all to the following process, which delayed the production and created large in-process inventories. In the improved future state, the assembly and mesh production are combined into a single work cell, eliminating their in-process inventory. Further, a pull system is implemented between the processes in the steel workshop (as indicated in Figure 2), where each processed panel is moved right away to next process to minimize the lead time and in-process inventories. These modifications decrease the inventory time and inventory amount significantly, where the inventory was reduced from 5 days for entire 100 panels to 2.9 days for only 35 panels.

Similar improvements were implemented in the painting workshop, where the first four processes are combined into two work cells, as shown in the future state VSM, eliminating in-process inventories. A supermarket pull system was also introduced between these two work cells with an 80% threshold. Furthermore, the wrapping activity was removed, because it added no value to the customer. These changes decreased the inventory time and amount in the painting workshops from 3.1 days per 100 panels to 1.2 days per 35 panels with almost no additional cost.
Figure 2: Future State VSM
5 DISCUSSION

In this study, the response time corresponds to the lead-time of producing a batch of the fence panels and gates. As shown in Figure 3, the abovementioned improvements resulted in reducing the response time by about 50% in the three product families, as follows:

- The side panels: The response time decreased from 8.1 days to 3.9 days,
- The back panels: The response time decreased from 7.1 days to 3.6 days, and
- The gates: The response time decreased from 7.1 days to 3.7 days.

The reported improved performance was achieved in one steel workshop and one painting workshop. However, the other steel workshop showed significant resistance to change as will be discussed in this section. The following paragraphs discuss (1) success factors; (2) observed barriers; and (3) reported impacts on other metrics.

First, based on the researchers’ observations, there were three main factors of success; (1) setting clear goals and cascading them throughout the subcontractor’s organization and to the workshops; (2) the willingness of the crews to accept change, which represents a learning culture; and (3) the nature of proposed changes, which was characterized by their low cost and no need for advanced technologies. Regarding the first factor, in the case study at hand, it was clear to the subcontractor’s management that reducing the response time is a top priority. Accordingly, various processes needed to be changed to fit this organizational goal, as discussed in the previous section. As for the second factor, the two workshops that successfully adopted the proposed improvements were both characterized by a very skillful foreman and a crew of semi-skilled young workers, who showed complete obedience to their supervisor. For these two crews, the changes in the processes were designed and verified with their foremen’s aid and consultancy, and the changes were then implemented with minimal resistance from the workers. Third, the proposed process improvements did not come at a noticeable cost and did not need the use of advance technology. This is an important aspect to facilitate the adoption of such changes in a relatively primitive and cost-conservative working environment.

The main observed barrier to implementing the proposed improvements was a culture of resistance to change, as experienced with the other steel workshop. It is noteworthy that the resisting crew is the one with the most skilled workers, which might explain why they showed the least cooperation and the most resistance to any change in their usual processes, especially that these changes were proposed from an outsider to the crew.
The implemented process improvements affected two other metrics; the products quality and manufacturing time per piece. First, the products quality generally improved. For instance, in the traditional mass production approach, defects might not be detected until a complete batch of 100 panels is produced. In the proposed approach, defects are identified and addressed early in the value stream. On the other hand, the manufacturing time per piece (unit lead-time) showed an increase by an average of 27% in the proposed approach, as follows (and as shown by Figure 4):

- Regarding the side panels: manufacturing time per piece increased from .65 hours to .89 hours,
- Regarding the back panels: manufacturing time per piece increased from .57 hours to .8 hours, and
- Regarding the gates: manufacturing time per piece increased from 5.7 hours to 5.9 hours.

![Figure 4. Manufacturing time per piece before and after the changes](image)

From the management perspective, the increase in the overall production time is an acceptable cost to the decrease in the response time in the operation at hand. This increase might be attributed to the learning curve effect, where the modified processes were only tested on two consecutive batches.

6 CONCLUSIONS

This paper presented an action research project, which involved designing, implementing, and testing an improved construction operation process using value stream mapping. The studied operation involved the production of three product families of fence panels and metal gates. A current state VSM was first developed based on actual observations. Second, sources of waste were identified and process improvements were proposed. Third, a future state VSM was developed to encompass and implement these changes. Fourth, the improved processes were evaluated. This research project represents the first attempt to apply value stream mapping to the Egyptian construction industry.

The results showed the superior performance of the improved process in terms of response time to customer's needs (which is the main target of this research) and the products quality. On the other hand, the manufacturing time per piece showed an increase, especially in the fence panels production. It was observed that with a clear delineation of organizational goals and discussing them in a respectable and involving manner to the working crews, a valuable enhancement is achieved to the whole operation and to the relations among its members. It is noteworthy that most of the value added is achieved through the use of the most simple and inexpensive changes. However, a resisting culture to change remains a main barrier to such improvements.

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EXPLORING THE BEHAVIORAL PATTERN OF STAKEHOLDERS IN CONSTRUCTION PROJECTS WHICH USED BEST-VALUE SELECTION

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Abstract: Best-value is a procurement method that combine price and non-price factors when selecting a contractor or design-builder. While, several researchers have evaluated the impact of best-value selection on project outcomes—such as cost, schedule, and quality—there are a limited number of studies that qualitatively evaluate the experience of different parties on projects that have been procured through best-value. To address this knowledge gap, this study aims to explore project stakeholders’ experience, team interactions, and behavioral patterns during best-value project execution. To achieve these objectives, three healthcare-construction case studies were selected and in-depth phone interviews were conducted with representatives of owners and contractors. The interviews were transcribed and a content analysis was implemented to explore the relationship between the procurement method and the team’s behavior in those projects. Three themes of team behavior emerged from the study, including innovation, partnering, and problem solving. The results of the interviews indicate that best-value selection encourages innovation, enhances partnering, and facilitates problem solving. The results also demonstrate that the time required to go through contractor selection and project scope development are major challenges of projects procured using best-value selection. To achieve successful completion of a project, one should: provide early project planning that includes clear definition of each party’s responsibilities; provide proper training; involve end users; and provide proper details in request-for-proposals. This research makes a cross comparison between the findings of this study and the existing literature related to best-value. The results of the study provide new insights regarding the team-building process through best-value selection. Furthermore, this study provides a basis for future data collection and quantitative analysis to compare various procurement methods and provides a foundation for exploring team integration in construction projects.

1 INTRODUCTION

One of the major decisions that an owner should take in the process of acquiring a new capital facility is to choose an appropriate procurement method. Traditionally, low-bid selection has been favored by public owners as a standard method for procuring construction projects as a means for efficiency, transparency, and corruption prevention (Boukendour and Hughes 2014). However, low-priced products or services can fall short of owners’ expectations and may cause adverse relations between client and contractor as well as low profitability for the contractor (Yu and Wang 2012, Horstman 2013). Owners in both the public and private sectors can choose best-value procurement and introduce non-price procurement factors that may negate the shortcomings of low-bid procurement. (Yu et al. 2013).
Best-value is a procurement approach aimed at getting the highest value and customer satisfaction for the lowest price. A review of best-value procurement practices for design-build transportation projects revealed that the approach demonstrates flexibility for owners since it allows for the consideration of factors that are specific to each project (Gransberg et al. 1999; Scott et al. 2006). The best-value approach deviates from traditional procurement methods by using other key factors such as past performance, relevant experience, and quality management plans as well as bid price in the contractor evaluation and selection. In addition, researchers observed that projects procured using the best-value approach consistently satisfied owner’s expectations regarding price and quality. The best-value system is viewed as a balance between the consideration of price and qualifications. Abdelrahman et al. (2008) showed that best-value is useful for the owner and the project due to the reduction in cost growth from 5.7% to 2.5% and a reduction in claims and litigation by 86%. Best value motivates stakeholders to choose this procurement method since it has the potential to eliminate waste, drive better and safer projects, improve quality, emphasize value for money, increase time savings, and lower life-cycle project cost.

Although previous studies indicated that best-value selection can provide significant benefits for some projects in terms of cost, time, and quality, there is no study that specifically seeks to understand the details of what happens during the project, specifically in terms of interactions among team members. To address this knowledge gap, the purpose of this qualitative study was to explore the behavioral changes of stakeholders in best-value projects in the U.S. construction industry. The main research questions of the study were: How does best-value procurement influence stakeholder behavior in the design and construction industry? What challenges have owners/designers-builders/contractors faced through the best-value process? What steps can be taken to improve best-value implementation in construction industry? What did the stakeholders learn from being involved in a project procured using best-value? By addressing these questions, this study will help practitioners and researchers to explore team behavior in best-value projects. The following sections elaborate on this research’s methods, analyses, and conclusions.

2 RESEARCH METHODOLOGY

2.1 Qualitative Method

To achieve the objectives of this study, we needed to hear the stakeholders’ voices about best-value’s impact on the behavioral pattern and collaborative interactions. To obtain a nuanced and detailed understanding of the issue, we chose a qualitative approach and case study as the main research methodology. The qualitative approach attempts to make sense of, or interpret, phenomena in terms of the meanings people bring to them (Denzin and Lincoln 2011). In addition, conducting a case study provides a suitable qualitative technique for this study because it helps to answer “how” questions and to capture the details of particular groups in a real-life context (Yin 2013).

To select cases and gain access to reliable sources, we used a large project delivery database developed by the Construction Industry Institute (CII) and the Charles Pankow Foundation (CPF). This database includes projects’ data from more than 200 building projects from across United States; such data were collected from a request to more than 8500 project managers in the past two years. To limit the scope of the study, we decided to focus on healthcare facilities because hospitals were some of the more challenging projects in the database to design and construct (Franz 2014). Here, we define healthcare facilities as hospitals, clinics, medical offices, and nursing homes. Purposeful sampling was used to select three healthcare projects that were procured using best-value selection. We then implemented a multi-case design in this research, within which we conducted case studies on three different projects. The process and criteria to select these projects were important since the participants needed to be knowledgeable about or have enough experience regarding the central phenomenon (Creswell and Plano Clark 2011). With these considerations in mind, the selected healthcare projects were chosen based on delivery method, project type, owner type, procurement, and team chemistry—Table 1.
Table 1. Overview of Case Projects and the Participants of the Interviews

<table>
<thead>
<tr>
<th>ID</th>
<th>Project Detail</th>
<th>Approx. Size (sq ft)</th>
<th>Delivery Method*</th>
<th>Procurement **</th>
<th>Builder Involvement</th>
<th>Cost Growth (%)</th>
<th>Schedule Growth (%)</th>
<th>Participant’s ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hospital</td>
<td>~500,000</td>
<td>DB</td>
<td>2 RFP</td>
<td>Conceptual Design</td>
<td>14.5</td>
<td>-11.6</td>
<td>DB, O, End User</td>
</tr>
<tr>
<td>B</td>
<td>Medical Clinic Building</td>
<td>~30,000</td>
<td>DB</td>
<td>1 RFP</td>
<td>Pre-Design</td>
<td>-1.7</td>
<td>-4.8</td>
<td>DB, O</td>
</tr>
<tr>
<td>C</td>
<td>Hospital</td>
<td>~177,000</td>
<td>IPD</td>
<td>1 RFP</td>
<td>Pre-Design</td>
<td>0</td>
<td>-5.6</td>
<td>DB, O</td>
</tr>
</tbody>
</table>

* DB: design-build, IPD: integrated project delivery
** 1/2 RFP: one/two stage request for proposal
*** DB: design-builder, O: owner

To reach the most knowledgeable people in a project, we used an effective type of purposeful sampling called “Snowball Sampling.” In this method, participants or informants for whom contact information is available will be asked to use their social networks and refer the researcher to the most informative person who can contribute to the study (Bernard 2013, Palinkas et al. 2013). To enhance the validity of the study, data were collected from multiple cases. For each case study, at least one owner and one contractor representative were interviewed, which helped research team to collect and compare information from multiple sources (Yin 2013).

After finding the best contacts, phone interviews were formulated according to five distinct sections: (1) a brief summary of research background, objectives, and research method; (2) a consent question for participation; (3) an opening questions to capture the participant’s perception of central phenomenon; (4) seven questions clustered around behavioral changes related to the best-value selection process; (5) five concluding questions to obtain best practices, challenges, and the interviewee’s lessons learned. There were two separate interview protocols for owners and for design-builders. Since the qualitative research is interpretative research (Creswell 2009), we made sure that all participants were acquainted with the topic; however the questions did not lead interviewees to a specific direction.

We conducted seven semi-structured interviews to gain insights from the experience of the project stakeholders in a best-value project. In total, 253 minutes worth of interviews were audio-recorded and transcribed. To protect the anonymity of the participants, projects’ name and interviewees’ personal information were coded. A comprehensive content analysis was then conducted on transcriptions using MAXQDA 11 software to identify and analyze preliminary themes and codes. More than 60 codes were defined in this process, most of which were “In-Vivo” quote and theory codes. Two independent coders analyzed the preliminary list of codes to remove redundant codes, combine similar codes, define new codes, and compare the codes with the current body of knowledge to maintain consistency. This iterative process led to defining three main themes related to behavioral pattern: innovation, partnering, problem solving; and two other themes including implementation challenges and best practices. In the next step each themes was analyzed in details to answer the research questions.

2.2 Validation and Reliability

Many perspectives exist regarding the methods of validation in qualitative approach. We consider “triangulation” as a valuable means of assessing the accuracy of the findings. In triangulation, researchers include corroborating evidence from various sources and methods to shed light on a perspective (Creswell 2013). To triangulate our interview results, we interviewed multiple stakeholders in each project and considered both the owner’s and the builder’s perspectives. Similarly, in qualitative research, “reliability” often refers to the stability of multiple coders’ responses in data sets (Creswell 2013). Our focus on reliability here was on inter-coder agreement. We used multiple coders to analyze transcript data separately. The list of codes and themes were developed in an iterative process.
3 FINDINGS

The qualitative analysis revealed that early involvement is one of the most important features when using a best-value approach as procurement method. Early involvement was found to have significant impacts on the behavioral patterns of the stakeholders. The construction industry is highly fragmented in part due to a lack of communication among designers and contractors. The traditional delivery practices—such as design-bid-build—also promote separation of design and construction processes. Such a separation hinders design and construction knowledge exchange; consequently, the potential for innovation will be reduced as contractors have no input for design decisions. To address these limitations and to integrate construction knowledge into the design process, many owners prefer to use integrated delivery systems that provide overlap between design and construction (Beard et al. 2001). Project delivery methods that use design-build or integrated project delivery, such as those in the three case studies, necessitate the use of best-value or qualifications-based procurement because the builder is hired before the design is done. These innovative systems are characterized by the involvement of contractors in early stages of projects. One of the participants mentioned:

The nature of these integrated delivery methods requires considering factors other than cost, because the selected constructor will be responsible for some sections of design. Therefore, to employ alternative delivery methods, owners need to purchase combined design and construction services through best-value rather than low-bid selections (Beard et al. 2001). In all case studies investigated here, project participants had some sort of early involvement; therefore, it became important to study the relationship between time of involvement and team behavior. In total, three themes were identified: (1) innovation; (2) partnering; and (3) problem solving. Moreover, other important information which were mentioned by stakeholders categorized in two groups including challenges and best practices. These themes and their related codes are discussed in more detail below.

3.1 Innovation

One of the important benefits of best-value selection noted in interviews is its ability to encourage innovation in a project. While, leadership and top management plays a critical role in creating an atmosphere of innovation in a project, it is important to pre-qualify team members and seek people who are enthusiastically looking for better solutions. One of the owner stated that relationships are far more important than a transactional contract in creating an atmosphere of innovation:

“[…] I learned that… tapping people’s intelligence is far better than holding them to a contractual [sic] terms and conditions. I learned that people, when challenged, will clearly step to the plate, and, and when they do that, and they innovate, that they have a much more satisfying life and, and job, […]”

As mentioned before, best-value selection is required with early involvement of various parties unless a purely qualifications-based selection is used. According to interviewees, the early involvement of project stakeholders can facilitate adoption of innovative ideas in many ways. First, in traditional procurement methods, contractors have to start a project with a project design that is almost complete; however, the design can have constructability issues and require contractors to request several change orders. In contrast, in best-value selection, because a small portion of design is frequently provided, the contractor has more control over design, and as a results, cost and schedule control become much easier. As one of the owner noted that:

“[…] successful offer came in with a three month improvement on the project schedule that was laid in the RFP; there was some scheduling innovation using building information modeling, […]”

In addition, early involvement of contractors in the design-phase and the selection of parties based on their safety performance provide opportunities to enhance safety using innovative ideas. One of the owner mentioned that:
“[…] one of the things that [early involvement] enabled was a fresh and frank discussion and dialogue on how project safety was going to be... treated. And that led to some innovative methods to work on project safety, and that of course all contributed through the relationships and the teamwork in that particularly important area for us contributed directly to the amazing project safety success, which again, don’t [work] if you copied it, but it was … over 2.7 million man hours of construction with zero loss time incidents. […]”

Including specialty contractors in the design process can also provide several benefits for the project. For example, Franz et al. (2013) conducted comparative case study analyses to investigate the impact of specialty mechanical-contractor design involvement in the healthcare industry. They found that increasing the involvement of mechanical contractors in design-phase can reduce cost growth, schedule growth, and safety incidents, and can improve the HVAC system performance. Our findings indicate that one of the benefits of engaging trade partners in the early stage of a project is to avoid re-work. The results of interviews supported this theory and indicated that including the trade partners can reduce the amount of rework in construction projects and can lead to cheaper, faster, and safer projects. For example, one of the design-builder stated that:

“[…] having the team involved, including the trade partners, and having the leaders that were going to manage the field operations involved in the design, we only drew things once. That was our goal to only draw things one time. […]”

Furthermore, utilizing best-value selection for hospitals provides a unique opportunity for owners to achieve higher quality. Flexibility in best-value selection allows owners to incorporate the latest technology in their facilities and to create a capability for tomorrow's growth. Such traits could further add to the value of the process.

### 3.2 Partnering

Partnering is an effective tool for improving the productivity of stakeholders, achieving cost effectiveness, providing opportunities for innovation, and decreasing confrontational interactions in construction projects (Wong and Cheung 2005). The role of partnering and trust-based relationships has become an important foundation in innovative delivery methods for achieving successful projects (Pena-Mora and Harpoth 2001). Some of the design-builders highlighted the importance of this long-term partnering in selecting teams in best-value selection:

“The team first was build based on prior positive experience working together. So … we assembled the team based on the fact that we have collectively worked together and been successful before… all decided to come together because we had previously been able to work together, and... make money together and deliver high quality work together.”

Building trust among various team members is necessary for establishing a long term and effective partnering relationship (Wong et al., 2005). The interviewees repeatedly mentioned that best-value selection enhanced trust among project teams; for example, one of the interviewee called the best-value project as “Nirvana, full of honesty.” Considering that trust is pivotal attitudinal point in a collaborative environment and that there is a positive relationship between partners’ trust levels and their partnering success (Wong and Cheung 2005), best-value selection can facilitate collaborative decision making in a project.

### 3.3 Problem Solving

It was found that people who were involved early in the project and selected based on criteria other than cost could offer alternative solutions for equivalent results that ultimately provided more values to the owner. Several other studies verify these findings (Mendelsohn 1997, Jergeas and Put 2001, and Arditi et al. 2002). Making major decisions early in the project provided more time for project stakeholders to make
decisions related to uncritical activities. Such flexibility in time provided confidence in the project team. For example, one of the design-builder stated that:

"[...] One example is... structural steel. Because we were involved early, and we were... having full visibility of the, the design process, we were able to have the confidence that the... basic layout of the building had been settled, and we could order structural steel, and be able to start structure early while still allowing for full time to design the interior, because we had confidence that the basic structural grid had been settled. That ultimately resulted in saving... it ultimately was 6 months overall for the project, but just the structural steel alone gained the project 2 months by being able to order earlier. [...]."

According to interviewees, best-value selection also allows team members to work together and discover their strength and weaknesses, this can have positive impact on problem solving. One of the design-builder mentioned that:

"[...] we worked for nine months together before we started actual construction. In those 9 months, we had opportunities to... have growing pains in our relationship. [...] when we got to the construction phase, we were able to build upon the lesson learned, the relationships, the problem solving that we did early on during the design phase, and, and... better problem solve later when the stakes were higher at the time of construction. [...]."

Some interviewees stated that when the team is formed early in a project, the hierarchy of authority becomes clearer from the beginning, which leads to easier problem solving. People in such a project were able to develop an understanding that they needed to solve problems without escalating them. Even when they had to raise an issue with the ultimate decision makers, they believed in the commitment of the decision maker to find the right solution. More importantly, when a decision was made, the team would accept it and move forward. Some interviewees named this phenomena as "trust between parties." One can infer that using early involvement jointly with best-value selection provides an opportunity to establish trust between parties and facilitate problem solving. Furthermore, interviewees consistently mentioned that early involvement can provide better team experience in a project. Such an experience can lead to higher commitment from team members to project goals.

3.4 Implementation Challenges

Best-value selection provides several benefits for both owners and contractors; however, there are some challenges in implementing this procurement method. While previous studies mentioned legal barriers in best-value implementation (Hilger 2009), the identified challenges through interviews provided unique perspective on potential barriers to successful implementation of best-value selection. For example, although the current literature portrays that the use of the best-value can reduce both time and cost growth (Scott et al. 2006), the findings of the interviews provided us with evidence that owners and contractors assume timing will be a challenge. One of the owner stated that they had a challenge to allocate enough time for the evaluation of proposals:

".... In the sense of the process it takes us to go through a best-value process, [it] takes a lot longer than if you just use cost. So for me, when I best-value a piece of equipment, I have to look at the, that equipment, plus all options to go along with that equipment, and I look at 3 or more different vendors. So in order to evaluate all of those vendors that provide me a quote for a piece of equipment, I have to go through each one of those and evaluate it..."

Another contractor said that in order to achieve best-value, they had to change a piece of the equipment. This change required them to go back out to several different vendors again and gain more information to achieve what they expected. Also, one of the representative of end user group stated that while this change impacted project time and cost, they could achieve long-term benefit:
“...it had a domino effect. Once we changed that piece of equipment, then it made major changes to the construction site. Best-value, for the next 50 years, […]”

Most of the participants stated that although selecting contractors based on best-value process can be time-consuming, the results paid off. In order to develop a better team and better partnering culture, and to get more value for the ultimate user, it was better for owners to take their time to select the right partner, and then to let the team self-form and develop a trust-based relationship. One of the owner noted that:

“... [it is believed that] The time required to go through the full best-value process, will result in a longer overall project time-line. This project proved that that is not always the case, and that the, the savings in time during execution often more than make up for... the extended procurement timeline up front.”

Another challenge in best-value procurement stems from a vague definition of parties’ responsibility, which can lead to higher expectations. For example, a contractor noted that the owner sometimes expected them to make the decision that gave the most value to the client without recognizing that even under best-value procurement, there are still ultimately some business decisions:

“[...] sometimes the owner expects that you’re going to… give them some scope for free, because… you promised that you were going to give them best-value.”

On the other hand, an owner stated that sometimes the contractor or design-builder do not have enough incentives to reduce project cost:

“[...] contractors or design builders... expect that because they were selected as best-value, that... there should never be any pressure on price. So that, ‘hey, you selected me because I was best-value, so now that... I need you to cover this cost, you should not complain because you already told me that you selected me ‘cause I was better than the competition.’”

In these cases, stakeholders need to adhere to their contract. One of the stakeholders suggested that providing a clear definition of each party’s responsibility would help to reduce relationship problems.

Another challenge in a project procured using best-value is related to scope development. Proper scope definition proved to be primary factor that impacts cost, time, quality, and relationship (Cho and Gibson 2001, Gransberg et al. 2006). The best-value procurement provides flexibility for owners to build a final product that provides highest value for them; however, the results of interviewees indicated that such flexibility can lead to scope creep. One should note that a design-build delivery method executed under best-value procurement can affect the project scope since the project criteria are usually identified in a broad, generalized manner rather than a narrow, specifically defined one. The detailed planning should be available in the request for proposal, since the chance for a portion of the proposal to not meet an owner’s objective is fairly high, resulting in either a change to the scope or a reduction in scope to meet the budget. In addition, the process of risk assessment during the pre-contract procurement phase can reveal programming flaws or incompatibilities, creating a change that could result in a bidding addendum prior to the award of the contract (Hilger 2009). One of the design-builder explained the difficulty of defining scope in a best-value project:

“Scope definition and expectations is probably one of the more significant challenges. You know, having the, the balance between properly defining the scope, while allowing true flexibility for the design builder. It’s … an intricate challenge. “

3.5 Best Practices

According to interviewees, to get the most benefits from best-value selection, there is a need for appropriate and early project planning that includes clear definition of each party’s responsibilities, authorities, and hierarchy structure. For example, the design-builder should have enough authority to
influence design decisions; alternatively, by developing an appropriate reward system from the beginning, contractors would have incentives to meet all required outcomes and even surpass owner’s expectations.

While best-value provides an environment for project team members to collaborate, there is a learning process for each team member who is participating in this process. Training is an essential tool for formally communicating changes in policies to a wider audience as part of project implementation. The process to deploy procedure and train staff should introduce the basic concept and procedure, and should provide open communication to further promote best-value implementation. Furthermore, staff turnover and loosing key personnel in the middle of a project highlights the importance of regular training to make sure that all parties remain committed to the project goals. One of the owner explained the training challenge related to team-participant turnover in the best-value project:

“...the challenge of keeping people from reverting back to their old traditional behaviors of, of silo and blame casting. And so there’s a, a constant need to educate and, and re-inform people of the commonality of the goals, regardless of the selection process. It’s, it’s the nature of the, of the construction process. So there’s new people constantly coming onto the team and others leaving, so there needs to be a constant educational process, so that all new participants understand the goals and the, and the methodology for the, for the delivery mentality.”

Some interviewees mentioned that one of the factors that enhances the chance of success in a project is to take users on tours and get their feedback. While this action has low cost, it increases integration of various parties in a project. These interviewees said the users and owner should not be considered on opposite sides of a war, and all affected stakeholders should be brought to consultation to achieve success throughout the project. Some other interviewees also suggested that it is a good idea to use best-value approach to choose subcontractors too.

In design-build projects, it is necessary to develop detailed documents after the procurement, but the detailed requirements and information should be provided with requests for proposals to clarify the owner’s expectations. Most of the interviewees emphasized that the best-value request for proposal (RFP) should be in a higher level of detail than what requesters normally provide. Such information would offer tremendous benefits. The combined detailed RFP, contract, and assurance lead to less control but more transparency in relationships. However, there is a challenge about balancing the amount of detail required while leaving enough room and authority for the design/builder to come in:

“...I would certainly have some dialogue with the new owner about, you know, what the right level is, and... trying to, to find that sweet spot if you will, between, not enough information which is going to lead to a longer design process, and too much information which is going to lead to... a designer that is constrained and therefore lacks full ownership of those design elements.”

In total, the themes, implementation challenges, and best practices found here resonate with findings of other studies. Previous studies found that the following factors significantly impact the degree of success achieved through the implementation of best-value (Anderson and Russell 2001): training, appropriateness of method for projects, communication, initial agreement, post-award agreement, integration of design, upper management support, a clear definition of the best-value criteria (both objective and subjective), a sound selection method for “trade-off” between cost and non-cost criteria, and an appropriate award algorithm to align selection method with best-value objectives. Our findings are consistent with the outcomes in other literature, thereby validating the concurrence between our qualitative investigation and the existing understanding of best-value procurement.

4 CONCLUSION

One of the owner’s early decisions that has a significant impact on project performance is selecting the procurement method. Traditionally, the public sector prefers low-bid selection; however, projects initiated based on the lowest price may not meet quality requirements or—more importantly—may lead to
adversarial relationships between stakeholders. Thus, some owners use procurement methods such as best-value selection. Several quantitative studies have been conducted to investigate the impact of best-value selection on project performance; however, the number of studies that explore the role of this selection process on team behavior during the project is limited. To address this knowledge gap, we studied best-value process using qualitative research technique. We purposefully selected three healthcare projects that used best-value as a procurement method and interviewed different stakeholders involved in the project. A rigorous content analysis was conducted on transcripts using two coders. The extracted three themes illustrated how best-value selection impacts on team behavior and performance.

The first theme showed that early involvement, considering the proper selection criteria, and maintaining flexibility—all of which are inherent in the best-value approach—enhanced innovation and creativity in projects. Since construction participants seem reluctant to innovate on their own, providing a collaborative environment helps develop trust among parties and facilitate innovation (Ozorhon 2013). The second theme focused on the impact of best-value selection on facilitating partnering. This finding is supported by previous literature, which noted that changing a challenging partnering relationship to an effective one requires building trust among team members, a process that is facilitated by best-value selection (Wong et al. 2005). The third theme is concerned with the impacts of the best-value on the problem solving process. Both the literature (Jergeas and Put 2001, and Arditi et al. 2002) and the interviews performed in this study indicate that the best-value approach due to early contractor involvement helps teams respond to problems quickly and avoid conflict escalation. The other group of codes landed on the challenges of implementing best-value selection—particularly in terms of time and role/responsibility definition—and last group of codes documented experts’ opinions about the best practices that inspire behavior improvements and the most benefits from the project procured using best-value. To summarize, this study provided evidence that best-value selection can indirectly enhance the performance of a project by bringing all parties together early and by facilitating collaborative problem solving. The unique contribution of this study is to help practitioners to understand how best-value selection helps project stakeholders to form high-performance teams based on the trust.

There are some limitations of this research that are worth noting. First, the researchers’ reflexivity might lead to bias in coding processes. To solve this issue, an unbiased coder can analyze the interviews and compare findings. Second, the projects were selected from successful cases and all of these cases involved early contractor involvement through design-build and integrated project delivery. No instances of design-bid-build projects that used best-value and performed poorly were studied; although the certainly exist. To address these limitations, further case studies should be conducted on projects with poor performance and later builder involvement. In spite of these limitations, the study provides a clear advancement in the body of knowledge.

For future phases of this study, the research team aims to conduct several semi-structured interviews on other project types to obtain a holistic view of the best-value selection impact on team behavior. The results will be used to develop a grounded theory to explain how high performance teams can be formed. It is also suggested to implement mixed methods analysis for comparing various procurement methods and provide a comprehensive guideline to establish an integrated team in a project.

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References

INVESTIGATING THE IMPACT OF DEFECTS ON KEY STAKEHOLDERS IN THE UK NEW HOUSING SECTOR

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Abstract: The UK house building sector is facing dual pressures to expand supply, along with delivering against tougher Building Regulations’ requirements, predominantly in the areas of sustainability. A review of current literature has highlighted that the pressures the UK house building industry is currently under may be having a negative impact on build quality, causing an increase in defects. A review and synthesis of the current defect literature with respect to new-build housing and the wider construction sector has found that the prevailing emphasis is limited to the classification, causes, pathology and statistical analysis of defects. There is thus a need to better understand the overall impact of individual defects on key stakeholders within the new-build housing defect detection and remediation process. As part of ongoing research to develop and verify a defect impact assessment rating system, this paper seeks to contribute to our understanding of the impact of individual defects from a key stakeholder perspective by undertaking the literature review and synthesis phase. The literature review identifies the three distinct, but interrelated, dominant impact factors: cost, disruption, and health and safety. By pulling the strands of defect literature together the theoretical lens and key stakeholder sampling strategy is formed as the basis for the subsequent impact weighting development phase.

1 INTRODUCTION

In the United Kingdom (UK) there is a substantial shortfall in the number of dwellings available (Wilcox & Perry 2013) amid claims that the UK requires an additional 240,000 homes per year to meet demand (e.g. Holmans 2013). In order to satisfy the demand the UK government has introduced a number of new-build focussed policies and incentives to increase the housing supply (HM Government 2011). For example, the Get Britain Building investment fund is designed to enable house builders to progress sites that have stalled, not started or are on hold (DCLG 2014a). The UK house building industry has responded to the increased demand and government incentives by significantly up-scaling supply, with a 23% increase in new housing starts for 2013 compared to 2012 volumes (DCLG 2014b). In addition to the pressure to increase housing supply, the UK house building industry is under a further pressure via the introduction of a target for all new houses to be 'zero carbon standard' (Zero Carbon Hub 2014) from 2016 (UK Government 2012). The zero carbon homes agenda has resulted in the introduction of tougher Building Regulations, for example, changes to part L 'Conservation of Fuel and Power' (DCLG 2013), which has resulted in the house building sector incorporating new technical solutions into new-build houses to achieve compliance (e.g. NHBC Foundation 2012).
A review of current literature has highlighted that the pressures the UK house building industry is currently under may be having a negative impact on build quality, causing an increase in defects (e.g. Hopkin et al. 2014). There is increasing evidence that the inclusion of new technologies can and does adversely impact new-home quality; both in the material sense of the home itself and in the well-being of occupants (e.g. Yao & Yu 2012, Gill et al. 2010). In much the same way, it has long been advocated that an increase in housing supply can reduce build quality. For example, tightened delivery dates cause materials and workforce capacity to become stretched, and site management becomes less stringent due to workload (e.g. Sommerville et al. 2004). This situation is worsening as the UK house building sector is currently reporting materials, skills and workforce shortages (e.g. HBS 2013, UKES 2012). Further evidence of the increase in the number of new housing defects is in the Home Builders Federation (HBF) survey results (HBF 2014), which show that in 2014, 92% of home owners reported defects within their new-build house, the first time there has been an increase since 2011.

This paper offers an insight to the impact of individual defects from a key stakeholder perspective by undertaking the literature review and synthesis phase from a wider project to develop and verify a defect impact assessment rating system.

2 DEFINITIONAL DEBATE ON DEFECTS

A synthesis of construction defect literature has highlighted a wealth of research into defects, ostensibly utilising a multitude of separate terms and categories to define defects, for example, defects (e.g. Atkinson 2002), snags (e.g. Craig 2007), faults (e.g. BRE 1990), failures (e.g. Porteous 1992) and non-compliance (e.g. Baiche et al. 2006).

A 'defect' is defined as a shortfall in performance occurring within the life of the product, element or dwelling (BRE 1988). More specifically, Watt (1999) defines a 'building defect' as a failure or inadequacy in the function, performance, legal or user requirements of a building, and can become apparent within the structure, fabric, services or other facilities of the building.

A 'failure' is defined as an unacceptable difference between expected and observed performance (Ahzahar et al. 2011). Porteous (1992) further defines a 'building failure' as a shortfall in the technical performance, to an extent that the user and impartial expert evaluator define the building as defective. Josephson and Hammarlund (1999) conclude a defect to be the failure to achieve intended usage requirements.

A 'fault' is described as an unacceptable departure from good practice set out in Building Regulations and other authoritative publications (BRE 1990). Ilozor et al. (2004) argue that a defect and a fault are one in the same.

A 'non-compliance', also known as 'non-conformance' (Abdul-Rahman 1995), is described to be a deviation from the design specification (Assaf et al. 1995). Baiche et al. (2006) infer a non-compliance to be simply a 'failure' to adhere to Building Regulations, or approved standards; a term Sommerville and McCosh (2006) define as 'regulatory defects'.

A 'snag' is argued by Sommerville and McCosh (2006) to be the same as 'errors' and 'defects' within a new house, whereas Atkinson (2002) argues 'errors' as a cause of 'defects'.

These terms appear to be used interchangeably to describe the same phenomenon, i.e. imperfections in buildings (defects), causing minimal difference in the approach or outcome, as discussed in section 3 below.

3 OUTPUT THEMES IN CURRENT CONSTRUCTION DEFECT RESEARCH

The extant literature, regardless of the chosen designation for defects, tends to adopt a similar position where it limits itself to the classification (e.g. Macarulla et al. 2013), causes (e.g. Josephson & Hammarlund 1999), pathology (e.g. Atkinson 2002), and statistical analysis (e.g. Sommerville & McCosh
defects. The construction defect literature can generally be grouped into three different defect-related output themes: those that produce general findings; those that differentiate between individual types of defects; and, those that introduce a level of importance to individual defects. Each theme is discussed below.

3.1 General findings

The defect scholarship tends to produce general findings in respect to the causes, pathology, and statistical factors of defects. For example, Sommerville and McCosh (2006) analyse the overall numbers of defects within new homes in the UK. Love et al. (1999) review the total remediation cost of defects as a percentage of the production cost of construction projects. Atkinson (2002) examines the responsibility for defects taking place on construction sites, in general. Josephson and Hammarlund (1999) explore the typical causes of defects in construction projects. Whilst the general findings can produce a useful insight into the current status of defects within the construction industry, it can be prone to assuming all defects have the same characteristics, causes and level of importance. The literature can also be susceptible to providing generic recommendations in respect to defect reduction, including: training for trades and better management on site (e.g. Sommerville & McCosh 2006). By differentiating between individual defects, the literature could provide more relevant tailored guidance to reduce individual defect types.

3.2 Individual types of defects

There is literature available that identifies and classifies individual types of defects. However, this identification tends to be through the frequency in which different defects are encountered over particular stages of a construction project. For example, Baiche et al. (2006) identify the most common Building Regulations contraventions taking place during construction, including radon protection, misplaced damp proof membranes and damp proof courses, and inadequate thermal insulation; Craig (2007) presents a list of prevalent 'snags' in UK new homes during the first two years post completion, including making good, paint, cleaning, plastering, mastic, fitting, doors, sealant, and grout; and, Mills et al. (2009) stress the most prominent sources of warranty claims in Australia including, slab foundations, strip foundations, roof leaks, shower base leaks, external water penetration, plumbing, shower cubicle leaks, drainage, pier and beam foundations, leaking windows. The defect classification literature provides valuable detail as to the most prevalent type of defects occurring within the construction industry. However, it does not identify a level of priority with regards to approaching targeted defect reduction. Bringing a level of priority to defects will help to guide this decision (e.g. Sommerville 2007).

3.3 Priority of individual defects

A small subset of the defect classification literature has started to introduce a level of priority to defects, albeit in respect of the process for remediating defects identified on a building survey. This level of priority tends to be based upon the current physical condition of the individual building element. de Oliveira Pedro et al. (2008) proffer a condition survey to identify the severity of the defects identified within a number of building elements, giving individual building elements a weighting coefficient based upon their perceived level of importance. Che-Ani et al. (2011), influenced by the RICS HomeBuyer survey, extend this logic to establish a priority for repairing individual defects, based on two contrasting input parameters: condition and repair priority (ranging from (1) cosmetic to (5) health and safety risk). The survey develops an overall score based upon the product of the contrasting input parameters, with the repair priority being displayed in a traffic light format. Whilst the building condition survey has brought a level of priority to the defect remediation process, it appears to be based around the individual surveyor's perception of importance and urgency. Sommerville (2007) argues that an approach of being able to establish the impact of individual defects will further develop the ability to determine whether individual defects are significant or not, and guide what should be focussed upon. There is, however, a dearth of literature seeking to understand the overall impact of individual defects.
4 THE IMPACT OF DEFECTS

A review of existing construction defect literature has identified a number of common aspects which have the potential to impact on a variety of stakeholders involved with construction projects, including: cost (e.g. Georgiou et al. 1999, Mills et al. 2009, Josephson & Hammarlund 1999, Love & Li 2000, Rosenfeld 2009), potential health and safety/regulatory non-compliance (e.g. Georgiou et al. 1999, Baiche et al. 2006, Ilozor et al. 2004, Love & Edwards 2004, Macarulla et al. 2013, Smith et al. 2013), and disruption (e.g. Davey et al. 2006, BEC 1991, Rosenfeld 2009, Sommerville et al. 2004). Each aspect is discussed below.

4.1 Cost implications

Existing research argues that defects in general have cost implications for the builder and warranty provider. For the builder defects are argued to reduce the amount of profit available from projects (e.g. Sommerville & McCosh 2006, Davey et al. 2006) while for the warranty provider defects are argued to cost vast sums of money to remedy (e.g. Mills et al. 2009). It is claimed that remediation of defects occurring during the construction stage and the defects liability period (first two years post completion) cost the builder on average between 2.3% and 9.4% of the production cost (e.g. Josephson & Hammarlund 1999, Love et al. 1999, Love & Li 2000). Outside of the construction and defects liability period, construction projects tend to be subject to warranty cover (e.g. Sommerville & McCosh 2006). The cost of defect remediation during the post completion warranty period in Australia (seven years post occupation) is argued to be circa 4% of the contract value (e.g. Mills et al. 2009). The generalised cost argument offers valuable insights and headline figures with regards to the overall cost of defects to both builders and warranty providers; however it can be disposed to assuming that all defects have the same cost characteristics. There are notable exceptions that acknowledge the diverse financial nature of defects. For example, Davey et al. (2006) point out that it costs a minimum of £50 for an operative to attend to a single defect. Mills et al. (2009) further identify that different defects cost varying sums to remedy; for instance, remediation of external water penetration is more costly than plumbing, on average. Rosenfeld (2009) drills down deeper to identify a number of specific costs associated with identifying and resolving individual defects. The costs identified include the cost of investigating the cause of the defect (either by internal staff or external specialists, or both), the cost of the repair (including materials, labour, and equipment), the costs of staff time in handling customer complaints (along with any legal fees and/or compensation paid during the complaint process), and the cost of warranty repairs. Along the same line of associated costs, Davey et al. (2006) argue that post completion defects also incur travelling costs during both the investigation and remediation processes. Finally, Georgiou et al. (1999) propose that individual defects with high associated costs should be seen as “major” defects.

4.2 Potential health & safety (H&S)/regulatory implications

It is argued that defects can have a negative impact on project safety (e.g. Love & Edwards 2004). The implication is that reducing defects has the potential to improve construction health and safety (H&S) in general (e.g. Macarulla et al. 2013). There is also a more specific H&S concern proffered within the literature, regulatory non-compliance. Sommerville and McCosh (2006) comment that the majority of construction defect research concentrates on defects that do not comply with the Building Regulations. Smith et al. (2013) further explain that this is because the Building Regulations are the minimum set of standards that a construction project is required to meet. Building Regulations compliance is to certify that reasonable standards of H&S are ensured for building users (e.g. Baiche et al. 2006). Regulatory defects have the potentiality to jeopardise the H&S of the occupants, with Smith et al. (2013) arguing the need to consider human safety once the building is occupied. During construction, a building inspector must take all reasonable steps to satisfy themselves that the requirements of the Building Regulations have been met; however the primary responsibility for achieving compliance remains with those who commission and undertake the work (e.g. LGO 2014). Under the Building Act (1984) if a person carrying out building work contravenes the Building Regulations, they may be taken to the magistrates’ court and ordered to pay a fine for the contravention, and a further fee for each day the contravention continues post-conviction. In specific circumstances, under a new build warranty the warranty provider will provide cover for defects (that contravene Building Regulations) where they present a danger to the H&S of the
occupants (e.g. NHBC 2012). This generalised approach provides a clear indication of the H&S implications associated with non-achievement of regulatory compliance, along with those affected. However it neglects to discuss in detail the varying H&S implications of individual defects. There is a small pool of literature that acknowledges the heterogeneous nature of defects and the accompanying H&S concerns they pose. Georgiou et al. (1999), for example, argue that individual defects with the potential to damage H&S should be deemed a “major” defect. It is also recommended that focus should be placed upon reducing individual defects in areas deemed detrimental to the H&S of the home occupants (e.g. Baiche et al. 2006). Ilozor et al. (2004) further argue that there is still a need to concentrate on defects that are low in number, if only to ensure safety. NHBC (2012) drill down deeper by highlighting ‘chimney and flue defects’ as types with the potential to present an imminent danger to the H&S of the home occupants.

4.3 Disruption implications

It has been argued that defects generally cause disruption to both home occupants and house builders (e.g. Davey et al. 2006). Rosenfeld (2009) identifies that defects occurring during the construction process can cause disruption to the builder through resource usage, for example, site management investigating their causes, and the deployment of labour and equipment to remedy the defects; instead of undertaking new work. Remediation of defects has the potential to cause delays in handover, and put builders at risk of complaints from the home occupants (e.g. Sommerville et al. 2004). Post completion defects are also argued to cause disruption by way of operatives having to return to, and be granted access to a previous job (by the home occupant) (e.g. Davey et al. 2006). The BEC (1991) suggests that home occupants are unlikely to welcome disruption that occurs due to work being carried out incorrectly. Rosenfeld (2009) identifies that handling post completion defects has the potential to cause disruption to a builder’s staff. Disruption to staff can include time spent travelling to investigate and remediate defects, and the process of having to arrange for trades to return to properties to undertake repairs (e.g. Davey et al. 2006). It is further argued that invaluable time of managers within a construction company is consumed dealing with issues of the past, when it could be better spent concentrating on the company’s current and future projects (Rosenfeld, 2009). Over prioritisation of current and future projects in place of resolving defects during the defects liability period (first two years post completion) often results in poor quality service, and breakdowns in communication between construction companies and clients (e.g. Davey et al. 2006). Existing research provides valuable evidence by identifying a number of defect related consequences with the potential to cause disruption. It however can be susceptible to discussing defects only in a universal context. Individual defects have differing potential disruption impacts on both house builders and home occupants, such as divergent levels of inspection, varying repair durations, fluctuating demand on labour and equipment, and the unstable levels of communication and service the combination of these aspects will invariably cause.

What has become apparent from the prevailing literature relating to the impact of defects in construction is how a number of the identified factors are closely interrelated and can involve a number of stakeholders. For example, a post completion defect that is a non-compliance with the Building Regulations has a number of related implications: first, cost implications for undertaking the repair, and/or any potential fines for the contravention; second, potential H&S implications due to Building Regulations compliance being to ensure that reasonable standards of health and safety for building users are achieved; and, finally, disruption implications by the way of operatives having to return to the property, and be granted access by the customer to rectify the situation. Sommerville (2007) has made a useful contribution to the debate by identifying that there are a lack of models available to quantify the overall impact of individual defects. Further, the same defect would likely include a number of stakeholders, including: the home buyer/occupier, builder and building inspector. The following section further examines the defect detection and remediation process, and the key stakeholders involved.
5 THE IDENTIFICATION OF KEY STAKEHOLDERS INVOLVED IN THE NEW HOUSING DEFECT DETECTION AND REMEDIATION PROCESS

Despite the limited research or models to identify the overall impact of individual defects on key stakeholders, the literature has established the defect detection and remediation process in house building along with the key stakeholders involved in the process. Figure 1 provides a simple overview of the process. Four key stakeholders are identified: the home buyer/occupier, house builder, warranty provider, and building inspector. These stakeholders and their involvement within the process are discussed below.

![Diagram of the defect detection and remediation process](image)

Figure 1: Typical defect detection and remediation process in the UK new house building

During the construction of a new home, an inspection procedure involving examination of work on site takes place to assess whether compliance with Building Regulations is achieved (e.g. Smith et al. 2013). The inspection procedure can be undertaken by either a building inspector from the local authority or an independent approved inspector (e.g. CIC 2014a). As shown in Figure 1 building inspectors frequently observe non-compliance (identify defects) during the construction process and produce checklists of faults that require correction (e.g. Baiche et al. 2006). The house builder typically accepts the inspector’s decision and rectifies the defect (e.g. Smith et al. 2013). As work progresses on site employees of the house builder, typically either site or project management, will also undertake quality inspections of the building area. If defects are identified a tradesperson will then be required to rectify the defect for the builder to approve (e.g. Sommerville et al. 2004).

During the builder’s liability period (first two years post completion), the UK house building industry utilises a snagging process which is heavily reliant on the home buyer/occupier (e.g. Sommerville et al. 2004). The home buyer/occupier is responsible for identifying and reporting any problems back to the builder’s customer care department so that they can deploy trades to rectify them.

Outside of the first two years, most new homes are subject to warranty cover. Warranties are typically ten years in length. After the builder’s liability period of two years, the warranty is used to cover building defects in years 3-10 (e.g. Premier Guarantee 2013). According to Construction Industry Council (CIC, 2014b), there are seven key players in the new home warranty market in the UK, each offering new home warranty products; they are Building LifePlans, Local Authority Building Control, Build Zone, Castle 10, CRL, Premier Guarantee, and National House Building Council (NHBC). If the home occupier notices a defect that requires attention, they are required to contact the warranty provider and notify them of the identified defect, and afford the warranty provider the opportunity to inspect the home. Upon acceptance of a valid claim, the warranty provider will make the necessary arrangements to have the defect remedied (e.g. NHBC 2012). Warranty providers will keep a record of claims history as part of their risk assessment procedures and for calculating the builder’s renewal fees (e.g. Auchterlounie 2009). Mills et al. (2009) argue that the warranty provider spends large sums of money rectifying defects. However it is acknowledged that repairs are also undertaken directly by the original builder to protect their renewal fee from increase (e.g. NHBC 2011).
6 DISCUSSION

What has become clear from the review of literature relating to the impact of defects is that there is scant rigorous empirical evidence to identify the overall impact of individual defects on key stakeholders. There is only a small pool of literature that discusses, in isolation, some of the individual facets that contain the potential to impact on a variety of stakeholders, i.e. cost, disruption and health and safety/regulatory (e.g. Georgiou et al. 1999, Baiche et al. 2006, Ilozor et al. 2004). Furthermore, the scholarship has identified that the three aspects with impact potential are closely linked. This close link suggests that it would be difficult to consider one impact criterion without considering the others. Despite this close relationship the review has identified a lack of models available to quantify the overall impact of individual defects (e.g. Sommerville 2007). Such a model would develop the ability to establish the impact of individual defects and will further develop the ability to determine whether individual defects are significant or not, and guide what defects should be focussed upon for targeted defect reduction.

7 RESEARCH AIM AND OBJECTIVES

The aim of this research is to better understand the impact of defects on key stakeholders within the new-build housing defect detection and remediation process.

In order to achieve the above aim, the following objectives will need to be satisfied:

• Determine which of the identified aspects are more important to the relative stakeholders, and why.
• Develop and verify a defect impact assessment system for the purposes of defect analysis.

8 RESEARCH METHOD

To successfully achieve the aim and objectives set out in section 7, further research will be undertaken in three phases (see Figure 2): the development of impact weighting, testing of impact criteria, and validation of impact criteria.

8.1 Development of impact weighting

The literature review and synthesis undertaken in this paper has helped to form the initial defect weighting criteria and identify the key stakeholders in the new-build housing defect detection and remediation process. Questionnaires will be employed to establish the weighting coefficient for the identified aspects of defects with potential to impact upon stakeholders within construction projects. The questionnaire will establish which aspect is deemed to be the most important to the respective stakeholders, and why. As the defect scholarship takes a normative position of the identified aspects, the why question within the survey will seek to explore the stakeholders’ perceptions of these terms and the underlying factors behind their selection. The questionnaire survey will be distributed to the four key stakeholders identified in
section 5, home buyer/occupier, house builder, warranty provider, and building inspector. First, a list of home owners who have had a defect rectified under their warranty within the last year will be sourced from the UK’s largest new home warranty provider. Second, members of the same warranty provider’s staff will be identified. Third, building inspectors from the UK’s largest independent building inspection service will be located. Fourth, active house builders held within the UK’s leading warranty provider and independent building inspector’s register will be identified. (Note: the UK’s largest independent building inspection service is responsible for over 50% of the building control market, and the UK’s largest warranty provider provides cover on circa 80% of new build houses, therefore making them a representative sample).

Developing a weighting coefficient for each of the individual components (e.g. de Oliveira Pedro et al. 2008) and multiplying them together (e.g. Che-Ani et al. 2011) will allow for the overall impact of the combined criteria of individual defects to be calculated. Primary data drawn from the questionnaire survey results will generate the capability to empirically develop a weighting for each of the predefined aspects, which will allow us to identify which of the elements should have the largest influence to the overall impact rating.

8.2 Testing of impact criteria

Upon completion of criteria development, the developed impact model will be tested through its application to defects extracted from the defect records of the UK’s largest new home warranty provider’s claims database. Claim files provide objective information with regards to the magnitude, cost and cause of defects, therefore making them an ideal source of data for research in to defects (e.g. Georgiou et al. 1999). Testing new systems on secondary data is a method frequently employed. For example, Georgiou et al. (1999) tested the suitability of their defects classification system by analysing defect records for Australian homes. The UK’s largest warranty provider provides cover on circa 80% of new build houses, therefore making them a representative sample.

8.3 Validation of impact criteria

The impact criteria will finally be validated through exposing it to expert focus groups to establish whether the system is clear, relevant and produces findings in line with expert expectations, along with identifying any improvement opportunities. Georgiou (2013) argues that expert validation and achieving a level of consensus is necessary to prove that the author’s objectivity is sufficient. The expert focus groups will consist of two comparative focus groups to validate findings (e.g. Adams & Cox 2008). The focus groups will consist of participants, including; Chartered Surveyors, Chartered Engineers and Chartered Building Engineers. Focus groups have been chosen as they offer rich amounts of data and different perspectives on a given topic, and serve as a useful tool for gaining insight in to different views and dynamics within a group context, for example, consensus and disagreement (e.g. Litosseliti 2003).

9 CONCLUSION

This paper set out to contribute to our understanding of the impact of individual defects from a key stakeholder perspective by undertaking the literature review and synthesis phase from a wider project to develop and verify a defect impact assessment rating system. The synthesis of the current construction defect literature established a number of aspects with the potential to impact on stakeholders involved with the construction process. The literature review also identified a number of key stakeholder groups within the defect detection and remediation process in the new house building. This paper is concluded by offering the theoretical lens and key stakeholder sampling strategy as the basis for the subsequent impact weighting development phase, the findings of which to be presented at the upcoming conference.

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References


A CASE STUDY ON THE USE OF LED TEMPORARY CONSTRUCTION LIGHTING SYSTEM

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Abstract: Adequate lighting is a necessity on construction sites not just for work completion, but also for the work quality, worker safety, and project productivity. This paper discusses the problems associated with traditional temporary lighting on construction sites and presents a case study on using LED temporary construction lighting as a potential solution. Various studies have shown that the traditional methods of providing temporary lighting are inadequate due to their non-compliance with OSHA requirements; visual discomfort; constant maintenance; and impacts to productivity, safety and health. On the other hand, studies have shown that using LED as a source of temporary construction lighting provides benefits over the traditional lighting system, even though such uses are still rare within the industry. Using LED for temporary construction lighting, however, is subject to the high initial materials cost and other drawbacks. To this end, the objective of the research is to provide a deeper understanding of LED temporary construction lighting and ascertain its benefits and limitations through a case study. The study involves the University of Washington’s Bothell Science and Academic Building Project. The study involves interviews with both the lighting system vendor and onsite project personnel; survey questionnaire distributed to the field workers; and cost analysis of the LED temporary lighting system. The case study concluded that the benefits of using LED temporary construction lighting outweighed its limitations, but the individual cost savings may belong to different parties and may not necessarily be passed on to the owner depending on the contractual arrangements.

1 BACKGROUND

Adequate lighting is important on the construction site not just for work completion, but also for the work quality, worker safety and productivity of the workers. Whilst construction sites can be lit by natural lighting, temporary lighting is usually required to supplement the natural lighting especially for enclosed work areas, during early/late work hours, and around evacuation egress. Often, a general contractor would place the duty of providing and maintaining temporary general lighting (and temporary power) under its electrical contractor’s scope of works and include it as part of the electrical bid package. Whilst task lighting has always been the responsibility of individual subcontractors, the scope of temporary general lighting has always been ambiguous with the level of illumination required not being clearly defined in the contract provisions.

Various studies have shown that the traditional methods of providing temporary lighting are inadequate. Non-compliance with the regulatory illumination standards during daylight hours was found (Smith and
Azhar, 2007) and only very high wattage light sources (e.g. 400 W metal halides) spaced at an appropriate distance could achieve the illumination standards (Smith, 2008). However, high wattage light sources are very bright, creating glares, shadows, and visual discomfort. The traditional method of temporary lighting also creates safety concerns. It is not uncommon that the lamps would burn out from overloaded source of energy, expose workers to high voltage wires, or become tripping hazards because of the extension cords and wires attached. Based on field observations and experiences, workers’ productivity tends to be negatively impacted with the use of traditional methods of temporary lighting. The traditional method requires constant moving of the lamps, resulting in the lamps being dropped, broken, or smashed easily. Oftentimes workers are required to replace the damaged lamps, or to locate, move and set-up task lighting due to the insufficient illumination of the general temporary lighting. The last area of concern is worker health. When light bulbs break, workers cleaning up the broken bulbs might be exposed to the escaping Mercury vapor or UV rays commonly seen in compact fluorescent lights.

Due to the problems associated with the traditional method of providing temporary lighting, the Capital Project Office at the University of Washington (UW) deployed the use of low voltage temporary LED lighting system to replace traditional temporary lighting on the UW Bothell Phase 3 (“UWB P3”) – Bothell Science and Academic Building project. This is the first west coast installation of low-voltage LED temporary construction lighting system in the U.S. Construction for the 74,000 square foot UWB P3 building consists of four levels and one basement and was delivered using the GC/CM (General Contractor / Construction Manager) and EC/CM (Electrical Contractor / Construction Manager) approach to have the general contractor and electrical contractor on board early. While studies have shown that there are benefits of using low voltage LED lighting system over the traditional methods to provide temporary lighting, there are limitations as well with the most significant one being the high initial system cost. To this end, this paper: (1) introduces the case study background, (2) describes how the LED lighting system was deployed in the studied project UWB P3, (3) discusses data collected through interviews, survey questionnaires, and cost estimates, and (4) presents findings and concluding remarks. It should be noted that as most of the data collected are of qualitative nature, the case study discussion and results although were produced following a scientific procedure are still subject to human bias.

2 DEPLOYMENT OF THE LOW VOLTAGE TEMPORARY LED LIGHTING SYSTEM AT UWB P3

The FLEX SLS lighting system by Clear-Vu Lighting was deployed at UWB P3 to provide temporary construction lighting to all corridors and stairwells, as well as individual rooms where necessary. A typical setup comprises of 450-watt power systems, LED modules with 10’ whips, a T connector and low voltage (24V) cables. As this system made use of low voltage, the temporary lighting power cables and drivers could be designed to be embedded within the concrete slab, with only the whips and LED light fixtures dropped and exposed below the ceiling deck. Installation of the temporary LED construction lighting system at UWB P3 was undertaken in a three-stage process, including pre-construction estimate, planning for the lighting and controller setups, and the physical installation.

During the pre-construction estimate, the electrical contractor estimated that 285 LED light fixtures would be needed based on the site conditions and layout, considering that each LED module’s coverage is roughly 17 ft by 17 ft. During lighting and controller setup planning, layout of the MEP was examined to determine possible locations that did not run across known MEP services. Locations of the walls that reached all the way to the bottom of the concrete deck were also taken into consideration, as they would block any light source once the walls were erected. Due to the capacity of the drivers, the number of LED fixtures connected to each driver was limited and therefore impacted routing of the cables, the number of drivers required to be installed per floor, and the number of circuits required to be run per floor. Upon confirmation of the locations of the fixtures and drivers, approximate measurements of their distances from gridlines were taken to aid the physical installation. During the physical installation, based on the approximate dimensions from the gridlines, the forms had to be drilled through so that the inserts could be placed within the concrete deck for both the fixtures and the whip. Coordination with ironworkers was necessary as the cables were installed concurrently with the reinforcement bars. During concrete pour, the electrical contractor would station a “pour watch” to ensure that the cables do not get damaged or pulled back into the slab during the pour. After the concrete has cured, upon stripping of the formwork,
the LED fixtures were installed on the floor slab and energized immediately to provide temporary lighting for that floor. Figure 1 illustrates how a LED fixture was deployed below a ceiling deck at UWB P3.

![Temporary LED lighting fixture dropped and exposed below ceiling deck](image)

**Figure 1:** Temporary LED lighting fixture dropped and exposed below ceiling deck (courtesy of Nelson Electric)

## 3 DATA COLLECTION

To verify the benefits and limitations of using the LED fixtures as construction temporary lighting at UWB P3, data were collected via various approaches to triangulate common themes. Site interviews providing qualitative data were conducted with the project management staff from the UW CPO, general contractor, and electrical contractor. The interview data can be summarized into six themes as described in Table 1.

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<tr>
<td>Immediate use of temporary lighting</td>
<td>The temporary lighting system could be energized immediately upon the stripping of the formwork, way before MEP rough-ins</td>
</tr>
<tr>
<td>Light reflection off drywall</td>
<td>Drywalls would reflect the LED light and brighten up surrounding spaces as the internal partitions being erected</td>
</tr>
<tr>
<td>Workers drilling into embedded cables</td>
<td>Workers drilling through the slab for their works would accidentally drilled through the embedded cables</td>
</tr>
<tr>
<td>Upward lighting requirement</td>
<td>The LED lights were generally hung faced downwards but upward lighting is required for HVAC works</td>
</tr>
<tr>
<td>Duration of use of temporary lighting</td>
<td>Due to the ease of light fixture removal, the temporary lighting could be used until permanent lighting was turned on</td>
</tr>
<tr>
<td>Contractual requirement</td>
<td>Temporary lighting as “means and methods”, up to the general contractor’s discretion</td>
</tr>
</tbody>
</table>
A survey was administered to solicit worker input on the lighting requirements specific to their tasks and on how the LED lighting fixtures compared to the traditional methods. Based on the 19 responses received, in overall, the workers appeared to have had a more positive experience with LED lighting as compared to the traditional lighting, consistent with the interview results. Based on the ratings of both systems (on a scale of 1 to 5), the average rating of LED lighting’s attributes (e.g. visual comfort) ranged from 3.5 to 4.0 as compared to an average rating of 2.4 to 3.2 for traditional lighting’s attributes. Particularly, plumbers were in more agreement in their ratings than other trades. The electricians, on the other hand, had mixed reviews as to whether working in LED lighting was a more positive experience than traditional lighting.

Estimated cost data were obtained (see Table 2) to compare the costs of providing a temporary metal halides lighting system and a temporary LED lighting system to meet the OSHA 5 foot candle requirements for UWB P3. As the electrical contractor had never tracked these cost categories for temporary metal halides lighting systems used in the past, estimates from a different electrical contractor, Clear-Vu, and NECA Manual of Labor Units were also consulted to provide a basis of comparison and to establish a range of possible costs.

Table 2: Summary of total cost comparison between LED and metal halides systems

<table>
<thead>
<tr>
<th>Categories</th>
<th>LED</th>
<th>Metal Halides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>$53,953</td>
<td>$40,990</td>
</tr>
<tr>
<td>Installation</td>
<td>$30,915</td>
<td>$26,757</td>
</tr>
<tr>
<td>Maintenance</td>
<td>$3,324</td>
<td>$26,985</td>
</tr>
<tr>
<td>Removal</td>
<td>$3,836</td>
<td>$10,228</td>
</tr>
<tr>
<td>Energy</td>
<td>$3,442</td>
<td>$24,527</td>
</tr>
<tr>
<td>Total</td>
<td>$95,470</td>
<td>$129,488</td>
</tr>
</tbody>
</table>

4 STUDY FINDINGS AND CONCLUSION

Use of the temporary LED lighting system does provide better illumination and minimizes the other identified problems of safety (less hazards), productivity (less maintenance required), and health (less risk of mercury and UV exposure). In addition, the case study revealed that use of the temporary LED lighting system allowed immediate use of temporary lighting on site as it could be energized upon the stripping of the formwork, allowing the building to be fully lit up at least one to two months earlier than it would have been in a traditional temporary lighting setting. However, it was also revealed that the temporary LED lighting system required additional pre-construction planning; more time and labor was required for installation, including additional works such as coordination with iron workers. These resulted in higher installation costs. Whilst the cost comparison showed that the temporary LED lighting system had lower overall costs, it is pertinent to note that the individual cost savings may belong to different parties and may not necessarily be passed on to the owner depending on the contractual arrangements. Verticality of a trade’s work space and the trade’s type of tasks also seemed to potentially influence the workers’ experience with LED lighting system.

References


ROLE OF FORMWORK SYSTEMS IN HIGH-RISE CONSTRUCTION

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Abstract: The selection of formwork systems in high-rise buildings is often governed by their competence in optimizing concrete activities in an isolated manner, without relating this choice to the entire construction workflow. This paper studies the role of advanced formwork systems in high-rise construction and analyzes this role in shaping not only the progress of concrete activities, but the entire construction sequence. In this context, known research efforts do not address this important aspect in analyzing high-rise formwork technologies, and formwork selection is usually left to constructors’ experience, and corresponding organizational knowledge. Employing process models, the paper investigates advanced high-rise formwork technologies versus regular ones to better advice scholars and practitioners. Results highlight the importance of advanced high-rise formwork systems in streamlining the workflow of concrete and other downstream activities, allowing for better resource allocation, more waste reduction, smaller work batches, less inventory, and safer working environment.

1 INTRODUCTION

1.1 Background of High-Rise Building Construction

High-rise building projects encounter several challenges that affect the progress of their execution. Some of these challenges are related to project location where most skyscrapers are built in tight land lots in cities’ business centers with serious limitations on space. This fact imposes high pressures on the supply chain management where on-time and smooth material delivery is of great importance. Other difficulties could be related to building design complexity, the technology used on site, labor availability and skills, the adequacy of the methods followed, and the capacity of planning professionals to foresee the dynamics of their site and proactively shape its progress. While multiple efforts targeted activity sequencing methods used in high-rise construction (Ranjbaran, 2007; Arditi et al., 2002; Thabet and Beliveau, 1994; Reda, 1990; Suhail and Neale, 1994), other researchers investigated the use of 4D modeling to graphically examine schedule progress on a 3D model where space clashes are detected and proactively solved to ensure smooth tasks handoff (Staub-French and Khanzode, 2007). However, none of the efforts linked the use of formwork systems to the workflow of activities. The choice of formwork systems is governed by several parameters (Gnida, 2010; Ciribini and Tramajoni, 2010), and cost considerations highly affect the final formwork selection especially that contractors try to minimize the cost of concrete activities in an isolated fashion without considering the indirect costs of the resulting schedule and related workflows affected by this choice.

To respond to the limitations of formwork selection procedures that focus solely on concrete construction sequence, this paper presents a comprehensive understanding of the effects of formwork selection that go beyond the execution of concrete elements and introduces to the industry a broader view of the
leading role formwork systems play in high-rise projects. In this regard, the paper: (1) compares advanced
and regular high-rise formwork technologies, (2) highlights corresponding workflow changes, and (3)
examines major enhancements on activities flow, production rates, inventory dynamics, and labor and
material delivery to work areas.

1.2 Repetitive Construction in High Rise Buildings

High-Rise building construction is characterized by the repetition of multiple activities at different
locations. Planners benefit from these repetitive tasks to maintain workflow continuity, decrease labor and
equipment idle times, reduce hire and fire actions, and take advantage of the learning curve effects
(Ranjbaran, 2007). However, these repetitive activities advance simultaneously in vertical and horizontal
directions and may create spatial constraints that hinder the execution of work (Thabet and Beliveau,
1994). To account for these constraints, practitioners and researchers sought scheduling solutions to
navigate the execution of tasks under these restrictions. Since the drawbacks of applying the CPM
method to schedule repetitive tasks were investigated in several studies (Reda, 1990; Hegazy and
Wassef, 2001), efforts targeted other scheduling techniques using the Line of Balance (LOB) method.
LOB allows operations on site to continuously flow from one activity to another by balancing different
tasks, resources, and space concurrently (Hegazy, 2002). While some researchers worked on combining
both the CPM and LOB methods to enhance work scheduling in repetitive construction (Suhail and Neale,
1994), other researchers used 4D modeling techniques provided by BIM technologies to simulate the
construction sequence and proactively account for possible on-site clashes (Staub-French and
Khanzode, 2007).

1.3 Formwork Choice and Construction Workflows

The logic of work execution followed to satisfy building safety and integrity shapes the scheduling of
involved activities. Structural works are the skeleton of every construction project and they set the pace to
other downstream architectural and MEP activities. Hence, ensuring a continuous and on-time execution
of structural framing is essential to keep the project on schedule. Assuming adequate availability of labor
and material, the choice of formwork systems (e.g., the climbing technique) directly affects the progress of
concrete works, and greatly influences the interlocking workflows of walls, shafts, and slabs where
several tasks from different trades are involved. For instance, crane-lifted formwork used for core wall
errection can congest the crane schedule and consequently delay the delivery of materials to other site
zones. Whereas, self-climbing formwork release the crane schedule and can be reused for other critical
activities. Another important factor that affects the progress of work is the resulting quality of cured
concrete. Concrete repair consumes a significant amount of time and affects the speed and quality of
finishing works that follow. In this regard, the quality of formwork system and the tolerance range it can
provide is essential to ensure a smooth progress of work from one phase to another, and from one trade
to another. Nonetheless, smaller tolerance ranges allow the incorporation of prefabrication and remote
assembly that can boost construction speed.

1.4 Formwork Selection Parameters

Construction of high-rise buildings requires innovative formwork system technologies to overcome the
limitations of space, budget, and time. However, many parameters affect the choice of formwork systems
and are mainly divided into internal and external parameters as shown in Table 1 (Gnida, 2010). While
internal parameters fall under designers and contractors control, external ones are affected by owner
requirements, project milestones, project location, and corresponding local rules and regulations.
Table 1: Internal and external parameters governing the selection of formwork system (Gnida, 2010)

<table>
<thead>
<tr>
<th>Internal Parameters</th>
<th>External Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td></td>
</tr>
<tr>
<td>Repetitive</td>
<td>Constraint of Existing Road or Building</td>
</tr>
<tr>
<td>Simple/Complex</td>
<td>Storage Area</td>
</tr>
<tr>
<td>Changing Geometry</td>
<td>Assembly Area</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
</tr>
<tr>
<td>Rate of Pouring/Concrete Pressure</td>
<td>Wind</td>
</tr>
<tr>
<td>Concrete Finish</td>
<td>Wind Load</td>
</tr>
<tr>
<td>Curing Time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Sequence of Work</td>
<td></td>
</tr>
<tr>
<td>Cycle Time</td>
<td>Crane</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
</tr>
<tr>
<td></td>
<td>Availability</td>
</tr>
<tr>
<td></td>
<td>Type</td>
</tr>
<tr>
<td></td>
<td>Boom Reach</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Formwork Choice</td>
<td></td>
</tr>
<tr>
<td>Existing Formwork Material to be</td>
<td>Safety</td>
</tr>
<tr>
<td>Reused</td>
<td>Special Requirements Needed</td>
</tr>
<tr>
<td>Rental or Purchase</td>
<td></td>
</tr>
<tr>
<td>Best Value for Current Project vs.</td>
<td></td>
</tr>
<tr>
<td>Flexibility for Future Projects</td>
<td></td>
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<td></td>
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</table>

To account for these parameters, many contributions were made to improve the efficiency of formwork systems resulting in several types. Choosing the appropriate type of formwork depends on many factors including cost, time, quality, and safety. An overview of these types is summarized in Table 2. Other studies linked the selection of the formwork system to building height and weather conditions (Ciribini and Tramajoni, 2010). Figure 1 presents appropriate formwork options according to three height ranges in the case of good or bad weather conditions.

![Diagram of formwork choice](image_url)

Figure 1: Formwork choice according to building height and weather conditions (Ciribini and Tramajoni, 2010)
Table 2: Formwork classification (Classification of Formwork, N.d.)

<table>
<thead>
<tr>
<th>Classification Category</th>
<th>Size</th>
<th>System vs. Location of Use</th>
<th>Construction Materials</th>
<th>Nature of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Timber:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Adaptable to complex shape.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Labor intensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Environmentally unfriendly</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Low initial cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Most popular</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steel:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Sections: Hot rolled or Cold formed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Heavy weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Suitable for large-sized panels</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Aluminum:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Stiff and light weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Excellent finish</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• High material and labor cost</td>
<td></td>
</tr>
</tbody>
</table>

1.5 Formwork Safety and Work Environment

Safety is a major challenge in every construction project especially in high-rise construction. Labor falls from heights are considered to be the major cause of accidents encountered and the most serious ones (Hinze and Russel, 1995; Huang and Hinze, 2003). Different studies targeted the work environment and investigated different safety procedures (Mohamed, 2002; Cecen and Sertyesilisik, 2013), and researchers as well as industry leaders are continuously developing tools and methods to enhance safety standards. Work environment is also affected by other factors that contribute to labor productivity and construction progress. Noise, for instance, is a major contributor to work stress and fatigue. Noise is created by the use of machines, equipment, and space congestion and can cause hearing problems for workers on site (Barkokébas et al., 2012). Methods to reduce noise were suggested by Barkokébas et al., and techniques can be inspired by their study in order to control noise production and transmission. Height is also considered as an additional risk in high-rise construction. Height changes affect workers’ perception of danger and could disturb their response in hazardous situations (Hsu et al., 2008). In this regard, safety measures were incorporated into the design of formwork systems in order to enhance the safety on site.

To respond to the limitations of formwork selection procedures that consider the optimization of concrete works in isolation, this paper presents a comprehensive analysis of advanced and regular formwork technologies and highlights their role in shaping the progress of concrete and non-concrete activities. Addressing the role of formwork systems in leading construction workflows in high-rise projects is a novel approach that allows researchers and practitioners to link the choice of formwork system to construction workflows on one hand, and to logistics planning, inventory dynamics, crane schedule, labor and material delivery and safety procedures on the other. The following sections examine advanced and regular formwork technologies, link the formwork choice to activities sequence, and investigate major related differences.
2 METHODOLOGY

The paper compares advanced and regular formwork systems to underline major differences, and employs a process model to describe construction activities and their interdependent relations in both cases. It also examines the resulting differences in construction sequence and flow from a scheduling perspective, to finally highlight the major enhancement the advanced systems present on inventory size and dynamics, crane availability for non-concrete activities and labor and material delivery to work zones.

![Diagram](image)

Figure 2: Research methodology

3 FRAMEWORK DEVELOPMENT

3.1 Advanced and Regular Formwork Comparison

3.1.1 Core wall Formwork

Advanced as most regular core wall formwork technologies used are self-climbing systems, lifted using hydraulic jacking mechanisms independent of any external crane or lifting equipment, and are available as single or double jump formwork assemblies (Figure 3). As the name implies, the double jump system jumps two floors at a time leading to significant reduction of cycle time; the work to be done is halved. For instance, steel fixing activities have to be done only once every two floors, and the same concept applies to concrete pouring as two consecutive floors are poured together. Other time-consuming activities such as surveying operations, formwork alignment, and reinforcement inspections are also optimized to boost core wall construction speed. Therefore, as the number of cycles is largely decreased, the construction time undergoes substantial drops. Moreover, the single jump system has also been proven to reduce the cycle time to three or four days per floor (Naylor, 2006) considering that the formwork is totally isolated from external weather conditions by cladded screens and a top deck free from mass constraints. This provides workers with a safe and adequate working environment.

![Image](image)

Figure 3: Advanced core wall formwork (Double-Jump System, n.d.)

In addition to time savings, the advanced core wall system also impacts cost savings. By merging two floors into one cycle, or one concrete pour, steel reinforcement splicing (or coupling) will only be done on every second floor. Thus, the number of splices (or couplers) is reduced which implies key cost savings on material. Furthermore, the advanced system ensures that building service elevators are made operational as early as possible. In this regard, lifts of the building are used to transfer material and labor
early on during the execution phase, thus decreasing demand on external hoists and tower cranes and boosting production (Glasby, 2009).

3.1.2 Floor Formwork

The selection of horizontal formwork is governed by several parameters as mentioned in Table 1. Yet, practitioners try to benefit from the repetitive nature of slab construction by standardizing formwork size and material and maximizing the number of formwork reuse. In this context, table forms are widely used on high-rise projects to decrease formwork setup time and slab cycle time to match that of core walls. However, regular table forms are crane dependent and obstruct the crane schedule every time they are moved from one floor to another.

Advanced formwork technologies provide innovative perimeter systems which combine construction and safety screens requirements. A self-climbing system is used to form vertical elements such as columns and walls independent of floor slab construction. The system jacking points are above floor slab giving clear access for slab formwork, reinforcement, and pouring below the system. The key advantage of the perimeter system is the accelerated construction of columns and slabs that progress independently. The system can also provide lifting services to move slab table forms internally without any use of tower cranes which are consequently released for other critical activities resulting in a faster overall construction process. Figure 4 shows the perimeter system where the columns are two floors ahead of slab construction, and pouring activities are taking place below the system's platform.

3.2 Construction Process Mapping

To examine the role of formwork in shaping construction workflows, two process maps, depicted in Figures 6 and 7, were developed to trace the differences in construction sequence between advanced and regular formwork systems. The trailing platform hanging from the advanced core wall formwork (Figure 5) allows internal lift specialists to start fixing lift rails and necessary accessories early on in the project, thus undergoing the same cycle as the core wall cycle. Whereas, elevator related tasks would not start until finishing core wall construction in the case of regular forms. Accordingly, service elevators can be made functional before final core wall erection and can be used to hoist labor and material for finishing crews.

Figure 4: Advanced self-climbing perimeter system (Double-Jump System, n.d.)

Figure 5: Schematic Representation of the Attached Trailing Platform
Figure 6: Construction Process Map Using Advanced Formwork Systems

On the other hand, the advanced perimeter system allows columns and slabs to progress independently, with defined Start to Start and Finish to Finish lag times to allow for the system to be assembled and disassembled as presented in Figure 6. Using regular formwork, floor construction follows successive cycles of columns erection and slab construction with a Finish to Start relation as shown in Figure 7.

Figure 7: Construction Process Map Using Regular Formwork Systems
3.3 Schedule Optimization and Workflow Improvements

Advanced formwork systems allow project managers to optimize the project schedule. The trailing platform plays a major role in opening downstream work early in the project and benefitting from the available core wall shaft areas which are usually wasted work spaces in regular formwork technologies as conveyed through Figure 9. The early engagement of elevator crews reduces corresponding material batches where required accessories can be delivered to site on demand without storing large inventories. On the other hand, the independent progress of columns and slabs helps streamline both activities together and reduce the risk of one process delaying the other as is the case of using regular formwork. It also boosts production of both activities due to learning curve effects. Higher availability of tower crane for none concrete activities when using advanced systems, along with making building service elevators functional at core mid-height, can increase material and labor delivery rates to work zones, thus increasing production rates of non-concrete activities as presented Figure 8. Nonetheless, core wall labors could be relocated to other activities once the core wall is erected, therefore decreasing total labor costs and allowing for more flexibility in resource allocation.

Figure 8: Schematic LOB Schedule Using Advanced Formwork

Figure 9: Schematic LOB Schedule Using Regular Formwork
4 DISCUSSION AND CONCLUSION

Formwork systems play a vital role in leading high-rise construction, and technological advancements are pushing the limits of formwork industry to new perspectives allowing it to surpass traditional constructability constraints. The role of formwork systems in high-rise projects goes beyond erecting concrete elements to set the pace of construction processes at different fronts. Innovative features provided by advanced formwork technologies play a major role in streamlining concrete and non-concrete activities where downstream tasks are more sensitive to formwork pace. For example, this applies to the case of elevator related activities that undergo the same core wall cycle and to column and slab-related activities that follow the advanced perimeter pace. Advanced systems also impact logistics planning as faster labor and material delivery rates are achievable due to crane schedule release and the use of building service elevators early on in the project. Faster material delivery is an important step towards decreasing material batch sizes, where required material can be smoothly delivered to work areas based on site demand instead of having large inventories in laydown areas which may not always be available.

Advanced formwork systems provide innovative solutions for today’s complex high-rise developments, and open the doors for greater improvements in construction methods. Future studies can link the use of advanced systems to the implementation of lean ideals on high-rise projects, such as waste reduction, Takt time calculation, and the use of pull systems and Kanban cards.

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SELF- CALIBRATED WSN FOR INDOOR TRACKING AND CONTROL OF CONSTRUCTION OPERATIONS

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Abstract: Effective tracking and timely progress reporting are essential for successful delivery of construction projects. In this respect, several research attempts have been made to identify and track the locations of material, equipment and labor on construction jobsites using wireless sensing technologies. Such developed methods utilize radio signal propagation models to estimate location based on measured received signal strength (RSSI). However, radio signal propagation models are highly dependent on the surrounding environment. As well, these methods are susceptible to interferences caused by metallic structures and obstacles, which are continually changing location on highly dynamic construction jobsites. This paper presents fundamental research work, designed to study the beneficial effect of self-calibrated wireless sensor network (SC-WSN) for higher accuracy of indoor localization. The developed SC-WSN hardware consists of fixed gateway unites mounted at predefined locations and mobile unites mounted on tracked objects. The designed network estimates a tagged object location based on its measured signal strength, which is then converted to corresponding distance using a dynamic signal propagation model. The developed dynamic model calibrates its parameters periodically to minimize errors in its estimated locations using particle swarm optimization algorithm. Experimental results are presented to illustrate the relative effectiveness of the developed system in comparison to commonly used fixed propagation systems.

1 INTRODUCTION

Considerable research work was conducted in recent years embracing the utilization of wireless technologies in construction with a focus on automated project tracking and control. Such application requires frequent location identification of material, equipment and personnel. Despite of the Global positioning system (GPS) success in outdoor localization, it cannot be used indoors due to the lack of satellite’s signal coverage inside buildings. A wide range of wireless technologies were utilized for indoor localization on construction jobsites. The fundamental key for reliable and accurate indoor location estimation is signal propagation model, which is used to convert measured received signal strength (RSSI) into corresponding distances. The dynamic nature of construction jobsites severely impacts the accuracy of location estimation. In the presence of moving resources, metallic objects and structural barriers, the signal propagation model produces poor distance estimates. In order to alleviate such impact, smart and adaptive path loss models are required to cope with the fast-changing environment. This paper was motivated with such need for an enhanced localization method incorporating a dynamic signal propagation model, which would increase the accuracy of location estimation.
2 LITERATURE REVIEW

In the construction management domain, several researchers have investigated indoor localization using three main categories of technologies: wave propagation based; image based; and motion based. Several wave propagation based technologies had been utilized by researchers, such as radio frequency identification (RFID), ultra wideband (UWB), wireless local area network (WLAN) and Zigbee. Each technology has its own inherited advantage and disadvantage with relative to accuracy, cost, coverage range, deployment requirements and scalability (Mahalik 2007). RFID had been used for object tracking without localization (Goodrum et al. 2006; Jaselskis et al. 1995) and for tracking with localization (Ergen et al. 2007; Razavi and Moselhi 2012; Montaser and Moselhi 2014). Researches utilizing ultra wideband (UWB) had reported higher localization accuracy of approximately < 1m (Teizer et al. 2007; Rueppel and Stuebbe 2008; Khoury and Kamat 2009; Shahi et al. 2012; Shahi et al. 2013; Vahdatikhaki and Hammad 2014), however the measurement accuracy is highly dependent upon the line of sight of the point to be located (Aryan 2011). WLAN had been seen as an attractive solution for indoor localization due to its existing universal infrastructure availability (Mazuelas et al. 2009). However, several researchers have reported its low accuracy to be approximately 4–7 m with 97% confidence (Khoury and Kamat 2009; Woo et al. 2011).

3 DEVELOPED SYSTEM

The developed system consists of hardware and software implementations. These implementations are designed to meet three main design objectives: accuracy, scalability and cost. The accuracy of the developed system is the main performance measure in comparing it to others. The higher the accuracy, the better the system; however, there is often a trade-off between accuracy and other characteristics such as cost. The accuracy is measured as the average error in location estimation. The scalability of the developed system is required to be applied to any project size without any need for further adjustment or development. Finally the cost of the developed system must be cost effective with respect to others.

4 DEVELOPED SC-WSN HARDWARE

The developed self-calibrating wireless sensor network configuration is a mesh topology with reference tags. The added reference tags, which are fixed at predefined locations, enable self-calibration of the developed system. This self-calibration feature is expected to enhance the performance of the typical mesh topology and provide the intelligence to dynamically adapt the network propagation models to provide optimal localization accuracy. The developed hardware prototype consists of three components: a Waspomote with ATmega1281 microcontroller; a Synapse RF300 radio frequency module and a BMP180 digital barometric pressure sensor. The microcontroller provides a flexibility to custom develop firmware programs for the purpose of indoor localization. The Synapse RF300 radio frequency module has a high indoor coverage range of 250 meters due to its high transmitter power which provides additional 10 dBm of link margin. The BMP180 digital barometric pressure sensor is distinguished by its relatively high accuracy of ±0.12 hPa (±1m), which provides reliable measurements for precise indoor-navigation applications.

Three types of prototypes were developed: tags (mobile tags which are attached to tracked objects and reference tags which are installed at predefined locations); readers; and gateway (where data processing takes place for location estimation and system calibration). Each tag is equipped with a Synapse RF module and barometric pressure sensor as shown in Figure 1a. The RF module is used to estimate the tag’s location in 2D space, while the barometric pressure sensor is used to estimate the tag’s altitude. The reader node consists of a Synapse RF module, which is programmed to continually scan for nearby tags and report their RSSI value and altitude to the gateway as shown in Figure 1b. The gateway node consists of a microcontroller, Synapse RF module and WLAN module as shown in Figure 1c. It collects data from readers; process the data to estimate tags’ locations; calibrates the system and submits the final location data to the database server.
In order to increase accuracy without placing more readers, the system employs the idea of having extra fixed location reference tags to help location calibration. These reference tags serve as reference points in the system.

5 DEVELOPED LOCALIZATION METHOD

The developed method is composed of two stages, prediction stage and calibration stage as shown in Figure 2. Each reader measures the signal strength (RSSI) from nearby tags and filter it to remove uncorrelated noise. Then filtered RSSI data is forwarded to the gateway node for processing. The prediction stage is initiated by converting the filtered RSSI to its corresponding distance using the dynamic signal propagation model. The initial settings for the signal propagation model parameters are calculated using indoor experimentations as explained by Ibrahim and Moselhi (2014). Once three distances from three readers for a given tag are available its location is estimated using the LSE trilateration algorithm. The localization accuracy is continually monitored by measuring the errors in location estimation generated based on a number of reference tags. These reference tags are deployed on site at pre-defined locations. When the system accuracy is degraded due to on-site interferences, a system calibration request is initialized. The user can define the accuracy limits to initiate the calibration requests. The calibration stage utilizes a particle swarm optimization (PSO) to find the best values for the signal propagation model parameters which maximize the system localization accuracy. Finally, at the end of the calibration stage, the dynamic signal propagation model is updated with the new set of optimized parameters.

Figure 1: Developed Prototypes: (a) Tag (b) Reader (c) Gateway.

Figure 2: Developed Localization Method Overview
5.1 Signal Propagation Model

A propagation model is a set of mathematical expressions used to represent the radio characteristics of a given environment (Neskovic et al. 2000). The signal propagation model used in this research is Log-distance Path Loss Model. The path loss PL (d) for a transmitter and a receiver with distance d is:

\[ P(d) \propto \left( \frac{d}{d_0} \right)^n \]

\[ PL(dB) = PL(d_0) + 10 \cdot n \cdot \ln \left( \frac{d}{d_0} \right) + \sigma^2 \]

Where \( n \) is the path loss exponent which indicates the rate at which path loss increases with distance \( d \). The reference distance \( (d_0) \) is determined from measurements at 1 meter distance from the transmitter. \( \sigma^2 \) is the shadowing variance in mDB. The value of \( n \) depends on the specific propagation environment, i.e., type of construction material, architecture, location within building. Table 1 lists typical path loss exponents obtained in various radio environments (Rappaport 1996).

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path Loss Exponent, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In building line-of-sight</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed in buildings</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>

Given that \( d_0 = 1 \) m, equation 2 can be simplified as:

\[ PL(dB) = A + B \cdot \ln(d) \]

Where \( A \) & \( B \) are the parameters for the signal propagation model. The signal propagation model parameters \((A&B)\) are estimated using lab experiments, then automatically adjusted on-site using the PSO.

5.2 Location Estimation Algorithm

Based on RSSI measurement and signal propagation model described above, the multilateration (Karl and Willig 2007) algorithm is used to calculate tag’s location based on its estimated distance from a set of fixed readers (Stüber and Caffrey 1999). When three readers are used, it is called trilateration, as shown in Figure 3a. The intersection of the three circles gives an exact solution for the tag’s location under ideal free space signal propagation (no fading or shadowing effect). However, in real environment, the three circles might not even intersect due to errors in distance estimates by RSSI propagation model. Stuber and Caffrey 1999 presented an optimal localization using least square estimation (LSE) as shown in Figure 3b.

Given the readers coordinates as following: \( A(x_1, y_1) \), \( B(x_2, y_2) \), and \( C(x_3, y_3) \); and their corresponding distances to the tag are \( d_1 \), \( d_2 \), and \( d_3 \); the three circles equations can be formatted as follows:

\[ (x_1 - x)^2 + (y_1 - y)^2 = d_1^2 \]
\[ (x_2 - x)^2 + (y_2 - y)^2 = d_2^2 \]
\[ (x_3 - x)^2 + (y_3 - y)^2 = d_3^2 \]

Where \( x \) and \( y \) are the coordinates for the tag location.
Figure 3. Localization using Trilateration

Using the LSE method the tag coordinates can be calculated using the following equation:

\[
\begin{bmatrix}
2 \times (x_3 - x_1) & (x_3 - x_2) \\
2 \times (y_3 - y_1) & (y_3 - y_2)
\end{bmatrix} \begin{bmatrix}
x \\
y
\end{bmatrix} = \begin{bmatrix}
(d_1^2 - d_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) \\
(d_2^2 - d_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)
\end{bmatrix}
\]

5.3 System Accuracy Estimation

Localization system’s accuracy depends mainly on the accuracy of the estimated tag’s distances from the fixed readers. It can be measured in terms of Euclidian distance error between the estimated location and the actual location. The location’s error is calculated as the distance in meters between the estimated and actual locations using Eq. 8.

\[
Distance_{error} = \sqrt{(X - a)^2 + (Y - b)^2}
\]

Where: \((X, Y)\) is the actual tag location, and \((a, b)\) is the estimated tag location.

The optimization algorithm described later is designed to find a near optimum solution for propagation model parameters in order to maximize its localization accuracy. However, using the Euclidian distance error as an objective function for the optimization algorithm increases required computational overheads by the microcontroller. Therefore, the error in the distance estimation (between a reader and a reference tag) is used to measure the system accuracy. Hence it was important to study and understand the sensitivity of the estimated distance on the location calculation using the LSE trilateration algorithm described above.

Monte-Carlo simulation is used to study the LSE trilateration algorithm sensitivity to the estimated distances. This simulation is used to quantify the effect of estimated distance errors on the estimated tag’s location. The identified sensitivity thresholds (limits) will be used to flag requests for localization system calibrations. To perform this sensitivity analysis; three fixed readers were placed at locations \((0, 0)\), \((0, 3)\) and \((5, 3)\). A tag was placed at the location \((2.5, 1.5)\), and its estimated distances were ranged to show four levels of error \((\pm 5\%, \pm 10\%, \pm 15\%, \pm 20\%)\). Figure 4 shows the tag’s estimated location against the tag’s actual location.
The empirical CDF of the estimated location errors was calculated to derive the thresholds for the system accuracy with 95-percentile confidence level as shown in Figure 5 and Table 2.

![Figure 4. Tag's Estimated Locations vs Actual Location](image)

![Figure 5. The CDF of Tag's Estimated Location Errors](image)

**Table 2: Location Estimation Error Thresholds vs Errors in Distance Estimation**

<table>
<thead>
<tr>
<th>Error in Distance Estimation</th>
<th>Location Estimation Error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>±5%</td>
<td>0.220</td>
</tr>
<tr>
<td>±10%</td>
<td>0.533</td>
</tr>
<tr>
<td>±15%</td>
<td>0.673</td>
</tr>
<tr>
<td>±20%</td>
<td>0.893</td>
</tr>
</tbody>
</table>
The developed system was designed to trigger system calibration when the error in distance estimation becomes higher than ±15% in order to keep the location error within 0.65 meters (however these settings are changeable by the user).

### 5.4 Propagation Model Self-Calibration

The developed calibration process is intended to automatically derive propagation parameters without any prior knowledge on propagation conditions. It relies on periodic calculation of reference tags locations and computation of system accuracy, and then auto calibrate the model parameters when experienced low accuracy conditions.

From equation 3, the measured distance $d_{\text{measured}}$ can be calculated as:

$$d_{\text{measured}} = e^{\frac{(PL(db)-A)}{B}}$$  \hspace{1cm} [9]

The absolute error $d_{\text{error}}$ in the measured distance can be calculated as:

$$|d_{\text{error}}| = |d_{\text{actual}} - d_{\text{measured}}| = |d_{\text{actual}} - e^{\frac{(PL(db)-A)}{B}}|$$  \hspace{1cm} [10]

Where is the actual distance $d_{\text{actual}}$.

The Average Absolute distance error for $m$ readings collected from readers:

$$\left|d_{\text{error}}\right|_m = \frac{1}{m} \sum_{i=1}^{m} \left|d_{\text{actual}i} - e^{\frac{(PL(db)_{i}-A)}{B}}\right|$$  \hspace{1cm} [11]

The calibration algorithm will determine the value of $A$ and $B$ to minimize the mean absolute error for each reader. The objective function of the algorithm is:

$$Z = \min \left(\frac{1}{m} \sum_{i=1}^{m} \left|d_{\text{actual}i} - e^{\frac{(PL(db)_{i}-A)}{B}}\right|\right)$$  \hspace{1cm} [12]

This objective function is non-linear which does not allow for an exact solution. Evolutionary optimization methods such as Genetic Algorithm (GA) or Particle Swarm Optimization (PSO) can be used to solve these kind of problems. PSO has the same effectiveness (finding the true global optimal solution) as the GA but with significantly better computational efficiency (Hassan et al. 2005). The computational efficiency of the selected optimization algorithm is very important for the developed method due to the limited computational resources of the microcontroller (memory and speed).

### 6 EXPERIMENTAL VALIDATION

For validating the proposed method, experiments were conducted using a grid formation test bed, where readers are installed at the corners of the area, then tags were placed one meter apart in grid formation as shown in Figure 6a. This test setup is repeated after adding physical obstacles in the surrounding environment (as shown in Figure 6b) to simulate the change in the environment and test how the proposed method self-calibrates its model to account for interferences caused by the surrounding environment. Experiments were conducted in a laboratory environment at Concordia University Construction Automation Lab. A total of 1062 data sets were collected covering 15 m$^2$ of surface area. The test bed had 17 mobile tags, 4 reference tags and 3 fixed readers, with an average density of one reader per 5 m$^2$ and one reference tag per 3.75 m$^2$. In the first experimental step the setup in Figure 6a was used and the dynamic signal propagation model (Eq. 3) has been initialized with initial values based on experimental measurements ($A = -38.909$ and $B = -8.989$) and tags' distances from the fixed readers were estimated accordingly. The system localization accuracy was measured at 87%.
After adding physical obstacles as shown in Figure 6b, the system location accuracy fell below 80% and the distance error was increased. Figure 7 shows a graphical display of the actual locations versus the estimated tag’s locations after adding the obstacles, the orange triangles represent the actual tag’s locations, and the black crosses represent the calculated tag’s location.

The calibration stage was initiated based on encountering low system accuracy. Each reader signal propagation model is optimized using PSO algorithm and the RSSI from reference tags, the enhancement in the location estimation is clearly identified in Figure 8, which shows a graphical display of actual tag’s locations versus the estimated tag’s location after calibration.
Figure 9 shows the CDF of estimated distance errors for reader 1 before and after the calibration stage, where the mean error in the distance shows a decreasing trend. The mean absolute percentage error before calibration was 37.69%, while it was 14.96% after calibration. The SC-WSN method decreased the mean absolute percentage error by 60%.

It is important to mention that from a practical deployment point of view, an in-depth analysis about the relationship between the density of reference tags and their geometrical distribution needs further investigation. Also, it is important to investigate the processing time for the proposed method with respect to its real time applications. These issues are part of this ongoing research.

7 CONCLUSION

This paper presented a newly developed method for indoor localization on dynamic construction jobsites utilizing a self-calibrated wireless sensor network (SC-WSN). The developed SC-WSN hardware consists of fixed gateway units mounted at predefined locations, reference tags and mobile tags mounted on tracked objects. The developed method consists of a prediction stage and calibration stage. The prediction stage estimates the tag’s location based on its measured signal strength (RSSI), which in turn is converted to the corresponding distance from fixed readers by a dynamic signal propagation model. The calibration stage is executed whenever the system accuracy falls below 80%, where the dynamic propagation model parameters are optimized to minimize the distance estimation errors of the reference tags. A particle swarm optimization (PSO) algorithm is used to find a near optimum solution for this non-linear problem. The PSO is not only able to find a solution effectively, but also has significantly better computational efficiency. Experimental results illustrated the significant accuracy improvement in estimating locations on construction jobsites, where the mean absolute percentage error before calibration was 37.69% while it was 14.96% after calibration. The SC-WSN method decreased the mean absolute percentage error by 60%.

References


AN INTEGRATED PROCESS-BASED SIMULATION PLATFORM FOR CONSTRUCTION PROJECT PLANNING

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Abstract: The application of simulation technique for construction project planning is a very promising but also a challenging field of research. Creating reliable and reusable simulation models is very complex, combined with high costs. This paper presents the development of Construction Simulation Toolkit “CST” and a collaborative simulation portal “ProSIM”, which supports the planning of construction project using discrete-event simulation method. The objective of this research is promoting a wider adoption of simulation in construction industry and support planning of real project using simulation technique through providing a construction-specific simulation toolkit allowing the rapid development of simulation models and an online collaborative platform in order to facilitate the integration of complex construction projects data. CST aims to support planning of production and logistic operations of construction projects in one unified simulation models and running “what if” scenarios in order to support decision making and improve planning quality, while ProSIM aims at enabling the collaboration among the simulation experts and other project design and planning teams. The paper presents the latest research work and the prototype implementation through study cases.

1 INTRODUCTION

Construction planning is a fundamental and challenging activity in the management and execution of construction projects. It involves the choice of technology, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions among the different work tasks (Chris 2000). There are many planning methods and techniques to help with project and resource planning; one of the advanced techniques is using simulation technique. It can help to optimize project schedules and run “what if” scenarios or test different construction strategies or different resource profiles to proof and compare different plans against different goals e.g. total duration of the project, total cost, and resource utilization aspects. However using simulation for construction projects is still limited compared to other branches of industries. Adoption by construction industry has lagged, for three potential reasons: (1) simulation is not accessible, (2) it cannot handle the complexity of modern construction projects, and (3) the benefits are not immediately obvious (AbouRizk 2011). Therefore, providing a convenient simulation tools and collaborative platforms to support and integrate the huge and complex projects data with low-cost entry for construction industry is crucial to promote a wider adoption of simulation in construction industry. With convenient we mean here tools which are designed especially to take in account the unique aspects and commonly used data models in construction industry. Consequently, having such tools will improve the planning quality and reduce costs, waste and construction conflicts.
The Construction Simulation Toolkit CST and the web-based collaborative portal for managing simulation models “ProSIM” have been developed within the national German leading research project Mefisto (www.mefisot-bau.de 2009-2012) which is a part of the IKT 2020 research for innovation intuitive. The development of CST aims to accelerate the process of creating reliable simulation models for production and logistic operations during the planning and operation phases of construction projects. ProSIM portal aims to enable communication and collaboration between involved planning and simulation experts.

In general, simulation models based on CST aim to support the planning process in order to reduce the total duration and cost of construction projects and to avoid any conflicts during the construction phase by improving the planning quality and utilization rates of resources. The simulation model should support the project manager to verify the feasibility of a given project schedule with a combination of different resource constraints or different building design alternatives or construction methods. The toolkit provides a set of reusable simulation components with a simple user interface for rapid building of process-based simulation models for planning projects with resource and activity calendar constraints. It has a modular structure and consists of a set of simulation reusable input and output components. Sections 2 and 3 describe briefly the concept of using formal reference process models of construction operations and the multi-model data exchange approach. Section 4 presents the simulation platform architecture and provides more details about CST and ProSIM implementation, finally in section 5 a two study cases are discussed.

2 REFERENCE PROCESS MODELLING OF CONSTRUCTION OPERATIONS

Reference models are generic conceptual models that formalise recommended practices for a certain domain (Rosemann 2002). As the knowledge in every domain keeps evolving, the reference models change continuously and goes through a "discover, model, evaluate, and optimize" modelling cycle. So new reference models will be added or existing models will be improved and detailed with time. Therefore, a continuous collaboration between planning, construction management and simulation teams is very important to capture the best practice of delivering construction and logistic activities as well as to validate and integrate the feedbacks during the construction phase of real projects. The reference process modelling method allows identifying, capturing, documenting, improving and sharing the knowledge about the best practice of construction processes and their related information. In our approach, there is a clear separation between the core simulation components and the process models for the application domains. Business Process Modelling and Notation (BPMN) models are used to capture and describe the logic of production and logistic operations and to transform them automatically in one step into simulation models.

Special BPMN Extension elements are developed in order to define resource requirements and durations of tasks inside the reference models in a flexible way. Each activity or task inside the project schedule is linked with a reference process model during simulation. In this way, the process models define the logic and level of details of simulation models. One needs to examine every detail of the construction process carefully and identify the major events and processes that will be presented in the simulation model in order to create a reliable simulation model (Aouad et al. 2006). The graphical representation of BPMN models makes models easy to understand between all involved teams and the formal specifications in XML allows transforming process models into simulation models automatically. The BPMN reference process models will be transformed and imported into a ready to use process templates repository in the simulation toolkit. The process repository includes reference process models which are reusable across different construction projects and their data definitions of resources and productivity factors.

In our approach, aforementioned BPMN modelling technique is used to create semantic and graphic process models for various construction operations. BPMN models consist of simple diagrams constructed from a limited set of graphical elements.

Flow Objects are the main elements to define and control the behaviour of a business process. The scope of BPMN elements which can be used inside the simulation process templates are:
• Start/End events
• Task and sub-process
• Sequence flow
• Gateways: Parallel Fork/Join, Data-Based XOR
• Conditional and default flow.

Process models will be imported into a process catalogue as ‘ready to use’ Reference Process Models (RPM) inside the simulation model. The process catalogue includes reference process models for the best practices of various construction processes that are reusable across different construction projects. In addition, RPMs are extended to include resource requirements and productivity factors. The knowledge accumulation enables a continuous improvement of the process catalogue.

A process template can be as simple as having one single activity or a set of serial activities which run sequentially without any kind of control flow or very complex ones including loops and conditional gateways which may result in skipping/ repeating some activities. In order to create reliable simulation model, one needs to carefully examine every detail of the construction process and identify the major events and processes that will be presented in the simulation model (Akhavian and Behzadan 2011).

In CST, the user has the freedom to move the logic and the dependencies between different tasks to be a part of the input data for each simulation model or to be included inside process templates. However this may lead to one of the following extreme situations:

1. Very detailed project schedule and a lot of tasks dependencies as a part of simulation input with a set of simple process templates for each task.
2. Very simple project schedule consisting of few tasks with a high level of abstraction combined with very complex process templates.

Both cases must be avoided to get the most out of the simulation model in the sense of ease of use and the flexibility of answering as many as “what if” scenarios. It is mainly the responsibility of the user to maintain balance between these options according to the simulation goal and the availability of data. Figure 1 shows as an example of a good balanced process template for erecting a wall for three construction methods: Precast, In-situ concrete and as bricks walls.

By using this template there is no need to use three different templates and link them explicitly to each wall as part of the simulation input, which reduce the time and efforts to prepare the simulation data. The definition of resources and duration value/formula for each single task can be embedded inside the BPMN process template or maintained in separate database.
3 MULTI-MODEL PROJECT DATA EXCHANGE APPROACH

Multi-model project planning is a paradigm shift from the building-centric approach, which tries to add and link all project data with building models toward an equivalent interlinked data models using special link models. The multi-model method offers solutions to structural problems of nD modelling in construction information processes (Akhavian and Behzadan 2011). A multi-model container comprises several data files and includes, besides the meta-information about the container content, several application models as well as link models (Schapke and Scherer 2010). It allows the combination of heterogeneous application models from different domains and various data formats. Inside multi-model containers link models bind the application models together (Fig. 2).

The link models specify the relationships between items from different data models. Multi-model containers can be used to exchange associated models among the project stakeholders by a common format (Fuchs et al. 2010). In their entirety the multi-models on a construction project open up a multi-dimensional information space of interdependent application models that can be independently processed by the project participants. Each participant has the opportunity to produce new application models on his/her own responsibility and interlink them with existing models. Depending on the situation these newly created multi-models can be maintained locally or published project-wide as a basis for further planning and controlling tasks. In comparison to the often pursued integration of project information in central project databases or product model servers, this approach distributed model-based collaboration represents a paradigm shift (Schapke and PfIug 2012). Multi-model approach is integrated with CST through providing import/export interfaces.
4 SIMULATION PLATFORM

The simulation platform consists of 5 main modules (Fig. 4): (1) Simulation engine and CST toolkit based on the event-discrete simulation software “Plant Simulation”, (2) ProSIM portal as Ruby on Rails web application, (3) Simulation database, (4) BIM data server based on IfcWebServer.org and (5) Apache web server.
4.1 Construction Simulation Toolkit CST

The CST toolkit is implemented on top of the simulation software “Tecnomatix Plant Simulation” © from Siemens PLM. Simulation components of CST can be added to the simulation models in a modular way as they are needed. Most of the core components are generic and are not related directly to the construction industry domain; therefore the toolkit can be used to solve planning and scheduling problems in different domains. Construction domain specific components are responsible of processing the input information coming from various data models of construction project data and to represent and evaluate simulation results and making them accessible and understandable for engineers without deep experiences in simulation techniques.

Both of production and logistic operations can be simulated using CST toolkit. They affect each other interactively i.e. production tasks starts after the material delivery, or logistic operations can block the key resources like tower crane and prevent production tasks to use them. Figure 5 shows the main simulation components on CST, which are described in details in this list:
- **Multi-Model-Container**: It is the import/export interface between a multi-model container and the internal data in simulation model.

- **BIM Data**: This component contains all the information from the BIM model that is relevant for the simulation and extracted from IFC models using special scripts based on the IFCWebServer.org data model server, or created inside the simulation model directly using the Floor-Editor component.

- **Task List**: This component is an important core element for simulation input. It contains all the information about the logistic and construction operations that they have to be simulated.

- **Resource-Pool**: This component is a manager and container for all available resources and the definition of their capacities during the simulation. It includes standard resources used in construction domain like labours, equipment, and building materials or any kind of resources, which can be added in a generic way. The availability of resources is defined as delivery tables (time, amount, attributes) so level of resources can vary over time in a planned manner.

- **Construction Site**: With the help of this simulation component the information of the construction site layout and equipment i.e. transportation routes, tower cranes, storage space, loading zone, arrivals and departures are managed. The changes to the construction site layout during the project progress are considered.

- **Process Repository**: This component manages the global Reference Process Models RPMs of typical construction process.

- **Process-Pool**: Process Pools are virtual hierarchical containers of process instances; each process pool can contain other process pool objects or process instances. In this way it is possible to put a set of related tasks inside one process pool object and define the “end to start” relationships between different groups of tasks using an alphabetic hierarchical string in a very flexible and powerful way. The status of any process pool object will change from “started” to “completed” when all process instances and sub-process pools inside it are complete. The hierarchy structure of the process pool is not restricted in any way, however it is recommended to use a similar hierarchy structure of the real project and to create sub-process-pools for each summary task in the project schedule, for example:

- **Construction site**: With the help of this component the information about construction site layout and equipment are managed. At moment CST supports the following elements:

- **Gantt Charts**: It represents the simulation results (planning schedules) as Gantt charts. It allows combining the individual sub-tasks to summary tasks, compare different simulation scenarios and export the results in various level of details to MS Project.

- **Draw-Panel**: With help of this component 2D graphical representation and animations of the progress of construction processes can be created during the simulation. Each task inside the process model can be provided with a special code to draw on a different layer with predefined colours regarding the kind and location of the construction activities.

- **Project Monitor**: This component displays the resource utilization and material consumption graphically during the simulation run, for example, the utilization rates of workers, tower cranes, concrete pumps and material consumption.

- **4D Visualizer**: This component provides the ability to visualize and animate (3D&4D) the construction progress and state of construction site elements at any time point. 3D models are exported using the standard format COLLADA and the export function can be configured to run based on fixed time intervals, (hourly, daily, weekly, etc.) or after the finish of certain construction processes. 4D visualization can be generated automatically using the 3D models and special scripts written for Trimble SketchUP®.

- **Floor-Editor**: With the help of this component the user can quickly create a simplified building model.

- **Project Template**: The input and output simulation components are combined together as the default simulation project template. This makes it possible to create simulation models very quickly and to simulate and compare different scenarios of the same construction project in parallel.

### 4.2 Collaborative Portal ProSIM

The ProSIM platform is designed as an online web-based portal to support the communication and collaboration among all project planning members and to publish simulation model results and all related input data (Ismail et al., 2014). It facilitates the verification of all input parameters and simulation results effectively.
Besides publishing simulation models, their scenarios and results, it offers the following functions:

- Online management of productivity factors of various construction operations (http://bci52.cib.bau.tu-dresden.de:3000/aws)
- Online management of resource requirements and task duration definitions (http://bci52.cib.bau.tu-dresden.de:3000/aws)
- Online repository of reference process models of construction activities as BPMN models (http://bci52.cib.bau.tu-dresden.de:3000/rpms)
- Multi-Model Navigator to explore and transform the content of interlinked project data (http://bci52.cib.bau.tu-dresden.de:3000/mmc)
- Online viewers of various input and output data (Gantt charts, resource utilization charts, 2D animations, Calendar view, etc.)

ProSIM is implemented using the modern web development framework “Ruby on Rails”. This web development framework was chosen because it is suitable for rapid development. It also emphasizes the use of well-known software engineering patterns and principles, such as active record pattern, and Model–View–Controller MVC. The Web application is deployed via Apache web server and MySQL database.

5 STUDY CASES:

5.1 Mefisto Office Project

The first demonstration and validation simulation project “Mefisto office” is a multi-storey office building. The structural work activities have been simulated based on a rough master project schedule. In this project all simulation input data was created or imported manually and the logistic (construction site layout, material delivery, etc.) and cost information were excluded. For this project 2 simulation models and various scenarios were implemented and analysed in order to: (1) Automatic generation of detailed project schedules for the whole building taking in account different construction strategies and maximal resource capacities, (2) Simulate and optimize the structural work for short term planning of construction phase taking in account the formwork and reinforcement work details. More details and simulation scenarios are this demonstration project are described in (Ismail and Scherer 2014).

![Image of simulation results]

Figure 6: The effect of changing number of workers on the of structural work duration
Fig. 6 shows the effect of changing the number of workers between 10-40 workers on the expected duration of structural work, workers utilization and the consumption of concrete for 2 floors.

All results of simulation scenarios for this project are available under: http://bci52.cib.bau.tu-dresden.de:3001/simweb/

5.2 Mefisto Airport Terminal Project

For the second demonstration project “Mefisto Airport” two simulation models based on CST toolkit were implemented and different scenarios were prepared and carried out.

The first test case was to generate automatically a detailed project schedule of construction work of the whole building based on the concept of “top-down simulation method” described in details in (Ismail 2011). The main inputs of this case are: (1) master project schedule, (2) high level reference process model which describe the logic of structure work in each floor, and (3) a set of detailed reference process models which describe the logic of structural work for different kind of building elements (slab, beam, column, etc.).

The multi-model project delivery approach and multi-model-container data exchange method have been used in order to extract all related project information and transform them to the internal data structure of the simulation model as following:

- The master schedule in the multi-model container (in iTOW XML format) has been transformed into a “Task list” simulation component. Each task represents the structural works within one floor or a work-section has been linked with the high level reference process model of structural work.
- The simulation related data inside the IFC model of the building were processed using MMQL, BIMFit and IFCWebServer data model server and converted to the internal data structure of the simulation database.
- Link model data has been imported into simulation model in one step

After the automatic generation of the detailed project schedule a “minimal project duration” scenario was carried out. In this scenario the capacity of available workers and building material was set to unlimited and only the capacity of tower cranes were considered. The aim of this scenario was to validate and test the feasibility of top-down simulation method and also to analysis the effect of changing the construction strategies and the dates of milestones in the master schedule on the ultimate minimum construction duration. The simulation model and the results of this test case are available through ProSIM under: http://bci52.cib.bau.tu-dresden.de:3000/sim_models/3

The second case study for the Mefisto Airport focused on the simulation of structural work inside one floor. The target was to analyze the effect of changing various factors like resource capacities, the interaction between production and logistic operations and construction methods (in situ concrete, precast) on the expected total duration and the resources utilization ratio. In order to simulate the logistic operations the necessary information about the construction site model was imported from a special IFC model. This model includes the following information: entry and exits gates, transport ways, tower cranes properties and location and yard storage areas. This information was mapped directly into the internal data structure of the “Construction Site” component, which convert them in turn into active and passive material flow simulation objects. With help of “4D Visualizer” component the construction site model can be generated automatically as 4D models including full movement records of crane operations and yard storage areas utilization rates. The simulation model and the results of both scenarios are available through ProSIM under: http://bci52.cib.bau.tu-dresden.de:3000/sim_models/8

6 CONCLUSION AND FUTURE WORK

The target of this research was to promote a wide adoption of simulation methods to support construction project planning. Systems integration and collaboration are believed to be the key enabling technologies that drive the construction industry in improving productivity and efficiency (Shen et al., 2010). This paper
presented the design and development efforts of a process-based simulation toolkit and a collaborative platform and discussed the integration of various project data models into the simulation models using multi-models data exchange approach. It discussed also the concept of using formal process models based on BPMN in order to capture and manage knowledge in construction domain and transfer them directly into simulation models. The results obtained from demonstration projects showed the potential of using CST and ProSIM by the rapid deployment of simulation models and the flexibility of applying various scenarios. The future development will include the integration between the simulation platform and the project real data collected on site and adding more reference process models for other project types or disciplines like bridges and electric and interior work.

Acknowledgements

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References


A CASE STUDY OF HYBRID LEARNING IMPLEMENTATION IN CONSTRUCTION ENGINEERING

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Abstract: Hybrid learning is an educational approach that combines the elements of online and traditional face-to-face instruction. When planned and implemented well, hybrid learning provide benefits at the student, faculty, and institutional level. The experience of a major Midwestern university in implementing hybrid learning is reported in this paper. Included are six semesters of experience and incremental improvement with a construction equipment course, three semesters of experience with a construction scheduling course, and two semesters of experience with a cost estimating course. The three courses were led by three different faculty members with various expectations, preferences, and approaches. The case study discussion reported here demonstrates the robustness of the hybrid learning approach. Workflow and effort in developing the hybrid classes, online and computer software application tools, best practices and lessons learned are presented.

1 INTRODUCTION

Hybrid learning is an educational approach that combines the elements of online and traditional face-to-face instruction (Garrison & Kanuka, 2004). Because of its blended nature, hybrid learning is commonly referred to as the best of the two worlds as it has the potential to provide the benefits while avoiding the challenges of the two formats (Lamport & Hill, 2012). When planned and implemented well, hybrid learning provide benefits at the student, faculty, and institutional level (Dziuban, Hartman, Moskal, 2004). Online content can be used to address the knowledge, comprehension, and application levels of cognitive activity while the face-to-face learning addresses analysis, synthesis, and evaluation levels while reinforcing learning at the previously mentioned levels. For hybrid learning to be successful, the asynchronous online component needs to be carefully planned and balanced with the face-to-face activities. Well-planned asynchronous online activities can promote student learning with less input of instructor effort and the instructor effort that is diverted can be invested to provide more student engagement during face-to-face activities where students are learning at higher cognitive levels.

The experience of a major Midwestern university in implementing hybrid learning is reported in this paper. Included are six semesters of experience and incremental improvement with a construction equipment course, three semesters of experience with a construction scheduling course, and two semesters of experience with a cost estimating course. The three courses were led by three different faculty members with various expectations, preferences, and approaches. The case study discussion reported here demonstrates the robustness of the hybrid learning approach. Workflow and effort in developing each of the hybrid classes, online and computer software application tools, best practices and lessons learned will be presented next.
2 CASE DESCRIPTIONS

2.1 Case 1: Hybrid Learning in Construction Equipment

*Construction Equipment and Heavy Construction Methods* is a three credit junior level course required for construction engineering students. In the traditional format, the course included two lecture hours and a two-hour calculation lab each week. The overarching goal behind the conversion of the course from traditional to hybrid format was to replace the passive lecture content with the online content and use some of the time released in class time for active learning exercises. Additionally, depending on how much time spent on online activities, the contact hours were reduced to create flexibilities in to both students’ and the instructor’s schedule.

The construction equipment course was the first in the department that was converted to the hybrid format. The instructor worked with an instructional development team consisting of instructional designer, graduate and undergraduate students. Using the screen-recording software Camtasia Studio®, the instructor recorded the content that he would lecture when using a traditional format. Then, the instructional designer worked with undergraduate students to edit the video, slice it into more manageable short segments, enhance it using additional visuals, and create quiz questions. For a more detailed explanation of the workflow for the online component please see Mallen, Jahren, Koehler, & Karabulut (2014). An example video lecture can be seen at [http://www.screencast.com/t/A9MCvuwlyhOG](http://www.screencast.com/t/A9MCvuwlyhOG)

Another unique feature implemented in this course was to replace the example problem sessions that typically follow a lecture presentation with online interactive exercises. These exercises were created using the content development tool Lectora®. The exercises present a problem statement which usually involves multiple steps. Students are required to go through each step to be able to reach a conclusion about the problem statement. Throughout this process, students are supported through additional explanatory videos and demonstration videos for how to solve the problem. A video explanation of how these online modules work can be seen at [http://www.screencast.com/t/MznFBUMh6aF](http://www.screencast.com/t/MznFBUMh6aF)

The face-to-face component of the course involved having students work on more open-ended and real-life problems in teams of 3-4. A teaching team consisting of the instructor, and graduate and undergraduate teaching assistants facilitated the sessions. Rather than spending time lecturing on the content, the teaching team was able to work with individual teams and address any emerging issues, and answer questions. For example, in one of these face-to-face sessions, students were provided with an instructions sheet; plans and blueprints of the jobsite; and a crane chart document. Students were asked to work in groups of three or four to design the whole crane sequencing process using the concepts they learned in the online lectures and modules.

The conversion of the course from traditional to hybrid format provided several benefits at the student and instructor level. First, it created flexibilities both in students’ and instructor’s schedule. The instructor was able to balance out all the administrative and research responsibilities he held as the division leader without sacrificing any teaching load. Likewise, students were able to work on the class activities on their own time. Second, students were able pace their own learning thanks to the recorded content. In their end-of-semester evaluations, they indicated that they liked being able to pause, rewind, and re-watch the portions of the videos as opposed to one-time-shot in traditional lectures. Finally, this format empowered graduate and undergraduate students as they played a major role in facilitating the face-to-face sessions and provided them the experience of teaching a junior-level course.

2.2 Case 2: Hybrid Learning in Construction Scheduling

*Construction Planning, Scheduling, and Control* is a-three-credit senior level course required for construction engineering students. In the traditional format, this course also included two lecture hours and a two-hour calculation lab each week. The overarching goal behind the conversion of this course to the hybrid format was to capture timeless, theoretical content that remains the same regardless of time in the best way possible so that students can watch it on their own time and at their own convenience. The online lecture development process was quite similar to that of the construction equipment course. First,
the instructor carefully analyzed the course syllabus to identify the topics that could effectively be
converted to the online format. Then, he recorded the lectures using the screen recording software,
Camtasia®. The instructional design team then worked on the recorded lectures to edit, animate, and
produce the content. Every semester, feedback was collected from students on these online lectures to
address any issues on a timely manner.

The conversion of this course to the hybrid format also provided two major benefits to the instructor and
students. First, it created a flexible schedule for everyone. The instructor was able to travel to attend
conferences on new construction scheduling technology without having to cancel any classes. In other
words, he moved the topics around based on his travel plans so that students could do the online
activities while the instructor was traveling. Similarly, students could work on the online activities at their
own convenience and balance their workload. The second benefit was the learning gain for students. The
informal feedback from the students and the anecdotal data from the instructor indicated that the students
in the middle range of the grading scale were the ones who benefited the most from this format. Because
they were able to pause, rewind, and re-watch the portions of the video, they were better able to retain
the information.

2.3 Case 3: Hybrid Learning in Construction Estimating

Construction Estimating is a three-credit senior level course required for civil and construction
engineering students. In the traditional format, this course also included two lecture hours and a two-hour
calculation lab. The overarching goal behind the conversion of this course to the hybrid format was similar
to that of the construction equipment. By taking the passive lecture component of the course to the online
format, the instructor was able to create space in face-to-face classroom time for team-based learning
and active learning exercises. The conversion process for this course has been a little more complicated
than the other two courses, and it is still under development.

The process started with recording a regular classroom lecture. The instructor used a regular audio
recorder to capture his traditional lectures. A graduate student transcribed the recordings, and the
instructor cleaned up the transcripts to better fit into a screen capture format (e.g. removing student
interactions, etc.). The instructor for this course is a non-native speaker of English and he wanted the
lectures to be recorded by a native speaker, so transcripts were sent to a native speaker who recorded
the audio for each slide of a lecture presentation. The instructional design team then combined the audio
files with slides, added visuals, and inserted quiz questions, and uploaded the materials to the course
management site.

Another online component in this course was software application tutorials. The instructional design team
worked with a graduate student who had been a teaching assistant for the course before to create
tutorials for the construction estimating software, WinEst. Students were required to use the software for a
few class projects. The tutorials were created using the screen recording software demonstrating the
main features of the application that could be helpful for students in completing their projects. These
tutorial videos were posted on the blackboard and made available for students’ convenience. However,
they were not required as the online lecture videos were. Rather, they were provided as on-demand help
videos. If students felt comfortable with the software, they did not need to watch the videos, or they could
choose which ones to watch.

Finally, the instructor revised the face-to-face activities and lab assignments and converted them to more
open-ended problem cases so that he could use the released class time for teamwork and active
learning. For this conversion, the instructor contacted industry leaders and asked them to provide real
construction projects and data for students to work on. The homework and assignments were re-written
based on the input received from the construction industry leaders. Although similar benefits are expected
in this course, we have not collected any feedback from students yet.
3 LESSONS LEARNED

Based on our experience in hybrid course development in a construction engineering program, we can conclude that hybrid learning improves learning and provides benefits for students and faculty by creating a flexible teaching and learning environment. These kinds of innovative teaching environments enhance life-long learning skills in students, as they have to arrange their own learning and study agendas, keep up with different learning activities, and improve their meta-cognitive strategies to be successful learners. We can make the following practical recommendations for those who are interested in converting their traditional face-to-face classroom to a hybrid format.

- **Required online content**: Students need to be held accountable somehow to ensure they are engaged in the online activities. In our case, we have embedded quiz questions along the videos to gauge students’ understanding of the content and motivate them watch the assigned videos which would be essential to be successful completing the in-class assignments. These quizzes were auto-graded and automatically recorded in the gradebook on course management site, which substantially reduced the instructor load.

- **Online support**: Because students will be learning a new concept on their own without an opportunity to ask for clarification immediately, the online environment should be designed in a way to facilitate student learning. In our case, we provided additional explanatory videos both for the content and how to solve problems.

- **Technical issues**: Technology should not get into way while students are trying to learn a new concept. Therefore, every effort should be made to reduce the number of technical issues to minimum, or they should be addressed in a timely manner.

- **Connection between online and face-to-face activities**: There should be a clear connection between online and face-to-face activities and they need to be meaningfully weaved together. This will help students better understand the rationale behind the hybrid format and how they can improve their learning in this new environment.

- **Preparing students**: Although the students engage in all kinds of online activities in their daily lives, this kind of learning environment can be new to them. Training students for hybrid format so that they know what it is, why it is done, and what is expected of them will help them be more engaged in their learning experience. In our case, we have found out that successful students used some study strategies (i.e. taking notes while watching, working on problems on one screen and watching the video on another screen, etc.) that helped them succeed in the course. We have taken those strategies and used them as recommendations for how to be succeed in hybrid courses in the following semesters.

- **Consistent structure**: A hybrid course may have different requirements for online and face-to-face activities and students may lose track of all the tasks they need to engage. Providing a well-established and consistent course structure will possibly help students keep track of the tasks.

References


INTEGRATING DECISION SUPPORT SYSTEM (DSS) AND BUILDING INFORMATION MODELING (BIM) TO OPTIMIZE THE SELECTION OF SUSTAINABLE BUILDING COMPONENTS

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Abstract: One of the challenges in sustainability analysis and its development is the selection of sustainable materials during the design stage, which can meet the owner’s expectations when investing in sustainable building projects. This expectation is achieved only when a strategic approach is adopted by decision makers (DMs) while selecting the construction materials despite of the complexity of this process. Building Information Modeling (BIM) helps designers assess different design alternatives at the conceptual stage of the project. Additionally, BIM aids in assessing the environmental impacts (EIs) of these design alternatives as well as their associated energy savings all over the building life. Thus, applying BIM concept would help designers to select the right type of materials at the early design stage and to make material related decisions that have great impact on the building’s life cycle. The main purpose of this study is to propose a methodology to integrate BIM tools with problem solving methods for decision making (i.e. Entropy-TOPSIS) in order to optimize the selection of sustainable components in an effective way at the conceptual design stage of building projects. Therefore, a Decision Support System (DSS) is developed by using Multiple Criteria Decision Making (MCDM) techniques to help design team decides and selects the ideal type of sustainable building components and hence design families for proposed buildings based on the sustainability main criteria: 1) Environmental, 2) Economical “cost efficiency”, and 3) Social wellbeing, in an attempt to identify the influence of design’s variations on the sustainable performance of the whole facility. The multi-criteria procedure embedded in the DSS relies on numerical models used to simulate alternatives’ situations, as well as ranking the best alternatives based on owners’ strategic preferences and the availability of sustainable materials in the market; and thus provide detailed and accurate results. The set of models included in the DSS describe the relationship between the different sustainability criteria, companies’ sustainable decisions, and interactions that take place when selecting sustainable materials for building projects. An actual case project will be used to validate the workability and capability of the proposed methodology.

1 INTRODUCTION

The variety of projects’ boundaries, decision makers’ preferences, and availability of sustainable building materials make the aspects of decisions more difficult to achieve in terms of sustainable development. Owners who choose to invest in the construction of sustainable buildings want to use materials and products that are fully sustainable, thus deciding on the ideal ones can be questioned especially when suppliers offer diverse ranges of these types of materials. Usually, a typical building’s component/product
is manufactured by using various elements, where each element may consist of several types of materials. In many cases, a chain of suppliers/producers assemble the products by processing and manufacturing their elements, which lead to a final release of the materials to customers (Aumonier, 2013).

The Multiple Criteria Decision Making (MCDM) approach is a well-known branch of the decision making process. It deals with decision problems under the presence of a number of decision criteria. The decision-maker is required to choose from different types of criteria that are either quantifiable or non-quantifiable or multiple. The objectives are usually conflicting due to their dependency on each other and therefore, the solution is highly dependent on the preferences of the decision-maker, which sometimes must be compromised. Generally, two different methods are used to solve the MCDM problems, which are the Multiple Objective Decision Making (MODM) and the Multiple Attribute Decision Making (MADM). MODM deals with many objectives to come up with an optimal solution to achieve the set objectives, which sometimes conflict one with another and accordingly makes the goal to attain an ideal solution more challenging and problematic. Whereas in the MADM method the decision maker transacts with alternatives that have variety of performance attributes and factors, which can be either qualitative or quantitative (Shanian and Savadogo, 2006). The MADM is generally a discrete method, with limited numbers of pre-determined alternatives. It specifies how to process the attribute's information in order to reach an ideal choice. Rao (2007) thinks that this method needs both inter-attributes and intra-attributes comparisons and should involve appropriate explicit trade-offs. To model these attributes, most of the MADM methods are presented through a decision matrix. This matrix consists of alternatives, criteria and relative significance of criteria where all the components should be normalized to a comparable scale. The key method for ranking the alternatives is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which is one of the objective weighting methods in MCDM. It is a method of compensatory aggregation that compares a set of alternatives by identifying weights and normalizing scores for each criterion and then calculating the geometric distance that exists between each alternative and the ideal one, which is the best score for each criterion.

The significant advancement in computers makes the application of MCDM methods simpler for decision makers and users who are dealing with multiple alternatives and complicated mathematical problems. Thus, Decision Support Systems are generated to aid in problem solving procedures by providing solutions that combine quantitative data and qualitative knowledge/perceptions, and process information in order to present, compare, and rank potential alternatives and, ultimately, select the one that meets the established decision criteria (Lu et al., 2007). DSS can help increase the decision maker's efficiency, productivity and effectiveness. It can also facilitate the communication between different parties in an organization and contribute to quick problem solving.

Building Information Modeling (BIM) is a recent concept used in the building industry all over the lifecycle of projects starting from design and documentation passing through construction and ending by operation. BIM Models not only provide graphical presentation of the project but also automatically generate information such as drawings and reports, design analysis, schedule simulations, and ultimately help the design team make better-informed decisions that affect the whole lifecycle of buildings (Byrne, 2009).

This paper proposes a methodology that integrates Building Information Modeling tool with Decision Making techniques in the format of a data-based Decision Support System (DSS) that systematically incorporates the selection procedures of sustainable components and green materials into BIM environment. The DSS is developed within the principles considered while creating an efficient integration between Building Information Modeling (BIM) concepts and environmental and socio-economic indicators for sustainable development. In particular, the DSS evaluates green building materials supplied by different suppliers and afterwards suggests the optimum selection.

2 LITERATURE REVIEW

Commonly, modeling the decision making step is considered as the most fault-finding phase in the whole decision making processes (Simon, 1977). Thus, it is essential to properly define the problem in order to
formulate the model. To solve the decision making problems, there are several approaches. Lu et al. (2007) described different methods and systems that can be used during the decision making process that include: 1) Analytic Hierarchy Process (AHP), which is a decision making method that allows decision makers consider both the qualitative and the quantitative aspects during the decision making process. 2) Paired Comparison Analysis method, which is employed in cases that alternatives are related to each other. The method enables decision makers consider priorities, which are sometimes on the contrary to the project demands. 3) Grid Analysis method, known as matrix or multi attribute theory, is an effective approach in which decision makers cope with many alternatives and criteria. In this method, the criteria and alternatives are first defined, then the importance of relative factors' is identified and after that the weights are employed based on the decision makers' priorities that are also combined with the criteria's importance. 4) Computerized Decision Support Technology System, which is a tool by which the decision maker is able to perform large numbers of complex models in a short period of time. This tool helps decision makers to share, store, and update and transmit the data in a faster and more economical way besides reducing the risks of human errors. Simon (1977), however, describes the Decision Tree Model as a graphical presentation of decisions and their likely results. This predictive model consists of data-sets of observations that are connected to each other through sets of nodes and leaves, where each interior node stands for a variable and each leaf demonstrates the expected values of that variable.

Due to the variety in MADM approaches, there are different methods that may be used during the process of selecting materials, these include: TOPSIS, ELECTRE, VIKOR, ANP, and PROMETHE. Each of these methods has advantages and disadvantages. Therefore, researchers have applied diverse approaches while identifying the proper technique. For example, Jahan and Edwards (2013) applied VIKOR method for the selection of materials for buildings. Peng and Xiao (2013) used ELECTRE decision making technique for the purpose of material's selection problems arising out of various engineering applications. Recently, Liu et.al (2014) utilized the novel hybrid multiple criteria decision making method, which simultaneously considers the qualitative and quantitative factors. That method is a combination of both the ANP and VIKOR approaches.

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method that was originally developed by Hwang and Yoon (1981). The principal objective in TOPSIS is to select the best alternative with the shortest distance from the ideal one (Yoon, 1981). The developers assumed that if each factor takes a decreasing and increasing variation, it is possible to find the ideal solution. The unique features of TOPSIS explains its popularity and efficiency where the vector normalization eliminates the units of criterion function so any change in one attribute can be presented in a direct or opposite behavior by the other factors. Also, the results can be ranked according to their preferences and their numerical values. This ranking gives a clear comprehension of the differences in the preferential alternatives and their similarities while other MADM methods (e.g., ELECTRE) show only the ranking values of the alternatives regardless of their differences and similarities. The main pitfall of the pair-wise comparisons in AHP methods is highly avoided. While working with vast numbers of alternatives and attributes, TOPSIS is more efficient and faster.

The impact of BIM on the design practice is significant since it raises new ways and processes of delivering design, construction, and facilities management services. Currently, owners not only want buildings to be designed and delivered on time, within budget, and with high quality but they are also interested in their services beyond the design and construction (Clayton et al, 1999). Based on Kubba (2012), Becerik-Gerber and Rice (2010) the development of a schematic model prior to the creation of a detailed building model, helps designers make more accurate assessments of the proposed scheme and identify whether it meets the functional and sustainable requirements set by the owner. This would increase the project performance and its overall quality. An integrated BIM model can facilitate the collaboration and communication processes between project participants during the early design phase to effectively provide a well-performed building during the operation stage (Hungu, 2013). BIM concept allows multidisciplinary information to be superimposed within one model by incorporating structural, mechanical, electrical, plumbing and lighting information into a single model (Tucker and Newton, 2009). It helps owners visualize the spatial organization of the building as well as understand the sequence of the project’s construction activities and their related durations (Eastman et al, 2008). Combining sustainable design strategies with BIM concept has the potential to change the traditional practices of
design and to efficiently produce high-performance designs for proposed buildings. BIM concept can be used to support the design and analysis of a building system at the early design phase. This includes experimental structural analysis, environmental controls, construction methods, selection of new materials and systems and detailed analysis of the whole design processes.

The methodology proposed in this paper can be used to implement an integrated platform to do sustainable design for new buildings at their conceptual stage. The methodology is implemented by designing and developing a Decision Support System (DSS) that simplifies the process of selecting building components and construction materials while designing sustainable buildings. The methodology incorporates an integrated model capable of guiding users when performing sustainable design for new building projects. Although previous studies described several methods and techniques used to help the project team in selecting optimum combination of building components, authors could not find any research that has been implemented with the focus on integrating BIM concept with DSS techniques. Creating and linking DSS with BIM tool helps users design and animate sustainable buildings easily and efficiently at the conceptual stage. Yet, part of the integrated methodology is to develop new plug-ins into BIM tool in order to link it with the DSS. The successful implementation of such a model represents a significant advancement in the ability to do sustainable design for buildings at early stages of their life, to optimize the selection of sustainable building components and materials and to evaluate the Life Cycle Cost (LCC) of every design alternative.

3 METHODOLOGY

![Flowchart of the integration Process](image)

One of the expected contributions of this proposed research is the development of an integrated model that incorporates a Decision Support System (DSS), which will be used by designers when selecting and deciding on the best type of sustainable building components and design families for proposed building projects. Traditionally, designers use to choose the construction materials whose characteristics are known or used in previous projects, which may cause multiple problems related to expectations, standards, and owners’ budget. The shortcoming of the traditional method can be handled by using the
MADM method, which is basically based on a complex comparison between the available alternatives. Since the proposed methodology integrates different applications, as shown in Figure 1, its development is implemented through three sequential phases.

**Phase 1** consists of designing the model’s relational database that stores information related to green materials in the form of predefined design families that can be recognized by BIM tool used by designers while designing sustainable buildings. The reason for developing a separate database is to have it loaded every time BIM tool opens by defining its path, which is linked to the predefined library of that tool (e.g., Autodesk Revit). The data related to green materials is saved as families with either (RFA) or (RVT) files format. Thus, in the external sustainable database, up to 3,000 design families are collected from different sources, such as suppliers’ web pages, USGBC and CaGBC websites as well as published data, and are arranged based on the 16 divisions of the Masterformat Work Breakdown Structure (WBS). The information stored in the external database consist of different types such as details about the materials used, suppliers’ contact data, assigned keynotes, potential LEED points and assembly codes.

**Phase 2** focuses on customizing BIM tool to fit the modularity requirements of the proposed model. The first step is to design and implement a 3D module capable of storing newly created families, in BIM tool, and their associated keynotes for components, commonly used in buildings, by using certified green materials. The module is linked to the database developed in Phase 1. Keynotes can be assigned to elements that are typically used in case the user wants to note an entire assembly, such as a wall assembly. The sixteen Masterformat divisions present the main WBS applied in this research. It is very important to select a unique code for each item that is presented in a separate line in the database to ease and simplify their retrieval and use.

**Phase 3** consists of developing a DSS module that assists in selecting sustainable building components. The DSS uses the conceptual design and decision-making parameters, along with material selection heuristics to generate a list of alternatives from the materials database for each design component. After the list of alternatives is generated for each design component, the weight factor extractor requires the user to enter a weight for the sustainability attributes. Generally, alternatives in the MADM problems are often defined by some attributes that are qualitative (Hwang and Yoon, 1981). For comparison purposes, qualitative attributes need to be converted to the quantitative scales. This conversion usually takes place by utilizing the five Point Likert-type scales (Lu et al., 2007). Although these scales convert the qualitative attributes to numbers, in many cases, the scales are not able to clearly distinguish the differences between scores that are close to each other (e.g., high and very high). To solve this problem, Saaty (1980) comes with nine point scale while more intervals are employed by Lu et al. (2007). The values of the sustainability attributes (the importance factor of every attribute to each other) will be collected from experts in the AEC industry. Then, the user’s weights are integrated with the attribute values for each potential material and sorted by the integrator, resulting in a relative ranking of the potential materials for each building component. The building components (products) with the highest ranking are recommended by the system. The user reviews the DSS’s recommendation for each building component, and selects a component for each design element either based on the user’s professional judgment and/or the system’s recommendation. As the building components are selected by the user, the DSS will execute an internal test by using its knowledge base to detect any potential conflicts between the selected alternatives and their associated components and materials. The list of recommended materials for each element is modified automatically as materials are selected for the design elements.

The database module includes information about the materials’ suppliers and their associated BIM information. This information is stored and organized based on the main suppliers of the different building components including doors, roofs, windows, ceilings, floors and walls. Afterward, Important Sustainability Factors are identified from the literature. After gathering all the required data, the DSS should be designed based on the applied decision making approaches involving TOPSIS and Entropy in order to be able to choose the optimal alternative. Then, by associating this data and the DSS, an integration interface is developed to import the tasks into BIM tool.

The DSS is based on the multi-criteria assessment weighting scale that is combined with Entropy, which enables the comparison and ranking of different potential alternatives and scenarios. This is a criterion for the amount of uncertainty through the structured prioritization of a variety of sustainability objectives and
indicators. The other method employed in this DSS is TOPSIS Logic, which is mixed with a weighted criteria matrix to show the shortest distance from positive ideal solution and the longest distance from the negative ideal solution. The multi-criteria procedure embedded in the DSS relies on numerical models used to simulate the baseline and alternative situations, as well as ranking the best alternatives based on owners’ strategic plans and the availability of sustainable materials in the market. One of the most critical steps for this research is the arrangement and selection of the criteria and attributes that affect the selection process of project’s sustainable materials. Mainly, the attributes’ assessment is made according to the literature review, previous researches and questionnaires completed by experts. The importance of this assessment is its categorization of the essential sustainable development criteria, which are divided into three categories: 1) environmental, 2) economical, and 3) social criteria. Each of those categories consists of sub-criteria that have been listed by the scoring system that is completed by experts. Table 1 shows the sustainability assessment criteria used by the DSS.

Table 1. Sustainability assessment criteria used for DSS

<table>
<thead>
<tr>
<th>Main category</th>
<th>Criteria</th>
<th>Sub Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental criteria</td>
<td>Environmental Impacts (EI)</td>
<td>Global Warming Potential, Ozone Depletion Potential, Acidification Potential, Eutrophication Potential, Smog Potential, HH Respiratory Effects Potential, Weighted Resource</td>
</tr>
<tr>
<td>Energy &amp; Atmosphere</td>
<td></td>
<td>Operational energy as Lighting and power, cooling and heating, Minimum Energy Performance, Embodied energy as mining, manufacturing, on site process, transportation and final disposal, Onsite renewable Energy, Energy consumption during building life</td>
</tr>
<tr>
<td>Material &amp; Resources</td>
<td></td>
<td>The application of renewable material, Recycled content</td>
</tr>
<tr>
<td>Economical factor (cost efficiency)</td>
<td>Cost</td>
<td>Costs of resources and materials, Labor costs, Operation &amp; Maintenance costs, Renovation and destruction costs</td>
</tr>
<tr>
<td>Investment criteria</td>
<td></td>
<td>The speed of return on investment, Initial investment, Exchange amount</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td>Approximated Construction time</td>
</tr>
<tr>
<td>Construction issues</td>
<td></td>
<td>Constructability, Flexibility, Material and equipment availability</td>
</tr>
<tr>
<td>Design and architecture issues</td>
<td></td>
<td>Daylight and Views, Productivity, Individualization and social identity, Physical space and performance, Aesthetics and architectural issues</td>
</tr>
</tbody>
</table>
4 MODEL IMPLEMENTATION

Interoperability processes will be implemented in order to develop a functional integrated BIM-based DSS. Knowledge, experience, and experts’ validations are required to implement the DSS. A portion of the technical knowledge required for this research is obtained by consulting with experts who are knowledgeable in sustainability and by using decision making approaches besides the literature. The design phase is followed by identifying the Criteria/Attributes and then calculating the Weight Matrix with Entropy method in order to establish the Decision Maker’s Matrix (DMM). Normalizing the decision making Matrix, which is made by the Decision Maker as well as multiplying the DMM by the Weights Matrixes to get the weighted decision making matrix to evaluate the Positive Ideal and Negative Non-Ideal Solution and to calculate the shortest distance from the Positive Ideal Solution (PIS), farthest distance from the Negative Non-Ideal Solution (NIS) and relative closeness to the ideal solution for each alternative is the further step to rank the alternatives according to their relative closeness proportion. To implement this method, programming the DSS algorithm as well as creating plug-ins in BIM tool, which is in this case Autodesk Revit, is needed. The data set required for this research is divided into two categories: (1) Alternatives (vendors of sustainable materials and basic assembly groups e.g., doors, walls, windows, ceilings, roofs and floor) and their correspondent BIM families; (2) green buildings' sustainability controlling criteria.

Due to the numerous numbers of companies that produce products, only leading companies with wider ranges of products have been selected. To ease the process of accessing the required data, the selected companies and their materials’ BIM information are hyperlinked to the list of products in the developed plug-in. In order to obtain the weight criteria’s matrix from the selected criteria as an output, the experts' opinions have been utilized. For this reason a blank weight criteria matrix has been sent to experts for scoring purposes. After distributing the prepared matrix criteria to the experts, the results should be interpreted. To merge all the collected responses into one matrix, a normality behavior test for the responses of each question has been run by using the Statistical Package for the Social Sciences (SPSS©) software’s normality analyzing tools. Based on the obtained results it is found that all the responses had normal distributions. Therefore, for each correlative score, the normal distribution’s average is substituted. To convert the un-weighted matrix to the weighted one, the Entropy weighting approach has been employed. To calculate the entropy values (Ej), the following formula is employed where k=1/ln (m) and (m) presents the number of criteria. Furthermore, pij is the normalized values of the weight matrix’ elements.

\[ [1] \quad E_j = -k \sum_{i=1}^{m} [p_{ij} \ln (p_{ij})] \quad j = 1, 2, \ldots, J; \quad i = 1, 2, \ldots, I \]

One of the benefits of entropy method is the possibility to mix the decision priorities with the sensitivity analysis. Thus, the final weight is the combination of both. If the priorities for the criterion are the same for the decision maker, the set of weights can be calculated with the following formula, where all the criteria have the same priority.

\[ [2] \quad w_j' = \frac{d_j}{\sum_{j=1}^{n} d_j}, \forall j, \quad d_j = 1 - E_j, j = 1, 2, \ldots, J \]

At the first stage, the matrix is normalized; then the entropy of the weights is calculated; after that the dj factor is estimated. Ultimately, the weighted criteria are determined including each dj on the summation of djs as represented in table 2.
### Table 2. Weighted Entropy matrix

<table>
<thead>
<tr>
<th>Environmental Impacts</th>
<th>Energy And Atmosphere</th>
<th>Material And Resources</th>
<th>Cost</th>
<th>Investment Criteria</th>
<th>Time</th>
<th>Construction Issues</th>
<th>Indoor Environmental Quality</th>
<th>Design &amp; Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment Impacts</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy And Atmosphere</td>
<td></td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material And Resources</td>
<td></td>
<td></td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td></td>
<td></td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment Criteria</td>
<td></td>
<td></td>
<td></td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td></td>
<td></td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Issues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor Environmental Quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design &amp; Architecture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.09</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

As part of the DSS design, a plug-in in Autodesk Revit is created. This plug-in helps designers evaluate the materials in terms of their sustainability features during the conceptual design phase. The plug-in procedure is created by using C#, the object oriented programming language, and afterward it is imported into Autodesk Revit as a shortcut in its tool bar. TOPSIS begins its procedures by employing two matrices: criteria’s matrix and decision maker’s matrix. The criteria’s weighted matrix is assessed from the previous step. While the developed plug-in aids users to import weights into the decision maker’s matrix, which are recognized by user’s comparison results based on the available products in the external database of BIM tool. The criteria matrix has been coded and inserted in the background of the plug-in’s procedure.

## 5 MODEL VALIDATION

To validate the developed model, its performance is examined through the use of an actual five floor office building project that can house around 300 people (occupants), which is currently under design in the city of Ottawa. The proposed construction site has a total area of 46,980 ft² and the building’s gross area is 88,587 ft². Building functions are distributed into three categories: public, semi-public and private. Public function is related to both ordinary people and employees such as conference and exhibition rooms. Semi-public spaces include secretary offices and managers’ rooms, which are used by employees and visitors. Employees’ offices and private gathering rooms are considered as private spaces used by employees and managers. In order to control the sunlight, louver systems are installed to improve indoor daylighting to limit glare and redirect diffuse light. The authors created a 3D conceptual design of the
current project where its associated sustainable components and materials are selected from the developed database. The components used in the design of this case project have their specifications as it is recommended by the DSS plug-in. Every component, such as floor, wall, roof, and window has its associated sustainability information linked to the families inherited into BIM tool, which includes the manufacturers’ web pages and contact information. Figure 2 shows a rendered snapshot of the sustainable office building case project, which is created by using the developed model.

![Figure 2. Snapshot of the sustainable case building model (Office Building)](image)

During the development of that case project, it is needed to make a decision while selecting the type of sustainable materials, which are supplied by different suppliers, and hence selecting from different alternatives of the current design including the materials for doors, roofs, ceilings, walls, windows and floors. To start the DSS, the user needs to click on the TOPSIS plug-in in BIM tool, Autodesk Revit in this case. After that, the user is asked to assess the decision maker’s matrix by providing a score for each of the alternatives based on the defined criteria. Every product has its technical specification linked to the web page of its supplier and producer. The help button, included in the plug-in, provides the user with necessary information and instructions on how to fill the blank spaces in the form based on the 9 points ranking scale. To run the DMM plug-in the user is required to click on the calculate button designed in the DSS. The final results will be presented as a list that ranks the alternatives with their companies’ names, and the (Ei) factor. Figure 3 shows a snapshot of the filled DM’s matrix and the final sorting of alternatives for the door component.

![Figure 3. The snapshot of filled form in the DSS and the results for door component](image)

6 CONCLUSION

This paper described the development of a model that integrates DSS with BIM tool in an attempt to help designers select the type of materials and components that best fit the design of sustainable building
projects. The focus of this research is at the conceptual design stage where decision makers are in need for assistance to make important decisions related to the continuation or dismissal of proposed projects. Therefore, any additional information would be an asset and helpful to support their decisions. The novelty highlighted in this paper describes the development of an integrated model that comprises Decision Support System (DSS), which aids the design team decide and select the optimum type of sustainable building components for proposed projects based on owners’ needs. The developed DSS is integrated with BIM tool through an automated process by creating new plug-ins for designers to use when doing the design of proposed sustainable buildings at the conceptual stage in a timely and cost-effective way. The specifications and requirements of the DSS implemented in this research are first established and afterward the system architecture is developed. Although this is an ongoing research, its potential for more development is proven to be possible. The DSS database is on a small scale, but it can definitely be expanded to Online Analytical Processing (OLAP) design in order to enable relevant green material producers to update their information online periodically.

References

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Liu H., You J., Zhen L. and Fan X., (2014), A novel hybrid multiple criteria decision making model for material selection with target-based criteria, School of Management, Shanghai University, Shanghai, China
ENERGY STAR WINDOWS’ PERFORMANCE AND ORIENTATION

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Abstract: In 2012 and 2013, ten building product categories were eligible for United States ENERGY STAR Federal Tax Credits. High performance windows that meet certain energy efficiency criteria are one of the qualifying products. The ENERGY STAR Tax Credit program sets U-factor and Solar Heat Gain Coefficient (SHGC) standards for these windows according to four climate zones. Research demonstrates that buildings with well-designed and constructed fenestration systems can lower requirements for heating, cooling and lighting during operation. However, previous research and energy modeling also demonstrates that, in addition to energy efficiency characteristics, orientation impacts the energy performance of windows. The ENERGY STAR tax program makes no distinction regarding window orientation or placement when evaluating tax credit eligibility. This research studies the potential impact of orientation on performance for qualifying ENERGY STAR window products. Using TRNSYS energy modeling comparisons, findings suggest that the performance of qualifying windows may vary up to 14 percent for different orientations depending on climate zone.

1 INTRODUCTION

In the United States in 2010, residential and commercial building sectors accounted for approximately 41 percent of nation’s primary energy consumption. In residential buildings, space conditioning (heating and cooling) accounted for 43 percent of energy consumption, followed by water heating and lighting (EERE, 2014a). Building Technologies Office (BTO) is a part of the US Department of Energy (DOE), with the mission “to improve the efficiency of existing and new building in both the residential and commercial sector through the development of high-impact energy efficiency technologies and practices” (EERE, 2014a, p. vii). A 2014 BTO report prepared by Energetics Incorporated identified windows and building envelope technologies as two areas with significant potential to reduce energy consumption in buildings (EERE, 2014a). The 2011 Building Energy Data Book states that 25 to 35 percent of the energy used for the heating, cooling and lighting of buildings is wasted through inefficient windows (BEDB, 2012). The BTO report on Window and Building Envelope Research and Development projects that the use of cost-effective and energy-efficient technologies could result in savings of 23.4 quads in the United States in 2030, 23 percent of which would be the result of improvements in windows and building envelope technologies.

Several tax incentive programs by the United States Federal government currently exist for energy efficient building features (DOE, 2014b). Specifically, 179D Federal tax deduction refers to Section 179D of the Federal Tax Code, which provides tax deductions for energy efficiency improvements (e.g., Building envelope, HVAC and lighting) to qualifying commercial buildings (EERE, 2014b). In 2012 and 2013, United States ENERGY STAR Federal Tax Credits were available for residential buildings for ten
product categories including: Biomass Stoves; Heating, Ventilation, Air Conditioning (HVAC); Insulation; Roofs; Water Heaters; Windows and Doors; Geothermal Heat Pumps; Small Wind Turbines; Solar Energy Systems; and Fuel Cells (EnergyStar, 2014a). A major difference between many of these eligible products and high performance windows, is the potential for orientation of installation to impact performance. Whereas many products, themselves, (e.g., biomass stoves, insulation, roofing, etc.) provide relatively consistent performance irrespective of the building orientation, research has shown that windows’ impact on building performance can vary significantly depending on the orientation (self-shading) of the building, as well as the façade on which they are placed. Specifically, a window’s performance is directly related to solar angles striking its surface and solar angles differ significantly relative to orientation. The goal of this research is to use energy modeling to begin to assess the performance range of ENERGY STAR windows based on orientation across climate zones.

1.1 ENERGY STAR Tax Credit Program

ENERGY STAR products can cost more than traditional alternatives. The goal of the ENERGY STAR program is to provide financial incentives to support technologies that pay back through lower energy bills within a reasonable amount of time. In order for windows to qualify as ENERGY STAR certified, they must meet three main criteria: (1) The product is manufactured by an Energy Star partner, (2) The products are tested and certified independently by National Fenestration Rating Council (NFRC), and (3) The products' NFRC ratings meet the guidelines set by US DOE (EnergyStar, 2014c). In addition, ENERGY STAR sets minimum qualification requirements for the windows’ performance characteristics according to climate zone (see Table 1). ENERGY STAR defines U-factor as the heat transfer per time per area and per degree of temperature difference, and Solar Heat Gain Coefficient (SHGC) as the fraction of incident solar radiation entering the space through the window. The windows must also be installed on your “principal residence” to be eligible for the Tax Credit. ENERGY STAR defines four climate zones (i.e., Northern, North-Central, South-Central and Southern) as relevant to these performance criteria (see Figure 1).

Table 1: ENERGY STAR qualification criteria for residential windows (EnergyStar, 2014c)

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>U-value ($\frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}$)</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>$\leq 0.30$</td>
<td>Any</td>
</tr>
<tr>
<td></td>
<td>$= 0.31$</td>
<td>$\geq 0.35$</td>
</tr>
<tr>
<td></td>
<td>$= 0.32$</td>
<td>$\geq 0.40$</td>
</tr>
<tr>
<td>North-Central</td>
<td>$\leq 0.32$</td>
<td>$\leq 0.40$</td>
</tr>
<tr>
<td>South-Central</td>
<td>$\leq 0.35$</td>
<td>$\leq 0.30$</td>
</tr>
<tr>
<td>Southern</td>
<td>$\leq 0.60$</td>
<td>$\leq 0.27$</td>
</tr>
</tbody>
</table>
In 2012 and 2013, homeowners could receive a Federal tax credit equal to 10 percent of the product cost up to $200, with a $500 maximum per homeowner for all energy efficiency tax credits (EnergyStar, 2013). The following sections present a simple study to assess the impact of orientation on minimally compliant Energy Star windows in all of the four specified climate zones.

1.2 Background

Research demonstrates that buildings with well-designed glazing and efficient fenestration systems can lower the requirements for heating, cooling and lighting. Several studies suggest that energy usage and total peak demand of buildings can be reduced by up to 15 percent through effective design of fenestration and daylighting systems (Johnson et al., 1984; Tahmasebi at al., 2011). Windows also provide many known psychological benefits resulting from access to daylight and views of the outside (Tahmasebi et al., 2011).

Several studies have used a variety of energy modeling or building performance simulation programs to investigate the influence of glazing characteristics in combination with various parameters such as window size, orientation, frame type, insulation, ventilation, internal loads, external shading devices and climate. Eskin and Türkmen (2008) used EnergyPlus to simulate the interactions between different building conditions and control strategies in office buildings across climate types in Turkey. The findings of the study suggest that low emissivity, double glazed windows can decrease the maximum energy requirement of the building as much as 15.9 percent (Eskin & Türkmen, 2008). Poirazis et al. (2008) used IDA ICE 3.0 to study the impacts of glazing type, window size, building orientation, shading devices and control set points on highly glazed office buildings in Sweden. The findings suggest that low SHGC values for windows greatly influence the cooling demand, however, increased window to wall ratio and window orientation appeared less impactful (Poirazis et al., 2008). Gasparella et al. (2011) utilized TRNSYS to investigate the impacts of double and triple glazed systems, window sizes, and orientation of the main windowed façade on energy usage and peak demand for well-insulated residential building across four climate types in south and central Europe in both winter and summer. The study suggests that placing the windows on south orientation improves the energy performance of the building, especially during winter, and recommended the use of shading systems to improve the summer performance without sacrificing winter performance (Gasparella et al., 2011).

Morrissey et al. (2011) investigate the implications of building orientation on residential houses in Australia in an attempt to maximize passive solar benefits (Morrissey et al., 2011). Another study by Persson et al. (2006) used DEROB-LTH to examine the performance of windows for low energy houses in Gothenburg, Sweden. Results suggested the size of the glazed surface does not have significant
impacts on the winter heating demand, but can contribute to reducing the summer cooling demands (Persson et al., 2006). Similarly, Wall (2006) used the same dynamic simulation tool to study the impacts of several building variables on passive houses in Sweden. Results suggest that energy efficient windows are essential in reducing thermal losses in buildings while providing thermal comfort for the occupants (Wall, 2006). Hassouneh et al. (2010) investigated the effects of different glazing types, window orientation and windows size using self-developed simulation software on residential buildings for the climate of Amman City. Results suggest that certain glazing types are more efficient in certain orientations. For example, clear glass is effective for south, west and east orientations, but increases energy losses when installed on the north facade (Hassouneh et al., 2010).

Although considerable research exists that suggests a range of factors can influence overall window performance, few, if any studies exist which assess the impact of orientation on ENERGY STAR qualified windows for the four ENERGY STAR climate zones specified by the program.

2 METHOD

For this research, the authors created a simple, square, one story 25 m² (269 SF) building model with facades oriented North, South, East and West. In all cases, a total of 15 m² (161 SF) of glazing was placed on the model façade(s). For the baseline model, the glazing was equally distributed on all facades. Four alternative models were also developed with all glazing placed exclusively on North, South, East or West facades respectively. Each of these five models was simulated using weather files from four cities, representative of the four ENERGY STAR climate zones: Denver, CO (Northern Zone); Albuquerque, NM (North-Central Zone); Atlanta, GA (South-Central Zone) and Miami, FL (Southern Zone) resulting a total of twenty simulations. Window specifications (U-factor and Solar Heat Gain Coefficient (SHGC) standards) were set to meet ENERGY STAR criteria in each climate (see Table 1).

2.1 Energy Model

The authors developed a simple energy model of a small, square building using TRNSYS software (TRNSYS, 2013). Modeling assumptions were based on similar, existing energy modeling research including (Clevenger et al., 2014; Saeli et al., 2010) as well as building codes and standards (ASHRAE, 2010). Simulation set time was one year, with data simulated every hour. Simulations were performed using climate data from four representative cities. In each of these climate zones, a market-available window which met the program’s criteria was selected and assigned a window type: A, B, C, D. The performance criteria of these products are shown in Table 2.

Table 2: Selected (ENERGY STAR eligible) window performance criteria per climate zone

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Representative City</th>
<th>Window Type</th>
<th>U-value</th>
<th>SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>Denver, CO</td>
<td>A</td>
<td>0.32</td>
<td>0.614</td>
</tr>
<tr>
<td>North-Central</td>
<td>Albuquerque, NM</td>
<td>B</td>
<td>0.28</td>
<td>0.392</td>
</tr>
<tr>
<td>South-Central</td>
<td>Atlanta, GA</td>
<td>C</td>
<td>0.17</td>
<td>0.230</td>
</tr>
<tr>
<td>Southern</td>
<td>Miami, FL</td>
<td>D</td>
<td>0.44</td>
<td>0.196</td>
</tr>
</tbody>
</table>

To model these windows, the authors used TRNSYS Type 56 window library. The window library is created using software developed by Lawrence Berkeley National Labs and references ASHRAE 90.1.99 Table A17, ASHRAE Standard 140 and the Building Energy Simulation TEST (BESTEST) Standard. These windows were placed in a baseline model with glazing equally distributed on all facades, plus four alternative models with glazing placed exclusively on North, South, East or West facades respectively. Subsequently, each of these five models was simulated using weather files from the four representative cities for a total of 20 simulations.
3 RESULTS

Table 3 shows the total estimated energy usage and the percentage difference between the baseline and each alternative by climate zone. A positive number indicates that the performance of the alternative has improved (uses less energy) compared to the baseline. A negative number indicates that the performance of the alternative has declined (uses more energy) compared to the baseline.

Table 3: Estimated energy consumption ($\text{W/m}^2$) and percentage differences by orientations

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>City, State</th>
<th>Baseline Energy</th>
<th>South %</th>
<th>South Energy Diff</th>
<th>West %</th>
<th>West Energy Diff</th>
<th>North %</th>
<th>North Energy Diff</th>
<th>East %</th>
<th>East Energy Diff</th>
<th>Delta %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>Denver, CO</td>
<td>479</td>
<td>0</td>
<td>468</td>
<td>2%</td>
<td>510</td>
<td>-7%</td>
<td>505</td>
<td>-5%</td>
<td>498</td>
<td>-4%</td>
</tr>
<tr>
<td>North-Central</td>
<td>Abq, NM</td>
<td>388</td>
<td>0</td>
<td>362</td>
<td>7%</td>
<td>413</td>
<td>-7%</td>
<td>406</td>
<td>-5%</td>
<td>413</td>
<td>-7%</td>
</tr>
<tr>
<td>South-Central</td>
<td>Atlanta, GA</td>
<td>304</td>
<td>0</td>
<td>289</td>
<td>5%</td>
<td>316</td>
<td>-4%</td>
<td>305</td>
<td>0%</td>
<td>306</td>
<td>-1%</td>
</tr>
<tr>
<td>Southern</td>
<td>Miami, FL</td>
<td>198</td>
<td>0</td>
<td>197</td>
<td>1%</td>
<td>198</td>
<td>0%</td>
<td>173</td>
<td>13%</td>
<td>197</td>
<td>1%</td>
</tr>
</tbody>
</table>

The far right (Delta) column of Table 3 shows the energy modeling results that assess the potential range of impact that orientation can have on energy consumption for the tested ENERGY STAR qualified windows. This number represents the greatest difference in potential building performance. Table 4 provides estimates of the potential average cost impacts (electricity only) of these differences in performance.

Table 4: Potential cost impacts of energy performance differences by climate zone

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>City, State</th>
<th>Average Annual Electricity Bill by State*</th>
<th>Potential Cost Impact per year (Electricity only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>Denver, CO</td>
<td>$971</td>
<td>$87 (9%)</td>
</tr>
<tr>
<td>North-Central</td>
<td>Albuquerque, NM</td>
<td>$895</td>
<td>$125 (14%)</td>
</tr>
<tr>
<td>South-Central</td>
<td>Atlanta, GA</td>
<td>$1473</td>
<td>$132 (9%)</td>
</tr>
<tr>
<td>Southern</td>
<td>Miami, FL</td>
<td>$1481</td>
<td>$15 (1%)</td>
</tr>
</tbody>
</table>

*2012 Average Annual Residential Electricity Bill by State (Data from forms EIA-861- schedules 4A-D, EIA-861S and EIA-861U). Costs account for electricity average price differences per State. However, no other fuel type (i.e.; natural gas or propane) is included.

4 DISCUSSION

This study presents preliminary energy modeling results to estimate the potential range of energy performance (use and cost) impacts of installing ENERGY STAR windows on various orientations. While the examples (all glazing on one orientation) are extreme, they, nevertheless, provide valuable insight about how design decisions on window product installation can have significant impact on energy and cost savings. Currently, the ENERGY STAR program for windows, doors and skylights does not include any provision for orientation.

One of the reasons that the ENERGY STAR tax credit program may not consider window orientation is that building science principles are complex and interactive. For example, a window’s impact on buildings’ energy performance is not a direct function of available solar resource. Table 5 demonstrates
the average annual incident solar irradiance on a vertical surface in all four orientations by representative city (Greenstream, 2014; NREL, 2014). Solar irradiance is the amount of solar energy that arrives at a specific area at a specific time, which varies throughout the year. However, the benefits of available solar resource is greatly influenced by other climate factors (i.e.; temperature) and building characteristics (i.e.; thermal mass, insulation etc.).

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Vertical Surface Irradiance</th>
<th>South % Diff</th>
<th>West % Diff</th>
<th>North % Diff</th>
<th>East % Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver, CO</td>
<td>971.35</td>
<td>37%</td>
<td>1064</td>
<td>56%</td>
<td>1064</td>
</tr>
<tr>
<td>Abq, NM</td>
<td>994.93</td>
<td>36%</td>
<td>1083</td>
<td>54%</td>
<td>1083</td>
</tr>
<tr>
<td>Atlanta, GA</td>
<td>805.34</td>
<td>32%</td>
<td>850</td>
<td>43%</td>
<td>850</td>
</tr>
<tr>
<td>Miami, FL</td>
<td>813.64</td>
<td>30%</td>
<td>849</td>
<td>39%</td>
<td>849</td>
</tr>
</tbody>
</table>

Comparing results from Tables 4 and Tables 5, it is clear that calculating performance using available solar resource alone, could over-estimates the impact of window orientation on energy performance. Therefore, more detailed and custom energy modeling is necessary for accurate assessment. Such modeling can quickly prove cost and time prohibitive and is likely a main deterrent to the ENERGY STAR program considering window orientation in the tax credit calculation. Nevertheless, results suggest (Table 4) that design decision related to the orientation of the installed window can have significant impact on pay back periods and the value of the tax credit investment.

The following additional observations and recommendations are based on the study's findings:

- Results suggest that placing the entire glazed surface on the south façade tends to improve building energy performance relative to baseline (evenly distributed glazing) in all climate zones. Improved performance over baseline ranges from approximately one percent in the Southern climate zone to seven percent in the North-Central climate zone.

- Results suggest that placing the entire glazed surface on any one façade on any orientation other than the south, tends to worsen building energy performance relative to baseline in the majority of climate zones, except in the Southern climate (i.e., Miami, FL). The magnitude of the negative impact ranges from one to seven percent. Interestingly, in Miami, FL concentrating windows on any one façade appears beneficial presumably because it limits the number of hours of solar exposure.

- Cumulatively, the annual energy consumption of the buildings could vary up to 14 percent between different climate zones based on the orientation of the glazed façade. This large variance could be seen in the North-Central area, where placing the window on the south façade improves the energy performance by 7 percent, while having the windows on the west side, reduces the building performance by 7 percent.

- Cumulatively, the annual cost impact for an individual residence of ENERGY STAR windows may vary on the order of magnitude of $15 (Southern) to $132 (South-Central) annually. Such a range can significantly change the economics and, specifically the payback of such an energy efficiency feature.

- In general, whether a climate is heating or cooling load dominated significantly impacts the role of ENERGY STAR windows (and their orientation) on overall building performance.
Available solar resource (i.e.; average annual solar irradiance on vertical surfaces, Table 5) is not an accurate basis for estimating the impact of ENERGY STAR windows (and their orientation) on building energy performance. Therefore, more detailed and complex energy modeling is recommended.

5 CONCLUSION AND POLICY IMPLICATIONS

This study provides preliminary results based on twenty energy simulations for a simple, representative building model used to illustrate the range of the potential impact of ENERGY STAR qualified windows by orientation across climate types. Results suggest that the cost effectiveness of the incentive programs such as the ENERGY STAR Tax Credit program will vary not only based on the performance characteristics of products, but also based on design decisions related to orientation of installation. Currently, the ENERGY STAR Tax Credit Program only specifies U-values and SHGC minimums according to climate zone. As a result, findings suggest that the Tax Credit's effectiveness could vary by as much as 14 percent depending on installation.

Buildings are complicated systems, and multiple internal and external factors influence performance. For example, heating, cooling and lighting requirements in a building are affected by space conditioning requirements as well as external factors like ambient temperature, solar gain and shading devices. Airtightness and the level of insulation used in buildings in addition to occupants’ preferences and behaviors could also have impacts on building energy performance. Such complexities present challenges for energy efficiency incentive programs. This research highlights the potential impact of orientation on qualifying ENERGY STAR window product performance and concludes that while performance can vary as much as 14 percent, accurate assessment is challenging since it requires detailed, custom energy modeling to account for such variation. Potential policy implications may be to tie incentives to installed performance. Additional energy modeling and economic studies related to the ENERGY STAR Tax Credit or other energy efficiency incentive programs are recommended to further analyze and illuminate the impact and effectiveness of such programs.

REFERENCES


COMPARATIVE STUDY OF RELATIONSHIP MANAGEMENT IN DESIGN-BID-BUILD AND DESIGN-BUILD PROJECT DELIVERY METHODS IN INFRASTRUCTURE PROJECTS

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Abstract: Supply chain management (SCM) concepts suggest that high fragmentation of roles on projects causes significant negative impacts such as lower processes integration and higher transaction volumes. Within the scope of construction SCM, relationship management (RM) is regarded as one of the most important aspects for achieving efficient SCM. The use of RM in construction projects administration worldwide is manifest on alternative procurement methods, drifting away from traditional systems to ones that are relationship-based. Despite the significance of relationships for project delivery, there were no previous studies that investigated the influence of supply chain RM on construction projects utilizing different project delivery methods (PDMs). The aim of this paper is thus, to determine how RM among parties may be influenced by the PDM utilized. This is achieved through conducting case studies to compare RM in multi-prime design-bid-build versus design-build projects. The researchers adopted the core values developed by Meng’s 2011 RM maturity model to assess RM on projects utilizing different PDMs. Based on the two case studies, the total project RM score was seen to be lower in DBB projects compared to DB projects suggesting that the PDM employed influences RM on construction projects. Such findings can serve as a preliminary evidence of PDM choice effect on project RM and can help project parties gain a better understanding of PDM association to effective supply chain RM implementation. This study could be further extended to encompass more projects to provide statistical evidence of the influence of PDM on RM.

1 INTRODUCTION

The construction industry is characterized by high fragmentation with significant negative impacts such as perceived low productivity, cost and time overruns, conflicts and disputes, and resulting claims and time-consuming litigation (Cain 2003). The application of Supply Chain Management (SCM) is a means of developing vertical integration in the design and production process and operation to link the process into a chain, focusing on maximizing opportunities to add value while minimizing total cost. As this application requires a significant shift in the mind-set of the participants toward collaboration, teamwork, and mutual benefits, it is surprising that only few sophisticated applications have been reported in the construction industry (Kadefos 2005). Within the scope of construction specific supply chain literature, supplier relationship management (RM) is regarded as one of the most important aspects for achieving efficient SCM (Maqsood & Akintoye, 2002; Bemelmans et al. 2012). Despite the significance of relationships for the delivery of projects, there is a dearth of research in this area (Bemelmans et al. 2012).

Over the past decade, there has been an increasing emphasis on the use of RM in the construction projects administration worldwide. This emphasis is manifest on alternative procurement methods, drifting
away from traditional procurement systems to ones that are relationship-based (Walker & Hampson, 2003). Though the dynamic nature (Teece & Pisano 1994) of the construction industry allowed for the continuous implementation of relationship-based systems through different project delivery methods (PDM), there yet remains a lot of room for improvement and development in this area. The aim of this paper is thus, to determine how RM among parties within the construction SCM may be influenced by the project delivery method (PDM) utilized in a construction project.

2 BACKGROUND

Reliance on the traditional project management approach which focused on scientific/mechanistic tools and techniques led to dramatic project failures in addressing cooperative, complex inter-relationships among project parties, especially in mega-projects with high uncertainties. The inadequacy of traditional project management to deal with uncertainty had driven the focus towards relational contracting, partnering, joint ventures, and other collaborative patterns, which target softer skills and show how crucial good relationships are to the successful management of projects. A relationship approach, based on relationship building and management, is emerging as a new construction management paradigm of the future (Pryke & Smyth, 2006). Whilst broader than relational contracting and RM, the relationship approach embraces social capital generally and the role of relationships in core competency development and adding value. It shows how to create and maintain effective relationships between the client and the project team, as well as intra-coalition relationships.

RM does not only play a key role in procurement and transactional relationships (Gadde & Snehota, 2000) but determines the realization of many other facets of business activities (Chen & Paulraj 2004). For example, Monczka et al. (2011) particularly emphasized the aspects where relationships play a key role such as value-driven interaction; communication; trust and commitment; and establishing close partnership relationships with strategic or key suppliers. Rowlinson & Cheung (2006) explored the use and operation of RM as a means for engaging stakeholders through parallel studies in Australia and Hong Kong. They identified stakeholder typologies and adopted a multi-perspective view of project performance in order to link RM, stakeholders and sustainability in a framework which allows exploration of projects and their success. In their research they pointed out that RM is useful for enhancing project performance and client satisfaction (Rowlinson & Cheung 2008). All of these elements have significant importance in the relationship development process but unfortunately, RM has not received adequate attention to reflect its critical role within construction supply chain management (cSCM).

2.1 Relationship Management in Construction Supply Chain

PDMs in construction define the relationships, roles, and responsibilities of parties and the sequence of activities required to provide a facility while RM is a process to establish and manage these relationships between the parties that aims to remove barriers; encourage maximum contribution; and allow all parties to achieve success. Studies suggest that relational approach, such as partnering, alliances, framework agreements and RM, provide positive contributions to social, environmental and economic sustainability and help satisfy client and stakeholder interests (Blau 1963; MacNeil 1978, 1985; Rousseau & Parks 1993). In other words, relational contracts provide the means to achieve sustainable, on-going relationships in long and complex contracts by an adjustment process of a more thoroughly transaction specific, on-going, administrative kind (Kumaraswamy & Matthews 2000). The essence of RM is also found in collaborative procurement. Collaborative procurement aims at engaging parties at all project stages; competitive bidding is no longer the only selection criterion for contractors and design consultants, as well as suppliers (Hughes et al., 2006). Also, some reliance is placed on the deliberate development of long-term working relationships which requires trust building.

Benefits of collaboration and relational approaches in construction projects include time and cost savings, trust, motivation, open communication, and joint risk management (Bennett & Jayes 1998; Bresnen & Marshall 2000a; Kumaraswamy & Matthews 2000; Wood & Ellis 2005; Wood et al. 2002). Successful sustainable relationships in the supply chain rely on relational forms of exchange characterized by high levels of trust and commitment between project stakeholders. Close collaboration with a wide variety of
stakeholders from various backgrounds and professions is essential for business to thrive. To truly benefit from RM, the whole supply chain including the project team, project organizations and stakeholders, must understand the principles of RM and be part of the process.

2.2 Core values in RM

A number of authors have given insights into the core values of RM in cSCM whether focusing generally on the core values of RM (Cheung, 2011, Pinto et al., 2009, Gulch & Raisanen 2009, Kadefos 2005) or specifically on partnering and its relation to RM core values (Marrewijk et al. 2008, Maqsod & Akintoye, 2002). Meng (2010) built upon those studies by integrating the main factors of RM included in previous studies to eight core values: procurement, objectives, trust, collaboration/joint working, communication, problem solving, risk allocation and continuous improvement. The next paragraphs will provide some background on these eight core values and their significance on construction projects.

Procurement and contract is the fundamental of the establishment of a supply chain relationship. The sub criteria of “Procurement” include “Selection criteria,” “Procurement route,” and “Form of contract (Meng et al 2011). Mutual objectives encompass the change in traditional relationships to a shared culture; based upon trust, dedication to common goals, and an understanding of each other’s individual expectations and values (Brensen & Marshall, 2000a). Integrative interactions are characterized by cooperative behavior; hence, parties in a business transaction seek ways to achieve mutual objectives while bargaining (Grover et al 1996). Establishing relational goals may reduce the negative influence of formal contractual rules on people’s behavior (Kadefos 2004) and instead align the goals and objectives of different parties (Meng 2010).

As for trust, it is a psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or behavior of another (Kadefors 2004). This could imply that trust is a process that begins within an individual and must rely on certain human qualities or characteristics, such as ability, benevolence and integrity (Kadefors 2004). Showing trust communicates to a partner that cooperation is anticipated and tends to be reciprocated with a behavior that validates trust (Kadefors 2004). However, in the construction industry trust has a different meaning for the parties involved in the industry, such as contractors and owners (Pinto et al. 2009). Trust has direct effects on work group process and performance. Successful collaborative relationships rely on relational forms of exchange characterized by high levels of trust.

Communication, on the other side, mainly involves the transfer of information between people in a group or organization (Gluch & Raisanen 2009). One of the major causes of delay in construction projects is communication problems, however, delays can be minimized by discussions that lead to understanding (Assaf & Al-Hejji, 2006). Performance can be improved in the construction industry if the focus was shifted to examining the constraints of organizational cultures (Gluch & Raisanen 2009) such as the lack of the “no-blame” culture, through communication which will encourage individuals within the organization to experiment with new ideas (Dulaimi et al 2002).

According to Meng (2010), joint working is generally reflected by joint decision-making based on clear understanding of mutual objectives, joint effort of problem solving and joint effort for continuous improvement. Bresnen and Marshall (2000a) suggested that project performance, in terms of cost, time, and quality can be dramatically improved if participants adopt more collaborative ways of working, however before collaboration can become a team effort it depends on individual behavior (Bresnen & Marshall 2000a). Although the willingness to share information and knowledge occurs over time (Gale & Luo 2004), construction project teams learn to part and share what they know in a short space of time. Lack of continuity of relationships, due to the short-term nature of most construction projects, undermines attempts to secure full benefits of collaborative working (Bresnen & Marshall 2000a).

As for risks, they cannot be eliminated; however, they can be effectively managed as they are perceived to be the occurrence of unwanted or uncertain events (Zou et al. 2007) that may negatively affect the success of a construction project. A successful project risk management process relies on the risk being thoroughly and properly understood before it is allocated or before the method of allocation is chosen.
(Rahman & Kumaraswamy 2002). Risk should be allocated to the party best able to anticipate and control that risk, however the willingness of that party to take on the risk is an important consideration in the allocation of project risk (Ward et al. 1991). Conditions of contract are themselves alone not sufficient to allocate risk properly (Rahman & Kumaraswamy 2002); an open and cooperative attitude towards risk by all contractual parties must be maintained for the risk management process to be successful (Schmidt et al. 1999). Risks are inherent in all construction projects, none the less due to the temporal and unique nature of construction projects, their precise and natural form is project specific (Rahman & Kumaraswamy 2002). The identification of risks as early as possible in a project’s life is important (Ward et al. 1991) in ensuring that the primary project performance objectives of time, cost, and quality are achieved.

Continuous improvement implies successfully establishing a culture of development and constant learning within an organization or a project team, and facilitating the learning process of the individuals is regarded as important to the continuity of the continuous improvement activities (Alstrup 2000). The construction industry has seen the introduction of various tools, techniques and methods such as partnering, benchmarking and joint ventures (Bresnen & Marshall 2000a), as measures of continuous improvement in the aim of improving the industry’s project performance. Partnering assumes that continuous improvement is a joint effort to eliminate barriers to improvement (Larson, 1997) and that it is a possible solution for reducing the adversarial nature of the construction industry (Love et al. 2002). Continuous improvement has been seen as a way of promoting long-term performance improvement (Bresnen & Marshall, 2000a). However, the short term nature of most construction projects is not a suitable one as it means that most project teams and organizations live from project to project and each time focus on the successful completion of these projects, as a result this may inhibit the learning process and thus the continuous improvement of project teams (Gieskes & Broeke 2000).

Lastly, according to Barron (2000), joint problem solving requires collaboration within peers and a willingness and openness to be influenced by others, which will result in joint understanding within the parties involved in a problem solving process. Construction projects frequently encounter unforeseen and unanticipated challenges which require the project team to be highly efficient and effective in responding to resolving such challenges. A focused project team with a range of skills and experiences to cope with such problems (Walker & Hampson 2003) and a right attitude to joint working can positively affect the performance of a project.

3 METHODOLOGY

The aim of this paper is to determine how RM within the construction SCM may be influenced by the PDM utilized in a construction project. To achieve this aim, the following three tasks needed to be completed: (1) identify relationship indicators to measure the relationship among project participants; (2) identify the parties involved in the processes and their interactions in different PDMs based on a construction supply chain perspective; (3) compare RM of key suppliers based on the relationship indicators in projects with different PDMs. The first task was completed through literature review where the researchers decided to use the core values of RM adopted from Meng (2011) maturity model as RM indicators. Meng (2011) maturity model included eight main RM core values (discussed in Section 2.2) each divided further to 3 sub criteria with each sub criteria having four maturity levels. The main criteria represent the main aspects of a supply chain relationship, whereas the sub criteria describe different detailed areas in each main aspect. For example, ‘procurement’ was broken down to selection criteria, procurement route, and form of contract each having four maturity levels.

The relationships at maturity Level 1 represent an extreme position dominated by self-interest and mistrust, mutual objectives do not exist, and parties only focus on achieving their own objectives and maximizing their own profits, with no regard to the impact of their actions on others. Trust is limited to the formal contract commitment with price competition being common practice. Win-lose business philosophy are prevailing resulting in adversarial relationships. At maturity Level 2, parties are mainly interested in their own objectives and interests. The mutual objectives are not established. However, a win for one party and a partial win for another enables limited degree of cooperation between the parties. Competition
does not focus on price anymore; instead quality competition becomes more common. Although the parties rely on the formal contract, trust is mainly built on the basis of mutual understanding of each other’s capabilities to carry out their tasks. At Maturity Level 3, alignment of objectives is achieved in a single project. Everyone’s interests are best served by concentrating on the overall project success. Partners work collaboratively as an integrated project team and the win-win attitude becomes the fundamental of the project partnering relationship. Finally, the relationship at maturity Level 4 is characterized by highest degree of trust and alignment of objectives over a series of projects, which focuses on long-term relationship. Fair gain sharing ensures that partners collaborate most closely in the whole supply chain. Continuous improvement is made jointly by learning from performance measures feedback and adopting innovative technology and management approaches. In general, this relationship is reflected as strategic partnering or strategic alliance (Meng 2010).

As for the second and third tasks, they were realized through conducting case studies to gain insights on RM in two projects implemented using different PDMs. The case study included analysis of project documentation and semi-structured interviews with project participants from owner’s, designer’s, or contractor/subcontractor perspective. Interviewing different parties involved in the project allowed the researchers gain a holistic view of the RM in the two projects studied. Interview questionnaire was divided into two parts. The first part aimed at gaining a deeper understanding of the project background and identifying contractual and relational issues among the project parties (including the project phase in which the different participants were initially involved). The second part was based on the core values adopted from Meng (2011) maturity model described above. It included close-ended questions about the eight main RM core values, each of which has four maturity levels. Respondents were asked to choose the statements/levels that was best suited for their project in each of the sub criterion for each of the different parties they defined in the first part of the questionnaire. Each response was assigned a score number equivalent to the level under which it falls, i.e., responses were assigned score between 1 and 4 which corresponds to the maturity level it lies at. For example, if the respondent in sub criteria ‘type of trust’ chooses the “contractual trust” - a statement in level 1 – then a score of 1 is assigned. On the other side if “Long-term goodwill trust” - a statement in level 4 – is selected, then a score of 4 is assigned. After obtaining a score for the sub criteria, the core RM score was obtained using the Equation 1:

\[
\text{Core Value RM Score} = \frac{\sum \text{Total for each subcriterion}}{\text{Number of parties} \times 4}
\]

and then the project total RM using Equation 2:

\[
\text{Total Project RM score} = \frac{\sum \text{Score for each RM core value}}{\text{Number of core values (i.e. 8)}}
\]

4 CASE STUDY ANALYSIS

4.1 Case I – DB project

Case I is a project delivered under a Design-Build PDM in which the owner procures both design and construction services in the same contract from a single, legal entity referred to as the design-builder. It is a value based DB project. The project started in 2011 valued at $200.35M. This $200 million project features the construction of 22 bridges (including two fly-over bridges and a one-of-a-kind cap with a cultural wall), 28 retaining walls, two new urban avenues, an additional lane for through traffic, additional lanes on both directions, wider sidewalks and improved lighting on bridges 4,000+ feet of 54” storm sewer micro tunneling, and roadway reconstruction along 29 alignments. There were eight parties that were identified by the respondents, both owner and design-builder, in this project (Figure 1). The project team included the owner, design builder, two owner consultant (one responsible for record keeping and paperwork tracking and the other assisting in quality oversight), subcontractors responsible for specialty work, consultants working for the design builder for quality assurance, design consultant working for the design-builder as well as subcontractors working for the design-builder. All the eight parties were involved in the early design stage of the project. One party was involved in the development of the construction
documents, six parties were involved in the bidding process, all parties were involved in the construction and finally six parties were involved in occupancy. The solid lines in figure 1 shows the contractual relationships while the dotted lines show non contractual relationships.

![Figure 1: Schematic representation of the organization of all the parties involved in the project](image)

As discussed in the methodology, both the owner and design-builder were asked in the interview to report the eight core values of RM model utilizing the four maturity levels for the eight parties involved in the project. In terms of core value 1 'procurement', the owner reported that the design-builder was selected based on multi-criteria from long-term perspective (level 4) which is the prospective for long-term engagement, while project record keeping and quality oversight parties were selected based on cost and quality (level 2). Subcontractor and sub consultants were selected based on multi-criteria from short-term perspective (level 3). Bidding was done based on two stage tendering (level 2) except for owner project record keeping and owner’s assistance for quality oversight parties where they used direct negotiation (level 4). The design-builder had the same responses as the owner but had more information regarding the subcontractors who were selected based on direct negotiation (level 4) that was possible because of previous projects that they had done together.

As for core value 2 'objectives and goals', the parties in this project seem to be differently informed. According to the owner, he intends to work with these parties in the future (level 4) except for the subcontractor for quality assurance that the owner intends to work with in prospect of future work through tendering (level 2). The design-builder intends to work with the subcontractors in future projects while with the design and quality monitoring units, the design-builder will work with them in prospect of future work through tendering (level 2). According to the owner, in terms of core value 3 'trust', there was a contractual trust (level 1) with the contractor and subcontractors while there was competence trust (level 2) with the record keeping and quality oversight parties and long-term goodwill trust (level 4) for final designer and specialty design parties based. As for the design-builder, there was short-term goodwill trust with some confidence within the parties in this project (level 3). In terms of monitoring, checking was 'somewhat reduced' (level 2).

In terms of core value 4 'communication', according to the owner, most information is exchanged openly (level 4) with the record keeping and quality oversight parties, while some information is exchanged openly with the contractor and subcontractors (level 2). With the other parties including subcontractor for quality assurance, final designer, and specialty designer, much information is exchanged openly (level 3). There is continuous sharing learning and innovation (level 4) except for subcontractor where there is sharing learning and innovation (level 3). Open book costing between two parties (level 3) is listed under the subcontractors, final designer, and specialty designer, whereas there is open book costing throughout the whole chain (level 4) for all the other parties. The design-builder response was that most information was shared among the parties (level 4) except for the consultant responsible for record keeping and paperwork tracking where, there was continuous sharing, learning and innovation throughout the whole chain and in terms of cost information (level 4), there was open book costing throughout the whole chain (level 4). As for core value 5 'collaboration', Owner reported close collaboration with the owner project record keeping and quality oversight parties (level 4). With the subcontractors, the owner has limited cooperation (level 2) and with the rest of the parties including the contractor, the owner has a
collaborative working relationship (level 3). The working relationship between the parties in the project was that of close collaboration (level 4) according to the design-builder. The parties abandoned the blame culture and always supported the weak party (level 3).

As for core value 6 ‘risk allocation’, according to the owner, risk sharing was greatly increased (level 3) with subcontractors reported as having limited risk-sharing culture (level 2). Risk is allocated to the party able to manage it in the project (level 3) for the project teams except for the project record keeping and quality oversight parties where risk is allocated to the party best able to manage it in the long-term (level 4). There are always appropriate rewards for the party taking the risk (level 4). The design-builder’s response to this particular core value was that risk-sharing was greatly increased in the project based (level 3) and risk was allocated to the party best able to manage it in the long-term based (level 4). The parties also always appropriated rewards for the party that took the risk (level 4).

As for core value 7 ‘continuous improvement’, continuous effort for better ways of working (level 4) is exhibited in the project according to the owner, with common measures, formal, regular, and continuous feedback. However, for subcontractors, common measures and regular and formal feedback in the project (level 3) was selected. Generally, there are multiple incentives by project parties for improvement (level 4). During the project, there was a joint effort to better ways of working according to the design-builder (level 3). Also, common measures, formal, regular and continuous feedback was given by these parties with multiple incentives (level 4).

As for core value 8 ‘problem solving’, according to the owner, there was early risk warning throughout the whole chain based (level 4) with project record keeping and quality oversight parties having most of their problems timely resolved at the lowest level (level 4). The other parties have many problems timely resolved at the lowest level (level 3). With subcontractors, final designer and specialty design parties, few problems are repeated (level 3) while rare problems are repeated by the other project parties (level 4). The design-builder stated that there was early risk warning throughout the whole chain (level 4). Many problems were timely resolved at the lowest level and rarely were problems repeated (level 4).

The responses in this case shows that the average score of all the eight core values is 3.5 on the designer-builder perspective while the average score is 3.2 based on the owner response. The case average is 3.34 (table 1) meaning that this case lie in level 4 of Meng, 2011 maturity model.

4.2 Case II - Multiprime project

Case II is a multiple prime contract which is a variation of the traditional Design-Bid-Build, in which the owner holds separate contracts with contractors of various work disciplines. In this system, the owner, or its construction manager (CM), manages the overall schedule and budget. Case II is a refinery construction project, a multiprime contract, valued at $2M located in Toledo Ohio. The project started in September 2013 and was completed in October 2014. The owner was represented by the CM who had direct contact with the prime contractors. All prime contractors’ communications to the owner was through the CM. The prime contractors also had several other subcontractors (Figure 2). The prime contractor interviewed has other projects going on with the owner because of their previous working relationships. According to the interviewees, there were nine key parties involved in the project, owner, prime contractors, subcontractors, architect/engineer, material suppliers and local authorities. The contractor was involved in the early stages of the project and gave input during preconstruction and design stages of construction. There were four parties involved in the predesign, three in the design and development of construction documents, four during bid process, all parties in the construction, and two in the occupancy stage. There was a contractual relationship between the prime contractors and the owner representative.

In terms of core 1 ‘procurement’, according to the interviewees both from the owner and contractor perspective, single-stage tendering (level 1) was used in selecting contractors except the architect/engineer who had direct negotiation (level 4) with the owner and also the CM was selected through tendering then negotiation (level 4). For core 2 ‘objectives’, according to the respondent from the contractor’s perspective, some parties in the project were aware of the mutual objectives of the project
and were working towards achieving these project objectives (level 2). Other units focused on the mutual objectives in the long-term while working towards achieving these project objectives (level 4).

Figure 2: Schematic representation of the organization of all the parties involved in the project

In terms of core 3 ‘trust’, there were mixed reactions between the project participants. According to the owner and contractor, some had long-term goodwill trust (level 4), others had competence trust based (level 2) while others only had the contractual trust (level 1). One of the parties that showed contractual trust (level 1) was a new company and this was their first job while the other ran out of business even before the start of the actual construction. One of the interesting parts in this project is that there was transparency on the side of the CM. One of the interviewees representing the contractor said that towards the closure of the project the CM realized an accounting error of $25,000 owed to the contractor of which they were unaware.

As for core 4 ‘communication’, some information was exchanged openly (level 2) in this project while the construction manager and the owner exchanged much information more openly (level 3). It was interesting to note that there was little sharing and learning information (level 2) in this project while on cost information there was either little cost transparency (level 2) or open book costing (level 4) between two parties. All correspondences and change of scope was done through the CM. The CM held weekly meetings with these other units and was in charge of change orders.

As for core 5 ‘collaboration’, there was close collaboration (level 4) between the owner, CM and the primes. Limited collaboration (level 2) was noticed in the relationship between the primes and the subcontractors, who usually sought self-defence as part of their working culture (level 2). The contractor, owner CM relationship was a problem solving focused culture and always had to support a weaker party (level 4). The designer for this project only supported with the issues related to self-interest (level 2) while subcontractors often had support for a weaker party (level 3).

In terms of core 6 ‘risk allocation’, there was limited risk sharing (level 2) between the parties in the project. Basically the interviewees responded by saying that nobody would wish to share risk because they already have enough. Risk was always allocated to the party best able to manage it in the project (level 3). Some rewards for the party taking up the risk were awarded (level 2). As for core 7 ‘continuous improvement’, there was continuous effort for better ways of working between the owner and the CM (level 4). Limited joint effort (level 2) was noticed between these other units within the project as there was no common measure and no formal feedback (level 4). As for core 8 ‘problem solving’, notably missing was the incentives (level 1) for the units except for the owner CM where there were multiple incentives (level 4) for the CM. Few problems (level 3) were repeated throughout the project. Risks were identified and early warning issued throughout the chain (level 4) and most problems were solved timely at the lowest level (level 3).

From the findings, there seems to be a variation in terms of how the RM values are affected in each project. For both cases, subcontractors obtained the lowest level in the RM core values. The consultants or the professionals working for the owner seem to rank highly in the hierarchy in all the indicators of the RM. The average scores for owner and contractor/design-builder responses are summarized in Table 1.
In case I, the DB project, even though all the parties were involved in the early stages of the project especially in the design phase, they don’t seem to be aware of the objectives and hence not working towards achieving them. However, all other indicators especially on problem solving, the design-builder’s response rank the core values at the highest maturity level. In case II, the contractor reported levels 2 and 3, with risk allocation and trust being the lowest while owner also reported trust being the lowest.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Case I (Design-Build)</th>
<th>Case II (Multiple-Prime)</th>
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<tbody>
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<td></td>
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<td>Owner Prime Owner</td>
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<td>2.8</td>
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<td><strong>Respondent Average</strong></td>
<td><strong>3.5</strong></td>
<td><strong>3.2</strong></td>
</tr>
<tr>
<td><strong>Case Average</strong></td>
<td><strong>3.34</strong></td>
<td><strong>2.8</strong></td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

RM is different from investigating the contractual relationship on a construction project. The aim of RM is to build upon the partnership by going beyond typical partnership ‘rules’ and draw on co-existing social and cultural norms. RM requires that all parties to the contract agree to align their individual goals, thereby establishing common or aligned goals for the project. The gain share/pain share mechanism is structured so that the parties (client, designer and contractor) will either win or lose together. There can be no blame - success or failure is a joint responsibility. This is a significant departure from traditional project practice. DB PDM is assumed to have better/improved relationships as compared to DBB just by the virtue of early contractor involvement. To investigate that preposition, an assessment to compare between a traditional and an alternative PDM is needed. This paper presents a comparative analysis which compares two project delivery methods. It also goes further to look at the interaction structure of the project parties in the different phases of construction and investigates whether core values of RM are affected by the project delivery used on the project using two case studies. It was established based on the documentation and responses from the owner and prime contractor that in a multiprime design-bid-build project the average total project RM score during the assessment lie in Level 3 where the parties are engaged in partnering relationship while in design-build project, it lies in level 4 where the parties are engaged in strategic partnering/strategic alliance. Therefore, the results of the study can serve as preliminary evidence to that alternative PDMs have better RM compared to traditional project delivery methods. It also shows the benefits of cSCM implementation not only in assessing RM but also a tool that could be inherently used in the construction project operations. The research can be further extended to incorporate more projects to provide a statistical evidence of the influence of PDM on RM and compare RM in different types of construction projects such as commercial, residential and expand it to include other alternative project delivery methods.

References


SYMMETRICAL AND ASYMMETRICAL TOOL BELT LOADING EFFECTS ON THE POSTURAL STABILITY OF CONSTRUCTION WORKERS

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Abstract: Falls are a leading cause of fatal and nonfatal injuries in construction. One of the most important steps in analytical research to prevent falls is to identify and measure the factors that can affect the construction workers’ fall risk. While several intrinsic and extrinsic factors can affect workers’ fall risk—such as the effects of aging, jobsite environments, posture and movement characteristics, workers’ experience, and workers’ equipment type and use— one unanticipated factor that can increase fall risk is the incorrect use of personal protective equipment—including full body safety harnesses and heavy tool belts—when safety harnesses and tool belts are not worn properly or body loading balanced they can cause unstable posture, changes in walking gait, and center of gravity problems. The objective of this study was to analyze the effects of the wearing full body safety harnesses and heavy tool belt loading symmetry on construction worker fall risk. Using the time-series quantitative kinematic measures obtained from Inertial Measurement Units (IMUs) connected to the workers’ waistline, the postural stability of a group of subjects was measured by calculating the velocity of Center of Pressure (COPv) and the resultant Accelerometer (rAcc)—lower rAcc and COPv values mean lower fall risk for construction workers. The postural stability for each worker was calculated for two different postures (standing and squatting) and for three different configurations of the tools (without attaching tools to the full-body harness, symmetrical attachment configuration, and asymmetrical attachment configuration). T-test results for mean values of the calculated rAcc and COPv showed significant differences in the postural stability of subjects with different placement and loading balance configurations of tool belts connected to the fall protection harness. When tools were not placed in the tool belt connected to the fall protection harness, test subjects had the lowest rAcc and COPv values; asymmetrical tool loading configurations rAcc and COPv had higher values than symmetrical loading configurations. The higher risk values associated with asymmetrically connected tools to a full body safety harness suggests the importance of safety harness tool attachment to construction worker fall risk safety.
Keywords: Construction workers, safety harness, tool belts, quantitative kinematic measure, postural stability, IMU, fall risk

1 INTRODUCTION

Construction is one of the largest industries by economic impact in the U.S., employing 7% of the total U.S. workforce or more than 9 million workers. Construction is in the top 3 most dangerous industries along with mining and agriculture based on annual number of workplace fatalities. Occupational injuries and fatalities in the construction industry lead to high direct and indirect accident costs, such as income loss, reduced workforce productivity, reduced quality of life, increased total project time and cost, cost of medical treatment and follow-up, short term and long term disability, medical services burden, etc. (Horwitz and McCall, 2004; Lipscomb et al., 2003; Meerdng et al., 2006). Falling from height is the leading cause of injuries and fatalities in the U.S. and international construction industries (Bentley et al., 2006; Bobick, 2004; Chan et al., 2008; Chi and Wu, 1997; Huang and Hinze, 2003; Meerdng et al., 2006; Yung, 2009).

Many construction incidents could be prevented if the causal factors leading to workplace falls were identified and mitigated correctly. There are several identified factors that are associated with falls in construction sites, such as aging workforce effects, jobsite environmental factors, walking and movement characteristics, worker training and experience, and tooling and equipment. One of the overlooked factors that can increase fall risk is the incorrect use of personal protective equipment—including safety harnesses and tool belts—since construction workers and their supervisors often do not pay attention to the loading symmetry of heavily loaded tool belts attached to full body fall protection harnesses (Cory Lyons, personal communications, 2014). One of the reasons this problem exists may be due to the limited explicit knowledge and training related to the effects of improper tool belt loading as part of a full body harness. Proper loading and symmetrical tool placement in a tool belt and full body fall protection harness could help reduce construction worker fall risk. The objective of this study was to assess the effects of tool belt and full body harness loading symmetry on postural stability by measuring and analyzing whole body stability using a wearable inertial measurement unit (IMU) data collection system.

The ability to maintain a position of the body—or more specifically, the body’s center of mass—is defined as postural stability (Lord et al., 2007). There are several methods and metrics that have been suggested in clinical and healthcare settings to assess the fall risk of human body subjects by measuring their body postural stability, such as Hurst rescaled range analysis (HR/s), average velocity of center of pressure (COPv), and resultant acceleration (rAcc). Hurst rescaled range analysis examines fractal properties after integrating a time series and can be used to characterize a time series of motion data when studying a body’s stability (Delignlères et al., 2003). The average velocity of center of pressure (COPv) illustrate the total distance between each consecutive points of the body’s center of pressure in the total data collection time (Hufschmidt et al. 1980). COPv is considered to be the most reliable measure used in the biomechanical domain to measure the stability of human bodies in stationary motions (Lafond et al., 2004). Resultant acceleration (rAcc) is another metric used in the clinical domain to measure the human body’s stability in a stationary posture (Bruumagne et al., 2008; Liu et al., 2012; Soangra and E Lockhart, 2013). rAcc measures the total human body motion in a certain period of time using the accelerometer vector components from inertial measurement units (IMU). In this research, the COPv and rAcc parameters were selected as the metrics for measuring and analyzing construction worker postural stability based on body movement and center of pressure demonstrated by subjects in the standing and squatting postures in the experimental setup.

2 EXPERIMENTAL DESIGN AND METHODOLOGY

2.1 Instrument, Procedure and Test Subjects

This research project used IMU data to calculate the COPv and rAcc even though most previous research into COPv used a force plate (Bruumagne et al., 2008; Chaudhry, Hans et al., 2004; Clair and Riach, 1996; Karlsson and Frykberg, 2000; Önell, 2000; Soangra and E Lockhart, 2013) to measure human subject
postural stability. This decision reflects the fact that using a force plate in real world job sites would be cumbersome and difficult since such plates are expensive, heavy, not easily carried, and require a flat stable surface to maintain calibration, accuracy, and repeatability.

To provide a stable surface for the test subjects to use while performing different steps of the test, a flat, stable steel plate was provided. Test subjects were asked to do both standing and squatting postures on the steel plate since the plate could provide the same standing surface condition through all of the stages of the test (See Figure 1-g). For all test trials test subjects body motions were recorded using a tri-axial accelerometer (Shimmer 9DOF) (See Figure 1-h). Sensors collected 52 data points per second for anterior-poster (AP), medio-lateral (ML), and vertical (VT) directions, each of which were oriented with X, Y, and Z axes, respectively. IMU sensors were attached to the dorsal surface of each test subject's back at a height of 57% of subject's total standing height (stature). According to Mayagoitia et al. (2002), this location is the appropriate human body location that can be selected as the body center of mass point for tracking and analyzing total human body motion.

Ten healthy able bodied human subjects participated in this research. (Mean age: 30.8 years; mean height: 6 ft.; mean weight: 192 lbs.). The subject sample had no reported history of clinical conditions or disabilities that would disqualify them from participation in the research project. All subjects verified that they were not taking any medications, drugs or consuming substances like alcohol that could cause drowsiness or adversely affect their body posture or movement stability. Test subjects with corrected vision wore their eye glasses or contact lenses during the experiments. All test subjects were college graduate student volunteers with no construction work experience.

Test subjects were asked to perform two different postures (standing and squatting) for three different tasks. For Task 1, test subjects stood on the steel plate for 30 second while they wore a full body harness without any connected tools; the subjects then repeated the test for another 30 seconds in a squatting position (See Figure 1-a&d). For Task 2, subjects repeated the standing and squatting motions—same as Task 1—while their full body harness was loaded with tools in a symmetrical configurations (See Figure 1-b&e). Task 3 repeated the same test as the first two tasks but with tools attached to the full body harness in an asymmetrical configuration (See Figure 1-c&f). The tools used in these tasks were selected from common sets of ironworkers tools for tool belts (See Figure 1-i). The total weight of the tools, tool belt, and full body fall protection harness was 30.0 lbs. The total weight of just the tools was 9 lbs. For the symmetrical tool belt configuration, tools were loaded with an equal weight on the right and left side of the tool belt. For the asymmetrical configuration, all the tools were loaded into the left side of the tool belt and fall protection harness.

Visual inputs—such as high and low-contrast visual acuity, contrast sensitivity, depth perception, stereopsis, and lower visual field size— are considered one of the extrinsic factors that could affect human body stability as a destructive factor (Jeka et al. 2004; Lord and Menz 2000); Visual inputs can disturb the human subjects and affect their stability by moving their bodies upright posture. To provide the same conditions for the different subjects while they performed different tasks, a white screen was installed in front of the subjects that covered the subjects’ vision completely. Subjects were asked to look forward and not to move their heads. The testing location was in a human factors and safety test lab in almost an imperturbable place protected from noise, disturbance, or distraction sources. The test lab environment helped to eliminate test procedure interference and avoid test subjects distractions.

Factors that could have increased data collection error were: (1) assigned test task ordering effects and (2) confounding effects due to test subject physical fatigue. In order to prevent or reduce the task orders effects physical fatigue confounding, 5 minutes rest was provided between different test tasks for each subject, and test tasks were randomly assigned for each subject. Before starting the experiment subjects were informed about the experimental procedure and any questions about the procedure were addressed. Figure 1 summarizes the different experimental tests (Tasks 1, 2, and 3) in this study.
Figure 1: Illustration of the experiment: (a) Standing while wearing full body harness without any connected tools; (b) Standing while wearing full body harness laden with some tools in the symmetrical configuration; (c) Standing while wearing full body harness laden with tools in asymmetrical configuration (d) Squatting while wearing full body harness without any connected tools; (e) Squatting while wearing full body harness laden with some tools in the symmetrical configuration; (f) Squatting while wearing full body harness laden with tools in asymmetrical configuration; (g) Steel plate with a flat surface; (h) Inertial Measurement Units; (I) Selected connected tools (right to left: full body fall protection harness and tool belt bag, 5 lb. sledge hammer, finish construction wrench, erection wrenches, pry bar, and pinch bars)

2.2 Measuring the Postural Stability

In this paper, resultant accelerometer (rAcc) and the average velocity of the center of pressure (COPv) were selected as two measures to calculate postural stability of construction workers. Resultant acceleration (rAcc) is a metric that was introduced in the clinical domain to measure the human body stability in a stationary posture (Brumagme et al., 2008; Liu et al., 2012; Soangra and E. Lockhart, 2013). The rAcc measures the total human body motion in a certain period of time using the accelerometer vector components from inertial measurement units (IMU). Higher rAcc means higher instability for human subjects.

The average velocity of center of pressure (COPv) was introduced as the most reliable measure for assessing the stability of human bodies in stationary positions within the biomechanical domain (Lafond et al., 2004). COPv is calculated by summing the distance between each consecutive point of the body’s center of pressure and dividing this over the total data-collection time (Hufschmidt et al., 1980). In a stable situation, the location of the center of pressure is constant or has a minimum displacement. Increasing the displacement of the center of body location will increase the COPv, and higher COPv means higher instability.

Resultant acceleration (rAcc) was calculated using Equation 1.

\[ rAcc = \sqrt{\sum (a_{x}^2 + a_{y}^2 + a_{z}^2)} \]
Where \( a_x, a_y, a_z \) are the acceleration measurements from the IMU.

This paper used Mayagoitia et al. (2002) method to calculate the COPv. The main idea of this method is to measure the sway path of the accelerometer and to assume that this sway path is same as the sway path of the body's center of pressure. The magnitude of the resultant acceleration \( (A) \) for each point can be calculated using Equation 2 where \( a_x, a_y, \) and \( a_z \) are the acceleration measurements from the IMU across each axis (See Figure 2-A).

\[
[A] = \sqrt{\left(\frac{a_x^2}{A_x}\right) + \left(\frac{a_y^2}{A_y}\right) + \left(\frac{a_z^2}{A_z}\right)}
\]

After calculating the \( A \), the angle between the different directions of the accelerometer vectors and the magnitude of the resultant acceleration can be calculated using the group of Equations 3-6.

\[
\cos \alpha = \frac{a_x}{A} \quad \cos \beta = \frac{a_y}{A} \quad \cos \gamma = \frac{a_z}{A}
\]

\[
x = D \cdot \cos \alpha \\
y = D \cdot \cos \beta \\
z = D \cdot \cos \gamma
\]

Where \( \cos \alpha, \cos \beta, \cos \gamma \) are the directional cosine and \( \alpha, \beta, \gamma \) are the angles between the components of the acceleration and the resultant acceleration. \( D \) is the magnitude of the accelerometer vector.

In the above mentioned equations, \( D \) has an unknown value. \( D \) can easily be calculated from equation 6 since it can be assumed that \( z_i \) has a constant value equal to the height of the IMU. Finding the value of \( D \) and replacing \( D \) in equations 4 and 5 will lead to one finding the value of \( x_i \) and \( y_i \) (See Figure 2-b). Next, the average velocity of the center of pressure (COPv) was calculated by summing the distance between each consecutive point of the COP and dividing this over the total data collection time \( (T) \) using the equation 7 (Hufschmidt et al., 1980).

\[
[COPv] = \frac{\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}}{T}
\]

Where \( T \) is the total data collection time and \( x_i \) and \( y_i \) are the center of body's coordinates. All of the calculations were performed using custom-made software written in MATLAB (ver 8.1.0.604, The Math Works Inc., USA). The commercially available SPSS was used for statistical analyses.

Figure 2: Representative stabilograms obtained from a subject. (A) The time-series data captured by IMU in three directions (Vertical accelerometer, ML accelerometer, AP accelerometer). (B) Stabilogram of center of pressure.
3 STATISTICAL ANALYSIS

T-test Analysis

T-test analyses for small equal sample sizes were conducted for rAcc and COPv values between Task 1 (standing and squatting while wearing full body harness without a load) and Task 2 (standing and squatting while wearing full body harness laden with tools in a symmetrical configuration), and between Task 2 and Task 3 (standing and squatting while wearing full body harness loaded with some tools in an asymmetrical configuration). The alpha level for the t-test was set at $\alpha=0.05$.

Two-way ANOVA

Two two-way analysis of variance (ANOVA) were performed for rAcc and COPv values to compare the effects of the loaded-tools’ configuration on rAcc and COPv values. The alpha level for ANOVA test was set at $\alpha=0.05$.

4 RESULTS

The mean and standard deviation (SD) values of rAcc and COPv values are shown in the Figure 3. For both standing and squatting postures, rAcc and COPv had their highest value in Task 3. The highest overall COPv was found in the squatting posture of Task 3 as 41.05, while the minimum value was found in the standing posture of Task 1 as 5.379. Higher rAcc and COPv values specify the low postural stability of the subject, which can be interpreted as having a higher fall risk. Similar to the COPv results, the highest rAcc value was found in the squatting posture of Task 3 as 41.05, and the lowest rAcc was found in the standing posture of Task 1 as 1.848.

Table 1 summarizes the results of the t-test between different loaded tools configurations in the standing and squatting postures. The results show a significant difference in the comparison between Task 1 and Task 3 in both the standing and squatting postures, Task 2 and Task 3 in both postures, and Task 1 and Task 2 in the standing posture. The t-test only failed to confirm a significant difference in the comparison between Task 1 and Task 2 in the squatting posture. While the t-test did not show significant difference in comparing the Task 1 and Task 2 in the squatting posture, however, there was a significant difference in the mean value of both rAcc and COPv in these two cases. The lowest t-test p-value appeared in comparing Task 1 and Task 2 which implies that there is a significant effect of improperly loaded-tools’ configuration on construction worker stability.

Table 2 summarizes the results of the ANOVA test in the comparison between the different tasks in their respective standing and squatting postures. The ANOVA test results also indicate a significant difference in both rAcc and COPv among the three tasks in both the standing and squatting postures. The p-value of COPv in both standing and squatting postures was lower than the p value of rAcc, which again shows that COPv demonstrates more significant differences in the comparisons between the different tasks.

Although both rAcc and COPv metrics have the same trend in comparing different loaded-tools’ configuration in standing and squatting postures, there was a higher sensitivity in COPv values rather than rAcc values when changing the tasks, according to Figure 3. Another result of this paper is the higher value for rAcc and COPv for the different tasks in the squatting posture rather than the standing posture, which shows that construction workers have a higher instability in the squatting posture than the standing posture. Also, the difference of in the calculated COPv between different tasks is higher in the squatting posture rather than the standing posture. This implies that the load configuration may have a higher adverse effect in more instable postures—such as squatting—than in stable postures—such as standing.
Figure 3: rAcc and COPv values for different full body harness tool configurations in standing and squatting postures.

Table 1: T-tests p values between different loaded-tools’ configuration and measures in standing and squatting postures.

| Tasks | Standing Posture | | | Squatting Posture | | |
|-------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|       | T1¹              | T2²              | T3³              | T1¹              | T2²              | T3³              |                   |                   |                   |                   |                   |                   |                   |                   |
| T1¹   | -                | 0.0024*          | 0.00039          | -                | 0.1274           | 0.0101*          |                   |                   |                   |                   |                   |                   |                   |                   |
| T2²   | 0.0024*          | -                | 0.0495*          | 0.1274           | -                | 0.0152*          |                   |                   |                   |                   |                   |                   |                   |                   |
| T3³   | 0.0003*          | 0.0495*          | -                | 0.0101*          | 0.0152*          | -                |                   |                   |                   |                   |                   |                   |                   |                   |

¹Task 1
²Task 2
³Task 3

Table 2: ANOVA test p values between different loaded-tools’ configuration and measures.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Standing Posture</th>
<th>Squatting Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>COPv</td>
<td>0.005*</td>
<td>0.0008*</td>
</tr>
<tr>
<td>rAcc</td>
<td>0.018*</td>
<td>0.031*</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS AND DISCUSSION

The goal of this research was to demonstrate the effects of tool belt loading symmetry on posture stability of construction workers wearing a tool belt connected to a full body fall protection harness. Sometimes, young construction workers do not fully understand the importance of symmetrical tool belt loading and its relationship to working postural stability and lower fall risk. This research reinforces the importance of proper tool belt loading for young or less experienced construction workers.

The results of this research revealed that asymmetrical tool belt loading was associated with lower posture stability in the standing squatting postures when compared with symmetrical tool belt loading. In addition, it was found that even a symmetrical tool belt loading condition will result in some instability for construction workers when compared to a situation in which there are no tools loaded in the tool belt fall protection harness system. Another key finding was the confirmation of the usefulness of the suggested postural stability metrics in distinguishing the fall risk of construction workers while performing tasks with different fall risk profiles. These results also highlight the value of using IMU wearable sensors as a possible monitoring device to assess construction workers’ fall risk. IMU sensors can attach to
construction workers to measure the stability of construction workers’ while they perform different tasks in different postures on a construction site and can foreseeably be used as a method to prevent fall accidents.

Future research should examine the effects of other intrinsic and extrinsic factors—such as walking speed, construction site walking surface friction characteristics, worker age, worker training and experience—on the construction workers’ postural and work movement stability since these factors may adversely affect worker safety. Other future studies could study the sensitivity of different stability metrics in order to find the most sensitive metrics to compare the effects of different intrinsic and extrinsic factors on work posture and movement stability.

Acknowledgements

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References


FRAMING CONSTRUCTION USES OF VIRTUAL INFORMATION MODELS

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Abstract: Digital models incorporating 3D geometry and information attributes are becoming a standard for industrial facility and commercial building design. Despite the advancements in technologies to develop design models there is an opportunity to better leverage models within facility construction processes. The current work aims to identify the breadth of construction needs for using information models, and develop an approach to improve information accessibility to support construction. With a thorough literature review, the current work identifies the state-of-art workflows in using design content to support construction tasks. The existing gaps of using models for construction uses have also been captured, indicating the opportunities of better leveraging model content throughout construction process. Discussion of how a planning approach and implementation guidelines will be developed to advance model uses in construction will help conclude the paper.

1 INTRODUCTION

Digital models incorporating 3D geometry and information attributes are becoming a standard for industrial facility and commercial building design. Depending on the technology, a variety of model uses have been developed to serve particular purposes for project stakeholders, such as designers and contractors, across project phases. Practitioners have acknowledged the benefits of adopting the data-enriched models in integrating design and construction (Eastman et al., 2011). Regardless, challenges remain in better leveraging models within facility construction processes. Current practices frequently require significant design content remodeling or revision for construction, such as the creation of detailed fabrication models and coordination models adding details required for construction. Moreover, there is a need for a comprehensive understanding of construction information requirements that are not presently available, but could be delivered via a model. This presents an opportunity to create coordinated industry guidelines and a process for leveraging model content through the construction phase.

As an initial step, this paper focuses beyond the implementation of models for commercial building projects, and aims to identify the breadth of construction needs for using information models. A thorough review of recent academic publications has been conducted to capture the state-of-the-art construction modeling. The existing gaps of using models for construction uses have been revealed, indicating the opportunities of better leveraging model content throughout construction process. The need of developing a planning approach and implementation guidelines to advance model uses in construction is discussed as well.
2 BACKGROUND

Information modeling has been adopted in the architectural, engineering, and construction (A/E/C) industry since late 1980’s. Focusing on commercial building projects, Kreider and Messner (2013) defined a building information model use as “a method of applying Building Information Modeling (BIM) during a facility’s lifecycle to achieve one or more specific objectives.” There have been many efforts on listing BIM uses, documented in publications (Eastman et al., 2011), industry guides (Department of Veterans Affairs, 2010), and other industry efforts (Computer Integrated Construction Research Program, 2010). None of them are completely comprehensive or generated by a consistent methodology. Regardless, according to the BIM Project Execution Planning Guide (Computer Integrated Construction Research Program, 2010), which is the most widely adopted for BIM uses, there are 9 of 25 defined uses that can be adopted to support the construction. Among them, 3D coordination was reported in an online survey as the most frequently used BIM use and perceived as the highest beneficial use; while the others, digital fabrication, in particular, was considered as very beneficial, yet not used frequently (Kreider et al., 2010).

One of the main reasons to explain the challenges during adoption is managerial (AGC, 2005). There is a need to standardize the process and to define the guidelines for using the models along with the embedded information to facilitate construction process (Azhar et al., 2011). Driven by the managerial challenges, Kreider (2013) applied a methodology and generated a model use taxonomy for BIM implementation, which has also been approved for adoption in the National BIM Standard – US, Version 3 (still awaiting publication). The primary components of a BIM Use are shown in Figure 1, with five different purposes identified as “Gather,” “Generate,” “Analyze,” “Communicate,” and “Realize.” The ontology that applied in this study provides an effective methodology to categorize BIM Uses and also allows for future expansion of BIM Uses.

Therefore, this paper employs the ontology to capture the state-of-the-art model use and identifies the gaps and areas to potentially expand modeling implementation in the future. To avoid the challenges related to the perception of BIM’s application to be specific to a category of facilities, more broad language is used here by John Messner to define the “Model Use” as: “a method or strategy of applying digital modeling during a project lifecycle to achieve one or more specific objectives.”

3 METHODOLOGY

A review of recent academic research on the development and implementation of construction modeling has been applied to capture the leading model use and identify potential construction needs for future modeling implementation. Seven journals and five conferences were targeted as sources (Table 1). “Virtual model” and “construction” were used as key words to search the targeted journal publications and conference proceedings for relevant papers. With a total number of 53, Figure 2 shows the number of relevant papers in each 5-year period of the past two decades.

Through the literature review, matrices are used to capture the current model uses and to reveal the opportunities of future model uses to support construction tasks. In the current work, three types of matrices have been plotted:

- Model Use Technology verses Construction Task: to capture the construction tasks that can be supported by model uses leveraging emerging emerging technologies.
Model Use Technology versus Model Use Purpose: to capture the purposes of existing model uses in construction.

Construction Task versus Model Use Purpose: to capture the construction tasks that have modeling supported in different purposes.

In addition to capture the existing model use, the three matrices are expected to reveal the gap of model uses in construction, indicating opportunities of leveraging technologies and model information to facilitate construction operations. The next two sections will discuss the review results, starting with the description of the matrix components.

**Table 1: Publications of major construction journals and conferences for review**

<table>
<thead>
<tr>
<th>Source</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal</td>
<td>ASCE Journal of Computing in Civil Engineering</td>
</tr>
<tr>
<td></td>
<td>ASCE Journal of Construction Engineering and Management</td>
</tr>
<tr>
<td></td>
<td>Elsevier Journal of Automation in Construction</td>
</tr>
<tr>
<td></td>
<td>Journal of Information Technology in Construction</td>
</tr>
<tr>
<td></td>
<td>ASCE Journal of Architectural Engineering</td>
</tr>
<tr>
<td></td>
<td>Canadian Journal of Civil Engineering</td>
</tr>
<tr>
<td></td>
<td>Elsevier Journal of Advanced Engineering Informatics</td>
</tr>
<tr>
<td>Conference</td>
<td>International Society for Computing in Civil and Building Engineering (ISCCBE) Conference</td>
</tr>
<tr>
<td></td>
<td>International Symposium on Automation and Robotics in Construction (ISARC)</td>
</tr>
<tr>
<td></td>
<td>International Council for Research and Innovation in Building and Construction (CB) W78 Conference</td>
</tr>
<tr>
<td></td>
<td>eWork and eBusiness in Architecture, Engineering and Construction: ECPPM</td>
</tr>
<tr>
<td></td>
<td>Annual Conference of the International Group for Lean Construction (IGLC)</td>
</tr>
</tbody>
</table>

![Figure 2: Academic publications reviewed during the period of 1994-2014](image)

**Figure 2: Academic publications reviewed during the period of 1994-2014**

### 4 DIMENSIONS OF MODEL USE MATRIX

Three dimensions are used to develop the model use matrix and to capture construction modeling uses: model use technology, construction task, and model use purpose.

#### 4.1 Model Use Technology

The first dimension of model use matrix is “model use technology,” to capture the emerging technologies being leveraged for model use in the construction industry. Anderson and Schaan (2001) categorized the advanced technologies into five high-level groups: communications, on-site plant and equipment, materials and systems, systems, and design. Fenn (2010) mapped out a number of potentially transformative technologies, from augmentation to tablets, depending on the time to and the impacts on the mainstream adoption of each. In the current study, seven different types of models use technologies are categorized and summarized:

- **Simulating technology:** it described as the technology to create a model that behaves or operates like a given system with a set of controlled input (Anderson and Schaan, 2001).
- **Business management tools:** it includes all the systems and applications used by organizations to cope with the planning and management of expenses, process, resources, documents, field administration, and communication (Neelamkavil, 2009). Example tools can be Enterprise Resource Planning (ERP), and document management systems.
- **Geographic information system (GIS):** GIS is defined as a computer system “capable of storing, editing, processing, and presenting geographical data and information as maps” (Campbell and Shin,
2011). GIS applications allow users to query and analyze spatial information, edit geographical data in maps, and present the results of all these operations.

- Positioning systems (or tracking systems): it describes the usage of technology to determine or track the location of an object during construction (Grau et al., 2009). Related technology includes Global Positioning System (GPS), Radio-frequency (RF) Technology, and Ultra-wideband (UWB).
- Imaging technology: it indicates the application of technology that is used to capture, process, and preserve images to support construction operations, such as 3D video rage imaging, photogrammetry, laser scanning, and augmented reality (Turkan et al., 2013).
- Mobile technology: this technology provides support for small, handheld computing devices with a display screen, such as mobile phones and tablets, to be used by mobile workers to view, input, and transmit information (Kondratova, 2004).
- Robotics: it indicates the application of robots to support and even automate construction operations (Neelamkavil, 2009).

4.2 Construction Task

The second dimension of the matrix is “construction tasks,” to capture the construction activities that can be supported by model uses. Preliminary investigation of construction tasks was based on the schedule-based control structure approach (Halpin et al., 1987), also named as work breakdown structure (WBS).

As the first level of breakdown structure, those following categories can be subdivided into the level of detail as needed. The planning and management tasks throughout the construction process are considered as a separate category listed as follows:

- Construction planning & management: it describes the activities related to planning and management before and throughout construction, including construction scheduling and planning, progress monitoring, resource tracking and management, safety, and coordination activities.
- Procurement: it describes the acquisition of resources needed to transform a design to a physical facility, from purchasing to manufacturing/fabrication, and delivery to the construction site.
- Civil engineering activities: here it is considered as site development tasks based on hydraulic, environmental and geotechnical engineering, like surveying, drilling, boring, pavement, etc.
- Excavation & Foundation: it describes the construction tasks for excavation and foundation construction.
- Frame Erection: the erection of structural frame/components is the focus of this category.
- Assembly & Installation: it describes the construction assembly and installation tasks at site.
- Engineering Systems: it refers to the construction activities related to mechanical, electrical, and plumbing (MEP) systems.
- Enclosure & Finishes: it indicates the construction of building envelope and finishing work.
- Quality Assurance/Quality Control (QA/QC): activities that help to inspect and control the quality of construction belong to this category.

4.3 Model Use Purpose

Another dimension that used to plot the matrix is model uses purposes. According to Kreider (2013), there are five categories and eighteen subcategories of model uses purposes in the industry (Figure 3):

- Gather: to collect or organize facility information, covering the sub-purposes such as “Qualify,” “Monitor,” “Capture,” and “Quantify.”
- Generate: to create or author information about the facility, covering the sub-purposes such as “Prescribe,” “Size,” and “Arrange.”
- Analyze: to examine elements of the facility to gain a better understanding of the elements, covering the sub-purposes such as “Coordinate,” “Forecast,” and “Validate.”
- Communicate: to present information about a facility in a method in which it can be shared or exchanged, covering the sub-purposes such as “Visualize,” “Draw,” “Transform,” and “Document.”
- Realize: to make or control a physical element using facility information, covering the sub-purposes such as “Fabricate,” “Assemble,” “Control,” and “Regulate.”
5 RESULTS

Plotted between the three dimensions, three matrices are developed and explained in the following.

5.1 Model Use Technologies Supporting Different Construction Tasks

Figure 4 illustrates the matrix of model use technologies broken down by construction tasks. The data indicates the number of publications that employed the particular model use and technology to support construction operations. It should be noted that one case may use multiple technologies; and on the other hand, one type of technology use can be applied for multiple construction tasks. For the modeling effort that supports construction planning and management, it is also interested to capture the phases, from procurement to quality inspection, when the application emphasized and occurred.

![Model Use Technologies for Construction Tasks](image)

As illustrated, construction planning and management is considered as the primary task that needs the support from construction modeling with advanced technologies. More specifically, progress monitoring and resource management become the focus, considering the technological impacts on the improvement of craft productivity (Grau et al., 2009). They are widely tested in the procurement, erection, assembly, and installation of structural components such as beams and columns (Figure 4). Simulation technology, imaging technology, and positioning systems are mostly applied to support the activities. Compared with structural components, monitoring and tracking the work of engineering systems is found to be challenging. However, leveraging model uses and technologies for construction tasks regarding engineering systems is largely needed (Figure 4), since they constitute a large portion of construction costs and asset value (Bosché et al., 2013).

Robots have also been studied in order to support various construction operations, such as excavation and foundation work (Ha et al., 2002), frame erection (Kang and Miranda 2006), assembly and installation (Chu et al., 2013), finishes (Bai, 2007), and QA/QC (Shen, Lu, and Chen, 2010) (Figure 4). Regardless,
they are not implemented on a wide scale for many reasons, such as dynamic nature of construction sites, culture, human skills, and cost of applying robotics technology (Caldas and Goodrum, 2010).

5.2 Implementing Model Use Technologies with Different Model Use Purposes

Similarly, Figure 5 illustrates the matrix of model use technologies broken down by model use purposes. The numbers indicate the quantity of publications that leveraged the particular technology for certain model use purpose(s). One case may have multiple technologies applied together to serve a primary model use purpose. Thus, for each case, only the primary model use purposes of the study was plotted into the matrix. For example, Hammad et al. (2007) employed simulation technology and GIS to perform an equipment workspace analysis for infrastructure projects. The representation of the workspace (i.e., “Communicate”) through capturing the existing site information (i.e., “Gather”) can be two model use purposes. But considering that the goal of the study is to detect and resolve the potential equipment workspace conflicts, the primary model use purpose was identified as “Analyze” instead.

![Figure 5: Categorizing model uses and technologies by model use purposes](image)

As shown, “Gather” is the most popular model use purpose, majorly by implementing technologies such as positioning systems and imaging technology to track materials and monitor construction progress (Figure 5). This result is consistent with the high demand of technology uses for construction planning and management indicated in Figure 4. On the contrary, the least amount of studies on construction modeling are found to be driven by “Generate” and “Communicate” purposes. The reason could be that the benefits of implementing 3D modeling and mobile technology to generate, access, and transfer facility information has been widely demonstrated in practice. With the increasing experience of model use, the needs of model use gradually progress beyond the initial intent of visualization and coordination, and to sophisticated analysis (Taylor and Bernstein, 2009). Those analysis employed simulation technology (“Analyze” in Figure 5), to simulate and optimize construction planning, such as planning for site layout (Astour and Franz, 2014), logistics (Said and El-Rayes, 2014), and equipment workspace (Hammad et al., 2007). Moving beyond “Analyze,” the ultimate model use of robots, combined with other technologies, to automate the realization process of a facility product also attracted fair amount of attention in academia (“Realize” in Figure 5).

5.3 Construction Tasks Supported with Different Model Use Purposes

The third matrix (Figure 6) illustrates the construction tasks that can be supported by model uses on different purposes. Consistent with previous results, Figure 6 captures the primary need of implementing modeling for planning and management. The majority of model uses were applied to collect information about a facility at various phase, from procurement to quality inspection, for progress tracking and
resource management ("Gather" in Figure 6). Figure 6 also indicates the construction needs of more sophisticated model use, as the number of studies increases from category of "Generate" to "Realize." Even with "Generate" purpose, the modeling application shifted from creating or authoring information about the facility product to generating the plan of temporary structure such as scaffolding for frame erection (Kim and Teizer, 2014). The considerable number of studies with "Realize" model use purpose (Figure 6) reflects the interests of automated construction tasks such as fabrication. Regardless, in overall, there is still lacking model support for construction tasks such as excavation, engineering systems, and envelope and finishes (Figure 6).

![Construction Tasks Supported by Model Use Purposes](image)

Figure 6: Supporting construction tasks with different model use purposes

6 DISCUSSION AND CONCLUSION

To summarize, this paper captures the state-of-the-art model uses for construction tasks. These efforts have been mostly applied in progress monitoring, as well as resource tracking and management. Driven by the "Gather" purpose, technologies such as positioning systems and imaging technology have been used to support these activities. Moreover, this paper identifies the breadth of construction needs of model use, and indicates that the current model uses need to be broadened with sophisticated analysis to support construction operations, such as excavation and engineering systems. The lag of current adoption also calls for developing implementation guidelines, which are expected to address the model use purposes, process, and technology and information requirements, to better support construction needs. It is also important to note that multiple model uses can be combined to achieve an overall goal on a project. Examples of goals which require the integration of multiple model uses include a series of model uses to develop, visualize and analyze a site logistics plan, or the development, visualization and analysis of the material management information for a project. These overall goals require a defined series of activities which build the model content through a progression of model uses, and model information. This paper provides the ground of building such a model progression based on the breadth of construction needs and the paradigm of model use purposes.

Thus, future work will focus on defining an approach to organize the model uses that can be applied together to achieve an overall project goal. The information needs will be identified, along with the interactions between the model uses. Potential near-term future model uses will be explored and defined.

Acknowledgements

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RESEARCH FOR GENERATING 2D-DRAWINGS OF SUPERSTRUCTURE IN HIGHWAY BRIDGE

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Abstract: Maintenance of highway bridges built during the high economic growth period is performed based on their design drawings and as-built drawings. For these elevated highway bridges, however, drawings were produced on paper media at the times of design and completion; therefore, in many cases they have already been disposed, making it difficult to perform maintenance. In such a case, regenerating the detail design of the current status is required, but it takes huge cost. For this problem, a large number of researches have been made on automatic generation of three-dimensional models for maintenance of highway bridges from point cloud data obtained through MMS (Mobile Mapping System). However, it is hard to use the models generated in these researches because engineers do not consider the original geometric information of highways. Thus in this research, we aim to regenerate the CAD drawings of the superstructure of an elevated highway bridge, and propose a method for extracting alignment information of the elevated highway bridge from point cloud data of MMS. We verify the usability of our method and system by comparing the experimental data with surveyed drawings in our experiments.

1 INTRODUCTION

In Japan, many elevated highway bridges built in the high economic growth period have been worn out. Particularly for elevated highway bridges, it is urgently required to propose effective and feasible maintenance plans to extend their lifetime. Further, to ensure the appropriateness of inspection, repair plans and construction methods, the construction drawings (e.g. design drawings and as-built drawings) need to be provided to correctly understand the current status. However, drawings of many elevated highway bridges constructed during the high economic growth period around the 1970s were produced on paper media. After the lapse of 30 years document retention period (MLT 2010, MLT 2001), many of them have been disposed. In such a case, it is necessary to regenerate the detail drawings of current status. However, the field surveying will be necessary involving road closure, which will result in huge costs. To avoid this, many researches were done to obtain the data of current status without disturbing the traffic flow by using Mobile Mapping System (MMS). These researches, however, were made on automatic generation of 3D models from point cloud data, which were only tailored for visual data processing of the superstructure of an elevated highway bridge, without considering the original alignment information of the elevated highway bridge. Therefore, it is too hard to rely on as the drawing of current status to use for maintenance. Thus in this research, we aim to regenerate two-dimensional (2D) CAD drawings in SXF format (CAD Data Exchange Standards Subcommittee 2005) of the superstructure of an elevated highway bridge, and propose a method for extracting alignment information of the elevated highway bridge from the 3D data, in order to solve the problem of current status.
2 SYSTEM OVERVIEW

This research aims to regenerate the CAD drawings of the superstructure of an elevated highway bridge by performing a proposed method to extract alignment vector information of the superstructure from point cloud data of MMS measuring the elevated highway bridge. System flow is shown in Figure 1.

![Figure 1: System flow](image)

This system consists of two parts of functions: Generation of 3D data and analysis of alignment information. Firstly, in the generation of 3D data, we analyzed the point cloud data obtained through MMS to get the point range of plan, cross-section and longitudinal-section of elevated highway bridges, which generated the 3D data. Secondly, we extracted the joint of elevated highway bridge to segment superstructure and generate the 3D data which can keep the information in each span of them. Then in the analysis of alignment information, we used the 3D data obtained through the generation part of 3D data to calculate the alignment information through analyzing the point range of plan, cross-section and longitudinal-section, thereby obtaining the required alignment information. On this basis, we considered the association of geometric information of the front and back of the superstructure to correct the alignment information, thereby improving the precision of geometric information. Finally, we calculated the formula parameters of the alignment information in each span of superstructure, with CAD drawings generated.

2.1 Point-Cloud Analysis Function

The high-precision laser scanner carried in MMS can ensure the accuracy of data amount. However, the collected data amount through the laser scanner is too large, making it difficult to analyze via common software. Thus, in this function, we analyzed the feature of point cloud data as shown in Figure 2, to recognize the features of elevated highway bridges, thereby extracting only the useful data for generation of 3D data.

![Figure 2: Point-cloud analysis function](image)

2.2 3D-Data Generation Function

As such, we extracted the useful point cloud data through the point-cloud analysis function, and automatically generated 3D data which can be processed by common software. We also extracted the center line to use for maintenance based on 3D current status drawings. In this function, we used the point range and feature points of each cross-section obtained through the point-cloud analysis function as
input data, and output the point range representing the road alignment of the elevated highway bridge and the feature points of the cross-section point range at regular spacing, as shown in Figure 3.

Figure 3: 3D-data generation function

2.3 Function of Segmenting Elevated Highway Bridge

In drafting the construction plan, a design proposal is supposed to be made for each span of the superstructure. In this regard, we segment the 3D data from span to span of the elevated highway bridge, in order to fulfil the design requirement of the construction plan. In this function, we extracted out the joint parts between the spans of superstructure by using colour information. Then we segmented the structural points of 3D data based on the joints, as shown in Figure 4.

Figure 4: Function of segmenting elevated highway bridge

2.4 Line-Type Determination Function

To extract out the alignment information, it is essential to figure out the line type. In the alignment of road plan, we applied straight lines, arcs and clothoid curves. In addition, we used straight lines and quadratic curves in the vertical alignment. In this function, we chose the joints which were output through the 3D data generation part as the candidate locations of the start and end points of the alignments, and determined the line types of all alignments by performing the method of least squares as shown in Figure 5.

Figure 5: Line-type determination function

2.5 Line-Type Correction Function

When the curvature radius of an arc or a clothoid curve is too long or there are too many abnormal feature points, the line type may be misjudged. In this function, we harnessed the feature of a clothoid curve to link a straight line with an arc for improving the extraction precision of alignment information by correcting the possibly misjudged line type, as shown in Figure 6.
2.6 Function of Generation of CAD Drawings

In this function, we calculated the CAD alignment parameters based on the formula of various CAD alignments as shown in Figure 7, and generated CAD drawings. However, we used a cubic Bezier curve to represent a quadratic curve.

3 CONCLUSION

In this research, we tried to generate CAD drawings by using the features of 3D data obtained through MMS measurement of elevated highway bridges, as shown in Figure 8. In the future, we will verify the applicability of our method to practical business and aim to improve the precision of alignments so that municipalities in Japan can use CAD drawings generated by applying this method.

References


CONDITION DIAGNOSTICS OF STEEL WATER TANKS USING CORRELATED VISUAL PATTERNS

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Abstract: Insufficient, unreliable, and delayed condition assessment of steel water tanks is causing poor maintenance planning, wastes of maintenance resources, and unexpected structure failures. Visual inspection of water tanks heavily relies on engineers’ experiences for achieving comprehensive and reliable condition assessments. Recent studies reveal the potential of using imaging technology for improving the efficiency and comprehensiveness of capturing visual conditions of large civil infrastructures, but manual interpretation of imagery data still impedes engineers from reliable awareness of structural conditions. On the other hand, some studies show that deteriorations of structures result in correlated visual patterns that can assist engineers in structural diagnosis. The objective of the research presented in this paper is to examine correlated deformation patterns of a steel tank based on analyzing 3D laser-scanned point clouds collected in the field. Specifically, the authors aim at identifying correlated shape change patterns of a water tank through various 3D data analysis algorithms, and synthesize these 3D data patterns as knowledge for guiding data-driven condition assessment of the water tank. The authors examined two 3D data analysis approaches for revealing the deformation patterns of the studied tank. The first approach calculates the deviations of the 3D data points from as-designed shapes of the water tank for identifying structural deformation and defects. The second approach visualized anomalous variations in local shape descriptors, such as curvature, for identifying defects of structures. Correlations between the patterns could then reveal systematic changes of the tank for helping engineers conduct more reliable condition assessments.

1 INTRODUCTION

Many civil engineering structures are prone to damages and deformations. Structural damage evaluation has become very important part of maintenance. Statistics estimate that to eliminate the deficit bridges by 2028, the nation has to spend minimum of $20.5 billion per year by, however only $12.8 billion is being spent for design, construction, replacement, and rehabilitation of bridge structures (Cooper and Munley 1995). To accommodate these funds in a right way there is a need for a systematic approach that can find the root cause and avoid unnecessary repair work behind these structural failures. Detailed geometric assessment of civil infrastructure is essential for reliable maintenance planning and public safety. Non-destructive testing such as visual inspection of a structure only offers a broad view of the structures’ current state, but fails in providing the root cause of the structural damage. Hence, comprehensive geometric data is essential for effective structural rehabilitation. Using imagery sensors to capture meticulous data of a structure precise to 2mm range distance can support detailed structural assessment. Such detailed data could help in eliminating unnecessary repair work of an infrastructure by exactly identifying area that requires structural renovation. However, manual interpretations of such
detailed geometric data require professional experience and are sometimes error prone. Correlated deformation patterns can assist engineers in accurate visual data interpretation and achieving reliable structural assessment. For example, collective growths of cracks and deformations on interconnected components reveal the changes of loading paths across a structure and likely defects. Formalizing these correlated visual patterns as signatures of structural health conditions hold strong potential in reducing the reliance on engineers’ experiences in structural health monitoring.

Building surveyors play a key role in maintaining the structural integrity of the building during and after construction process. Surveyors use high quality optical instruments such as Total Stations for geometric measurements of a structure (Fröhlich and Mettenleiter 2004). These measurements include distance, horizontal and vertical angles and the coordinate information of the measured component. However, the density of the measured data completely relies on surveying time (Erickson, Bauer, and Hayes 2013). Furthermore, the instrument should move several times in order to get the complete structure and have portability limitations. Additionally the instrument requires a licensed professional to operate and record the measurements. Moore et al. (2001) highlights the limitations of visual inspection for surveying highway structures. Currently LIDAR (Light Detection and Ranging) technology has gained popularity over the conventional surveying systems (Jaselskis and Gao 2003). Researchers used 3D laser scanning technologies to analyze the deformations of bridges and identified the advantages of capturing geometric details for achieving more effective Finite Element Modeling (FEM) and analyses of existing facilities (Dai et al. 2013; Park et al. 2007).

However, reliable visualization of the captured data and accurate conditional geometric assessment is still error prone. Goor 2011 stated that registration errors and measurement errors could affect the quality of deformation analysis. He proposed using Iterative Closest Point (ICP) algorithm for accurate surface matching to eliminate registration errors. However, this approach is manual and requires lot of time to process. Many of the existing research indicate the challenge of reliably associating data collected from the laser scanner with the as-designed model of a building structure (Kalasapudi, Turkan, and Tang 2014). This association will aid in deformation detection by identifying changes between as-is condition and as-designed condition. Yet, identifying the root cause of detected deformation of a structure is still unreliable as many factors may cause the structure to undergo such deformations.

This paper focuses on formalizing the data processing procedures to detect deformation patterns for efficient structural health monitoring of water tanks to improve the 3D data interpretation in assessing a water tank. Initially, the authors detected the deviations of 3D as-is laser-scanning data with the as-planned model of water tank structure to analyze its spatial changes (Section 4). This step identifies various defects and deformation of every individual component of the tank. The authors then correlated the detected deformations to identify patterns that lead to systematic changes of the tank during its service period (Section 5). This detailed geometric assessment of the structure can help reduce the incorrect decisions of building maintenance, and reduce unnecessary costs or propagative errors.

2 APPLICATIONS OF 3D IMAGERY TECHNOLOGY IN STRUTURAL INSPECTION

Previous studies in the domain of construction and infrastructure management examine the technical feasibilities of using 3D imaging systems in geometric assessments of various buildings and structures. Park et al. 2007 carried out an experiment for health monitoring of a simply supported steel beam and compared to the results obtained from other diagnostic techniques such as electric strain gauges, long-range fiber optic sensors etc. Lee and Hyo 2013 estimated the maximum stress in a steel beam structure using a 3D coordinated data from a laser scanner. Allard et al. explored the potential of using 3D imagery data for mechanical damage inspection on an aircraft. They stated that the major advantage of using Laser scanning is to minimize the total time of inspection of the aircraft by fast decision making along with immediate on-site results. Lemmon (2011) has explained the feasibility of using laser-scanning technology for structural geometric calibration and deformation detection of large storage tanks.

Various 3D data processing algorithms developed in the past that can process the data obtained from a laser scan (Yang, Wang, & Chang, 2010, Tarsha-Kurdi, 2007, Girardeau-Montaut, 2011). Some
algorithms are computationally efficient enough to achieve real-time data processing that support decision making process of engineers (Girardeau-Montaut 2011). In this paper, the authors analyzed the 3D scans of the steel tank using existing algorithms and developed an approach for efficient geometric assessment of the large steel tank to correlate detected deformations. The following section details the data collection and processing procedure, and describes the diagnosis approach.

3 OVERVIEW OF THE TEST SUBJECT AND THE DATA COLLECTION PROCEDURE

In order to analyze the feasibility of using LIDAR data for geometric assessment, the authors selected an existing Steel Water Tank as a test subject. This Steel Water Tank is a combination of a cylinder at the bottom and a cone at the top. According to the as-built drawings, the tank has a radius of 21.34 meters and a height of 11.43 meters in total, in which 9.75 meters is of cylindrical part, and 1.67 meters is of the conical part. To identify the defects/deformations the authors use a cylindrical co-ordinate system.

The cylindrical co-ordinate system use ‘Radius’, ‘Azimuth’, and ‘Elevation’ to locate 3D points in space. The azimuth starts with 0 degree and ends with 360 degree to form a circle representing the cylindrical body of the tank. The authors define the East Direction as zero azimuth that serves as the origin to the cylindrical coordinate system (Figure 1 (a)). The authors collected eleven scans that comprise of four interior (inside the tank) and seven exterior scans. To filter the redundant data from the collected 3D scans, the authors pre-processed them for accurate data processing. Data pre-processing is an important step for obtaining efficient results. Scans collected for the Steel Water tank contains lot of redundant information, which influences the accuracy of geometric assessments. They contain large amount of noises such as reflections, unwanted background, movements of people, or other objects surrounding the test subject etc. The authors filtered the actual data from the noise and then executed the data processing algorithms in order to extract accurate information from the raw data. Most the pre-processing algorithms are available in many of the commercial software. The authors used Faro Scene (FARO Technologies Ltd.) pre-processing algorithm to filter the scans. The authors then performed the registration of all the 3D point cloud data collected at multiple locations together into a global coordinate system from their respective local coordinate axis (Figure 1(b) and Figure 1(c)).

![Figure 1: (a) 0° Azimuth Location. (b) 3D Point Clouds Collected outside the Tank after 3D Registration and Data Cleaning. (c) 3D Point Clouds Collected inside the Tank after 3D Registration and Data Cleaning](image)

4 GEOMETRIC AND DEFORMATION ANALYSIS OF 3D LASER SCAN DATA

The proposed framework involves segmentation of 3D Laser scan data of the steel tank into several individual components. Such components include roof, floor, rafters, and columns of the steel water tank. For analyzing the deformations of the tank, the authors aligned the registered 3D point cloud data against a cylinder with a radius of 70 feet. To compute the deviations of 3D data points, the authors extracted a cylinder from the point clouds. Such fitted model is a perfect cylinder, and deviations from it indicate
possible local deformations of the tank. Figure 2 shows the comparison of the 3D point cloud and the fitted model. This figure visualizes the deviations along the radial direction: red colors show “positive deviations” pointing outward the surface of this cylinder; blue colors show “negative deviations” pointing inwards the surface of this cylinder.

![Figure 2: Comparison between 3D point cloud and fitted model](image)

Table 1 shows the list of all the analyzed components and their respective detected deformations (Figure 3). Major conclusions for the geometric analysis include:

- The tank does not have obvious tilt, but the floor has a slight tilt that makes the West part of the floor lower than the East part. In addition, the central part of the floor observed to have higher elevation than the parts closer to the shell. Hence, these analyses may indicate settlements of the tank.

- The wall of the tank has elevation differences between the east part and the west part, such that the east slope of the roof is only 3.27 degree, smaller than the 4.42 degree slope specified in the as-built drawings.

- Both the conical shapes of the roof and floors have a smaller height than the as-built cones of the roof and the floor. The authors also detect that the central region of the floor is flat and horizontal, most of the slope angles measured on these two conical shapes are smaller than their as-built values, and the settlement of the central column may be the reason for such observations.

- The authors detected a Zigzag pattern on some rafters that are located on East part of the roof. The turning point of that Zigzag is around the connection between the internal rafters and the girders supported by internal columns.

- Curvature analysis of the roof shows that three regions on the roof have relatively larger curvatures possibly caused by deformations of the roof and girder.

![Figure 3: Observed Deformations of the steel water tank](image)
Table 1: 3D data analysis procedure and the observations

<table>
<thead>
<tr>
<th>ANALYSIS PROCEDURES</th>
<th>OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXTERIOR SURFACE ANALYSIS</td>
<td>Deviation of the exterior surface from a cylinder extracted from exterior point cloud</td>
</tr>
<tr>
<td></td>
<td>The maximum outward deviation and inward deviation is 0.248 m (9.76 inches) and -0.227 m (8.937 inches) respectively</td>
</tr>
<tr>
<td></td>
<td>Exterior radius distribution analysis along the height of the tank</td>
</tr>
<tr>
<td></td>
<td>The radius of the tank increases gradually from the bottom to the top except it decreases drastically at the top of the tank.</td>
</tr>
<tr>
<td>INTERIOR SURFACE ANALYSIS</td>
<td>Interior floor flatness analysis</td>
</tr>
<tr>
<td></td>
<td>1. Two small regions at the North and South borders of the floor surface are about 8 cm above the surface of the cone.</td>
</tr>
<tr>
<td></td>
<td>2. The central part of the floor has higher elevations compared with the parts close to the tank shell, the central part of the interior floor surface is flat and horizontal, while the North and South sides have some deformations</td>
</tr>
<tr>
<td></td>
<td>Above two observations seem to be indicators of the settlement of the central column (or the relative faster settlement of the central column compared with the shell of the tank)</td>
</tr>
<tr>
<td></td>
<td>Elevation and slope analysis of the roof</td>
</tr>
<tr>
<td></td>
<td>The as-design slope is 4.42 degree; average slope of the east roof is about 3.96 degree.</td>
</tr>
<tr>
<td></td>
<td>The west side of the roof has a slope of 3.27 degree.</td>
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<tr>
<td></td>
<td>Both sides have slope angles smaller than the as-designed value, while the West side's slope is steeper and closer to the as-designed model</td>
</tr>
<tr>
<td></td>
<td>The east roof and rafters seem to be “Zig-Zag,” and the turning point of this Zig-Zag is around the internal rafters' connection with the “internal circle” of girders connecting interior columns</td>
</tr>
<tr>
<td></td>
<td>Curvature analysis of the roof</td>
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<td>Curvature values of the roof interior surface are larger for three regions:</td>
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<td>External rafters from -90-degree to -45-degree (Southeast, using the 0-degree azimuth coordinate system described before).</td>
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<tr>
<td></td>
<td>Internal rafters from -135 degree to -45-degree (South).</td>
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<tr>
<td></td>
<td>Internal rafters from -30-degree to 45 degree (East).</td>
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<tr>
<td></td>
<td>Two of the 5 warped rafters have highest value of curvatures. (0.0378 and 0.0418)</td>
</tr>
<tr>
<td></td>
<td>Three regions on the roof have relatively larger curvatures possibly caused by deformations of the roof and girder.</td>
</tr>
<tr>
<td>RAFTERS</td>
<td>Curvature of roof girders (5 Rafters that are observed to be warped)</td>
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<tr>
<td></td>
<td>Two of the 5 warped rafters have highest value of curvatures. (0.0378 and 0.0418)</td>
</tr>
<tr>
<td></td>
<td>Three regions on the roof have relatively larger curvatures possibly caused by deformations of the roof and girder.</td>
</tr>
</tbody>
</table>
CORRELATIONS BETWEEN THE OBSERVED DEFORMATIONS OF THE WATER TANK

Correlated deformations between components of a structure occur if those components are connected, are in a similar environmental condition, or have same axis of orientation etc. Connected components move together under load conditions that cause correlated changes in them. For instance, the cylindrical body and the floor of the water tank show similar variations under loading conditions. The observed inward and outward deviations of the cylindrical surface (Figure 3(a)) of the tank correlate with the upward and downward deviations of the floor (Figure 3(b)) of the water tank. Similar environmental conditions can also lead to correlated deformation patterns. For example, common soil settlements have led to correlated tilt in the floor and roof of the water tank. The combined deformations of the roof and girders have caused the floor to undergo relatively large curvature changes at certain points, which have same axis of rotation.

Figure 4 shows the correlated deformation of the central column and the rafters of the tank. The authors observed that the differential settlement of the central column has caused the connected rafters to warp under axial compression. These warping of the rafters correlate with the inward and outward deviations of the cylindrical surface of the tank. In addition to the warped rafters and the surface deviations, the central column settlement correlates with the deviations of the floor of the water tank. The authors have tabulated (Table 2) all the observed correlations between individual segmented components to identify systematic shape change pattern of water tank for geometric diagnosis.

Using such correlated deformation patterns, the authors identify certain traits that can help in reliable geometric diagnosis. For example, thermal variations around the water tank can lead deformations in its exterior cylindrical surface. Since these deformation correlate with those of warping of rafter, such variations in temperature of the tank can further deteriorate the condition of the rafters. Further deviations in the cylindrical surface can predict the future warping of the rafter, which will be inaccessible during the service of the water tank. Similarly, the differential settlement of the exterior surface of the water tank could place the rafters in axial compression causing lateral bowing. Thus, predicting the long-term deformations of the inaccessible components of the water tank using their correlated deformation pattern with other accessible components can help in reliable life-cycle maintenance cost optimization.
### Table 2: Observed Correlations

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CORRELATED COMPONENT</th>
<th>REASON FOR CORRELATION</th>
<th>DEFORMATION CORRELATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cylindrical Surface</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>Connected</td>
<td>The outward and inward deviation of the cylindrical surface correlates with the upward and downward deviation of floor</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>Connected</td>
<td>The deformation on the cylindrical surface closer to the roof correlates with the Zig-Zag pattern and the elevation difference of the roof</td>
<td></td>
</tr>
<tr>
<td>Rafters</td>
<td>Connected</td>
<td>Warping of certain rafters correlate with the deviations of the connected cylindrical surface</td>
<td></td>
</tr>
<tr>
<td>Column</td>
<td>Same Axis</td>
<td>Settlement of the central column will eventually push the cylindrical surface to the outward direction</td>
<td></td>
</tr>
<tr>
<td><strong>Floor</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>Same Axis</td>
<td>Both the floor and roof have slight tilt from its original axis</td>
<td></td>
</tr>
<tr>
<td>Column</td>
<td>Connected</td>
<td>Differential settlement of the column caused upward and outward deviations in the floor</td>
<td></td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rafters</td>
<td>Connected</td>
<td>Zig-Zag patterns on the roof relates with the warping of the rafters</td>
<td></td>
</tr>
<tr>
<td>Column</td>
<td>Connected</td>
<td>Elevation difference (smaller height that as-planned) correlate with settlement of the central column</td>
<td></td>
</tr>
<tr>
<td><strong>Rafters</strong></td>
<td>Column</td>
<td>Central column settlement is likely the cause for warping of the rafters</td>
<td></td>
</tr>
</tbody>
</table>

### 6 CONCLUSION AND FUTURE WORK

This paper explores the technical feasibility of diagnosing a water tank structure based on analyzing correlated visual change patterns of the water tank structure. The studied structure underwent certain deformations during its life cycle. A 3D laser scanner captured detailed as-is condition of the structure to analyze the changes in structures geometry when compared to its as-designed model. The developed approach in this paper shows clear potential of aiding engineers in observing and diagnosing correlated deformation patterns for supporting the maintenance decision making of the structure. Based on these explorations, the authors determined systematic change patterns in the components of a water tank for detecting anomalous spatial changes from the 3D point cloud data for identifying structural risks.

This data-driven study of a water tank indicates that 3D laser scanning technology can help in reliable documentation of accurate as-built conditions of as structure in short time with high level of detail. Using the presented approach, the authors plan to develop automated geometric diagnosis of the structure from the data collected from a 3D laser scanner. This step includes generating algorithms that can automatically detect deviations of a structure, identify correlations between the identified deviations and create deformation histories for risk assessments. Detailed scans before, during and after renovation can provide an approximate disaster pattern of the structure. This study will also help in identifying the root cause of the damage to a structure and in proper resource allocation and rehabilitation planning.
Acknowledgement

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RISK OF WILDFIRES WITH KNOWN IGNITION POINTS: CASE OF RESIDENTIAL BUILDINGS

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Abstract: Wildfire is considered the dominant disaster in many regions of the world including the United States, Australia, Canada and parts of Europe. However, unlike other natural disasters, such as flooding, earthquakes and hurricanes, the risk of wildfire to the built environment is not vigorously studied. Most of the research in the wildfire risk management area is limited to the study and management of wildfire within the wildland. On the other hand, there is an increasing progress of housing projects towards the natural lands. The Wildland Urban Interface (WUI) is where the developed and undeveloped areas meet. Because of high vulnerability of the WUIs to wildfires, there is a need to identify, quantify and manage the expected damage of wildfires to the WUIs. This study calculates the risk of wildfires to residential buildings considering a specific ignition point. The model inputs include the spatial distribution of the buildings, an absolute or proxy value for the damage from wildfire, and atmospheric and landscape attributes needed to simulate the fire propagation on a specific land. The model outputs are the distribution of damage at each time interval from the initial ignition and total risk of a fire with a given ignition point.

1 INTRODUCTION

Wildland-Urban Interface (WUI) is where the undeveloped land intermixes or interfaces with man-developed land (Davis 1990). Also called flame zones, these WUI lands are developed areas vulnerable to wildfires. About 90% of the WUIs in the Western United States are classified as high severity fire regimes (Theobald and Romme 2007). However, this sensitivity has not suppressed the progress of housing development projects towards fire prone forest and park lands. WUIs have grown 52 percent in size during three decades from 1970 and are projected to increase by an additional 10 percent until 2030 adding up to over 510,000 square kilometers (Theobald and Romme 2007).

Chuvieco et al. (2010) defines a framework for fire risk assessment as an important component of risk management. In their model, they address the need of including vulnerability in fire risk assessment. The risk of wildfire is the product of fire danger and probability. The authors address ways to calculate and analyze different parameters of the risk assessment model from probability of ignition to a model of propagation prediction to finding tangible and intangible values at stake.

The probability of fuel-ignition on a specific land has been assessed using econometrics tools and neural networks. These approaches have been used for formulating the ignition as a function of the characteristics of the landscape and infrastructures (Romero-Calcerrada et al. 2007; Vasilakos et al. 2009; Chuvieco et al. 2010). Federal agencies in the United States such as the US Forest Service and its
associated labs have also produced the fire danger maps danger rating classes. These maps give information on the occurrence of fire.

There are different propagation models developed to provide decision support systems for specific forest management subjects. Chuvieco et al. (2010) assigned a propagation potential to each cell, in a coarse cell size, based on fuel type, moisture and wind. USDA's Rocky Mountain Research Lab has developed the Flammap software (Finney 2006). Flammap uses “Minimum Travel Time” to simulate the propagation of wildfire. Given the landscape, fuel, wind and ignition point, Flammap is able to return a set of outcomes including but not limited to the rate of spread, influence grid (number of nodes that succeeded burning from each cell), fire line intensity, and burn probabilities. However, Flammap does not consider probabilistic modeling for producing a probabilistic distribution of the expected fire propagation. Randig is the command line version of Flammap which can be used for random selection of wildfire ignition points and is used for estimating the efficacy of the treatment options in Oregon, USA (Ager, Vaillant, and Finney 2010).

Another approach that has the capability to do probabilistic modeling of wildfire propagation is known as Cellular Automata (CA)-based fire propagation model originally proposed by Clarke, Brass, and Riggan (1994). This model is used to simulate fire propagation and final wildfire perimeter. This model is also a command line program and gives the user flexibility in terms of choosing between using crisp or random variables. To model the behavior of wildfire, core concepts of fire propagation are adopted from Rothermel (1972) and the model is verified by simulating the Lodi Canyon fire of 1986, in California, USA. Due to its flexibility, simplicity and availability, this model is used in this study to assess the spatial and temporal distribution of buildings exposure to wildfires.

The probability that the fire can ignite a structure has received little attention in the literature. The fire attributes and the building materials and configuration can have an affect on this probability. Cohen (1995) proposed the Structural Ignition Assessment Model (SIAM) which links the flames and heat from wildfires and external material used in buildings to assess if a building will be ignited by specific heat from a fire or not. In his research, the author performed laboratory tests to define the ignitability of each component of the house.

Associated with wildfire, there are a variety of vulnerabilities in the WUIs from social to environmental, to economical, to the built environment. According to Cutter et al. (2008), along with the immediate and factual damage caused by the event, the vulnerability of the subject or the system should be accounted for in the calculation of the impact of the disaster. Vulnerability is a complex context (Cutter et al. 2008), however, exposure is a definitive element of the vulnerability (Hufschmidt 2011). Hollenstein (2005) defines exposure as an index of the spatio-temporal distribution of the elements at risk.

The elements at risk in this study are residential houses. In order to show the distribution of exposure to danger, an exact or proxy indicator should be adopted. Using historical records, Cohen (1990) assumes that once ignited, structures will be completely destroyed. One can justify this assumption since during a fire, suppression activities will be more likely diverted towards protecting un-burnt houses or assets; while for burning houses, the efforts will be spent on saving lives. However, in order for fire to ignite a building, the characteristics of the exposed materials play an important role in the probability of ignition of the house (Cohen and Saveland 1997).

In this study, structures ignition is formulated as a binary variable assuming that if a building falls inside the spatial burning cells of the fire, it will be ignited and totally destructed, and therefore, the expected damage of the house is its total estimated value. An ongoing study by the authors is the use of econometrics in order to formulate ignition probability as a function of the structural and neighborhood characteristics, which will help future research to represent ignitability of structures in probabilistic form. Since the analysis is in the form of raster data (some converted to matrices), a point is a virtual representation of a cell on the ground with an arbitrary resolution.
2 RISK AND VULNERABILITY ASSESSMENT MODEL

Wildfire is a complex phenomenon that is dependent on a variety of factors. The location of the ignition cell, the topography of the landscape, the fuel availability, the fuel moisture and the wind and atmospheric conditions, among others, affect the propagation scheme of a wildfire. In ecological assessments, the magnitude of wildfires is measured in terms of the amount of energy (in Kilowatts) released during different phases of the propagation of the fire; and sometimes the flame length is used as a proxy measure for this energy release (Keeley 2009).

As a danger, wildfire has a compound probability of occurrence. This probability is, at the coarse level, composed of the probability of ignition of a specific cell and the probability that the fire will propagate from that given cell and reach to the location of interest. Last, but not least, is the probability that the fire can damage an asset. Following Chuvieco et al. (2010), the risk of wildfire that has started on a given cell on the landscape \((x, y)\) to the location of a vulnerable asset of interest in the study area (denoted by \((i, j)\)) is shown in equation [1]:

\[
\text{Risk}(i, j, t)_{xy} = P_{\text{propagation}}^{ij|y;x,t} \times P_{\text{burn}}^{ij} \times V_{ij}
\]

Where, \(\text{Risk}(i, j, t)_{xy}\) is the risk of damage to an asset located on cell \((i, j)\) from a fire initiated on the cell \((x, y)\) of the study area, after \(t\) time. \(P_{\text{propagation}}^{ij|y;x,t}\) is the probability that the fire ignited on point \((x, y)\) will reach to point \((i, j)\) after \(t\) time periods and \(P_{\text{burn}}^{ij}\) is the probability that point or asset located at \((i, j)\) will start burning if the fire reaches to that point. \(V_{ij}\) is the value of the asset in danger located on point \((i, j)\).

As previously mentioned, an assumption made in this study is that the building that has been reached by a fire has been completely harmed. This assumption eliminates the need for detailed damage assessment while providing an upper bound for the calculation of damage.

Equation [1] represents the spatiotemporal distribution of risk of a wildfire initiated at cell \((x, y)\). The cumulative risk from the fire can be calculated as shown in equation [2].

\[
\text{RISK}(r)_{xy} = \sum_{i} \sum_{j} P_{\text{propagation}}^{ij|y;x,t} \times P_{\text{burn}}^{ij} \times V_{ij}
\]

\(P_{\text{propagation}}^{ij|y;x,t}\) is calculable through fire simulation. As previously mentioned, the propagation simulator used in this study is the CA based model proposed by Clarke, Brass, and Riggan (1994). At each time interval, the fire front will grow on the structure of the existing fire status resulting in a process oriented model. The growth of fire is defined as the movement of firelets\(^1\) from a burning point to a virgin (un-burnt) point. When modeling fire propagation, firelets are sent out of the existing burning cells (cells). The generation and direction of firelets is a function of the wind magnitude and direction, topography attributes (slope and aspect), availability of fuel on the destination cell, temperature and moisture. Except for slope and aspect, other attributes are of stochastic nature. As a result, the decision of fire front moving from each cell is modeled as a random process through a Monte Carlo simulation.

At the beginning of each simulation, the slope, aspect, and fuel layers (with unique cell size and projections) are input to the model along with a wind array representing climate of the study area. Wind array specifies the range of possible winds direction and magnitudes. A cell is selected as the place where the hypothetical fire will start. Eight immediate surrounding cells are weighted based on their slope and the direction of wind. These weights are associated with the probability that the firelets from the ignition cell will choose the cell as the destination. Using a roulette wheel-like selection procedure, firelets destination(s) will be selected. Once a new cell is selected as the destination of a firelet, it is treated as the original ignition cell. Random controllers restrict the number of propagations within each time interval.

\(^1\) Firelet is the term used by Clarke et al. (1994) to show the mobile elements of fire.
Next interval starts with current burning cells as the ignition points. The fuel load of burning cells is decreased by 1 at the end of each time interval. The termination criterion is reaching the time limit.

For a specific ignition point, the simulation will be run for a number of iterations to incorporate the randomness of the atmospheric conditions. During each simulation, a binary value \( j_{(i,j)}^{\text{iteration},t} \) is calculated for each cell to identify if the fire has propagated to that cell up to a specific time interval \( t \):

\[
[j_{(i,j)}^{\text{iteration},t}] = \begin{cases} 
1 & \text{if the simulated fire reaches point } (i,j) \\
0 & \text{otherwise}
\end{cases}
\]

The probability of propagation \( P_{ij}^{\text{propagation},(xy,\text{time}=t)} \) is then calculated as given in equation [4].

\[
P_{ij}^{\text{propagation},(xy,\text{time}=t)} = \frac{\sum_{\text{iteration}=1}^{n} j_{(i,j)}^{\text{iteration},t}}{n}, \text{ where } n \text{ is the total number of iterations (simulations).}
\]

As previously mentioned, another assumption made in this study is that if the fire can find a way to ignite the cell on which the building is located, then the building will get ignited. The probability of structural ignition is therefore calculated using equation [5]:

\[
P_{ij}^{\text{burn}} = \begin{cases} 
1 & \text{if } P_{ij}^{\text{propagation},(xy,\text{time}=t)} > 0 \\
0 & \text{otherwise}
\end{cases}
\]

The value of the expected damage is the total price of the building. The structures layer is overlaid on the time-dependent fire status layer in order to find the structures that are burnt according to simulation results (Figure 1).

![Figure 1: Overlaying structures layer and the fire status layer for calculating the value of the exposed asset](image)

The total risk from a fire ignited on point \( i \) is calculated using equation [2].
3 STUDY AREA AND DATA COLLECTION

The focus of this study is Los Alamos Census Designated Place (CDP) which is a town in Los Alamos County in the Northern New Mexico. The total population of the city in 2010 was 12,019 with median age of 43.5. There are 5,289 households residing in the city and 5863 houses. Among the unoccupied houses (i.e. 574 units), 221 are seasonal and recreational houses. According to US Census data, 3662 houses are owner-occupied and most of the remainder are rented. Median and mean income of the population are $106,016 and $116,563 respectively. Los Alamos is located within parts of Santa Fe National Forest, and it is also close to Bandelier National Monument.

In 2000, Los Alamos witnessed one of the greatest fires in the history of the United States. The Cerro Grande fire was initiated as a prescribed burn in the Bandelier National Monument when, due to adverse atmospheric conditions, the fire went out of control (Figure 2). The town was evacuated for a week and about 300 houses were burnt in the aftermath of this fire. The damage to the entire county was estimated to be about $1 million (PW Coopers 2001), almost all in the Northern part of the city (Los Alamos CDP).

A real estate investigation on physical and non-physical damage was done by Price Waterhouse Coopers consultants (2001). Aside from houses that were burnt during wildfires, 3 - 11 % value diminution was observed in un-damaged houses due to wildfire. A survey analysis contracted to a third party by Los Alamos county showed that 54% of owners of the damaged buildings decided to re-built their buildings in the same place, confirming the results by McGee, Mc Farlane, and Varghese (2009) that the experience of wildfire does not change the risk perception of the community. Interestingly enough, 35% of those who were re-building their homes on the same location said that they planned to build a similar structure (Price Waterhouse Coopers (2001)).

Case study data used for this study include topography data, fuel data, structures layer and value of the assets. Topography data (elevation, slope and aspect) are collected from the online database of the United States Geological Survey (USGS). Fuel data incorporated into fire propagation model is the Canopy Bulk Density (CBD) that is available through LandFire Project’s data set (Rollins and Frame 2006). Canopy bulk density is mass per volume (kg/m^3) of canopy fuel and is the property of a stand of trees rather than a single tree (in which case, it will be referred to as crown fuel)(Scott and Reinhardt 2001).

Amongst other types of fuel, buildings are highly exposed to fire in dense canopy and shrub fire (Menakis, Cohen, and Bradshaw 2000). On the other hand, when the wind magnitude and direction are in support, the embers from canopy fires can find their way to the roof system where they can ignite the structures.
Sometimes, through the ladder fuels\(^2\) surface fire can get elevated to the canopy fire (Scott and Reinhardt 2001). However, modeling the transition of surface fire to crown fire has a lot of complexities and reduces the efficiency of the analysis in the context of damage to the built environment.

The structures layer used for this study is limited to the single family housing in Los Alamos. The value for each house is the assessed value of the year 2013 provided by the Los Alamos County assessor’s office. The diminution of un-burnt house values after a fire is not seen in the damage assessments and only physical exposure to fire is accounted for.

4 SIMULATION RESULTS

The fuel and structures distribution is shown in Figure 3. The selected ignition point is close to the houses that were previously burnt due to the Cerro Grande fire; however, the fuel data are from year 2012. The study area is simulated in 505 rows by 272 columns. Each cell is 17m by 17 m in size (56 ft by 56 ft). The selection of the cells size is based on the finest resolution among the input raster files. Although it was possible to change the resolution in order to increase the accuracy of the model, longer run-times discourage pursuing higher accuracies. The result of the propagation model for a single iteration of the simulation is shown in Figure 4.

---

2 Ladder fuel is the fuels that will form the channel through which fire escalates from surface to crown or canopy of trees. (Menning and Stephens 2007)
The results of the model for a specific ignition point are shown in Table 1. The outcomes are narrowed down to represent cells that have been affected during simulations and received a value greater than zero.

Table 1: Assessed risks (time units are 10 minutes)

<table>
<thead>
<tr>
<th>Source ((x,y))</th>
<th>Burnt cell ((t,j))</th>
<th>(V_{ij}) (USD)</th>
<th>(P_{\text{propagation}})</th>
<th>(\text{Risk}(t,j)) (_{xy}) (USD)</th>
<th>(\text{RISK}(t)) (_{xy}) (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(125,3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(116,3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(113,3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(117,3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(120,29)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(120,25)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The average value of a single family housing in the study area is 190,004 USD. With the purpose of demonstrating the proposed methodology, two separate points, which were 68 meters apart, were selected as ignition points. One source \((129,29)\) is very close to the structures and unsurprisingly represents higher risk to the built environment under consideration: residential buildings. It is noteworthy that during all of the simulation runs, the fire initiated from the source \((120,25)\) reached the cell \((120,129)\) and ignited that cell. In other words, the vulnerability values to sources of fire on the wildland are not independent from one another. The relationship between the risk resulted from different sources is proposed in equation [6].

\[
\text{RISK}(t)_{xy} \leftarrow \text{RISK}(t)_{xy} + \text{RISK}(t-t')_{xyy}.
\]
where \( t \) is the time when source \((x',y')\) is ignited during propagation of fire from source \((x,y)\).

The results from Table 1 can be used to assess the time value of suppression activities in order to provide cost-benefit analysis of suppression cost and time. For example, in the case of the fire source \((120,29)\), there is \(685,940\) USD difference in the risk value between \(t = 10\) and \(t = 20\), which justifies any suppression activities costing less than this amount. However, the vulnerability value will be less than \(100,000\) USD after \(t = 20\) favoring the less cost suppression effort. Another notion is the difference between the total risk values for the sources. The total risk from source \((120,29)\) at each time interval is at least twice the risk from source \((120,25)\) and suppressing fire from reaching point \((120,29)\) is worth at least \(366,728\) USD. However, it is important to note that the value of the vulnerability in this study only reflects the residential houses as the value-in-danger and the results of risk assessment for different types of assets may not confirm the suppression cost trade-off described.

5 CONCLUSION AND FUTURE WORK

In this study, a risk model is proposed. A wildfire event is identified by the ignition point. The probability component of risk is composed of the probability of the propagation of fire from the specified ignition point to the location of the asset of interest multiplied by the probability of ignition of the asset when exposed to fire. Using a fire propagation simulator and landscape input including fire fuel and structures setting, the assessment of spatio-temporal distribution of the vulnerability was made possible. Results from this research can be used for assessment of treatment efforts and the evaluation of trade-offs between treatment and suppression costs, for raising social awareness about the effects of the risk mitigation activities and for studying policy and management implications in WUIs.

This study can support decision-making process for various managers. Identifying high risk ignition points on the forested lands helps the public land managers to prioritize their treatment effort accordingly, reduce the risk of wildfire and better protect assets. Furthermore, in case of a fire, firefighting efforts can be better invested on areas with higher risk. Last, but not least, zoning and housing departments can limit the progression of the built environment in order to cooperate with public land managers and to secure more assets or to increase the flexibility and efficiency of firefighting activities in the case of occurrence of a wildfire.

Potential future additions to the model will be the calculation of the probability of ignition on the wildland using regression analysis along with the calculation of the probability of ignition of the asset of interest using an expert-system. These additions enable the researchers to calculate the risk of wildfire initiated on any point on the wild landscape. The vulnerability that is accounted for is only the physical damage from wildfire. However, in the aftermath of most of the fires, un-burnt houses also undergo a value diminution which can be added to the total vulnerability. Ongoing research from the authors is addressing this issue.

One remaining noticeable remark is that although the social perception is that the occurrence of fire will reduce the risk, the simulation results showed that there are still vulnerabilities in the burn scar of Cerro Grande fire. Forested lands will restore the previous fuel stock and the fuel build-up coupled with the harmful atmospheric conditions exacerbated by climate change will reintroduce the risk.

Acknowledgment

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PERFORMANCE INDICATORS FOR SUSTAINABILITY ASSESSMENT OF BUILDINGS

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Abstract: During the past few decades, the construction industry has been exposed to “sustainable construction” processes, which address the triple bottom line (TBL) that is the environmental, economic, and social dimensions of sustainability, during the entire life cycle of a building. Due to the importance of sustainable construction, it is imperative to comprehensively assess the sustainability of the built environment, such as buildings. A significant step to evaluate the sustainability of buildings is investigating the existing building sustainability performance indicators (SPIs). In this paper, a list of building SPIs, including environmental, economic, and social, has been developed through conducting a content-analysis based literature review. The literature includes sustainable building rating systems such as Leadership in Energy and Environmental Design (LEED), Green Globes, Living Building Challenge (LBC), among others. In addition, other published literature related to sustainable construction is reviewed. Similar SPIs or those which have some overlaps are combined or modified. Finally, refined TBL SPI sets are created, which can be used for sustainability assessment of buildings. The results of this study indicate that among various environmental performance criteria used in different publications, 16 SPIs are the most significant ones. In addition, a total number of 9 SPIs and 12 SPIs are identified as the most commonly used criteria related to the life cycle economic and social performance of buildings, respectively.

1 INTRODUCTION

Since around 30 years ago, the “sustainability” concept has been widespread and various definitions have been provided (Forsberg and von Malmberg 2004). Nowadays, the percentage of the world’s population who live in urban areas is over 50% (UN 2010) and they spend 80% - 90% of their time inside buildings. This shows the importance of the built environment, e.g., buildings, in sustainable development (Andrade and Braganca 2011). Thus, sustainability performance assessments of the existing and new buildings can play a significant role in increasing sustainability (Ding 2008, Burgan and Sansom 2006).

It is widely accepted that sustainability has three main dimensions: environmental, economic and social, termed as triple bottom line (TBL). Therefore, to make a sustainable product, all these dimensions should be considered and addressed sufficiently. To evaluate the sustainability performance of a product, Kloepffer (2008) has proposed the life cycle sustainability assessment (LCSA) framework. By using the LCSA framework, product performance can be measured with regard to TBL. The LCSA framework can be applied by the following model (Kloepffer 2008, Finkbeiner et al. 2010):

[1] LCSA = LCA + LCC + SLCA
Where LCA is the environmental life cycle assessment, LCC stands for life cycle costing and SLCA is social life cycle assessment.

According to Traverso et al. (2012), the primary purpose of the LCSA framework, similar to LCA, is not to decide if a product should be produced, but to assist stakeholders and decision makers in making a more sustainable decision, thus producing a more sustainable product. In addition, one of the challenges faced by decision makers is to explore how separate environmental, economic, and social assessments can be used in practical situations to make trade-offs explicit (Swarr et al. 2011).

In order to enhance the likelihood of sustainable construction, the first step is to identify significant indicators of all the sustainability dimensions that can be used for assessing the sustainability performance of new and existing buildings over their life cycle. A sustainability indicator provides qualitative or quantitative information about the influence and impacts of a building project on the environment and society.

Currently, over 70 evaluation and classification tools (systems), based on sustainability indicators, have been developed. A building is regarded as a sustainable product only when all the sustainability dimensions, i.e., environmental, economic and social, are addressed and dealt with over its life cycle; however, the primary focus of most of the existing sustainability evaluation tools is on environmental characteristics (Braganca et al. 2010). In other words, they deal primarily with the environmental dimension of sustainability, and thus, they do not explicitly considering socio-cultural and economic dimensions which is a limitation. Furthermore, each sustainability evaluation tool has its own approach and accordingly provides different performance criteria and sub-criteria, which can be different from what other tools provide. Therefore, there are numerous indicators available, which can be confusing for the construction practitioners.

To address the limitations discussed above, the main objective of this paper is to develop generic and holistic building sustainability performance indicator (SPI) sets (i.e., environmental SPIs, economic SPIs, and social SPIs) that can provide a deeper insight into the most significant sustainability criteria currently used. The proposed TBL SPI sets are a key criteria list, which can be addressed in the design and construction of buildings. The results of this paper can assist different construction stakeholders in the development of sustainable construction.

2 METHODOLOGY

The research method in this paper is content analysis, which is a qualitative type of document analysis. Content analysis is a qualitative and systematic method to review and evaluate different documents. In other words, content analysis is the process of collecting and organizing information related to the primary research questions (Bowen 2009). Holsti (1969) gives a broad definition of content analysis as, "any technique for making inferences by objectively and systematically identifying specified characteristics of messages". All forms of documents, including electronic and printed, such as letters, books, survey reports, organizational papers, advertisements, etc., can be used as references.

First, a preliminary list of building SPIs was developed based on the review of two reference categories:

1- Sustainable building rating systems, such as Leadership in Energy & Environmental Design (LEED), Green Globes, Living Building Challenge (LBC), among others.

2- Journal and conference articles. The University of British Columbia (UBC) library databases, “Compendex Engineering Village” and American Society of Civil Engineers (ASCE), were used to retrieve the appropriate journal and conference articles. Key words used were combinations of: “building”, “sustainability”, “performance”, “life cycle”, “indicator”, “criteria”, “evaluation”, and “assessment”. These articles were further refined by reviewing abstracts and conclusions.

Then, using the content analysis method, the common SPIs were prepared, modified, and combined to form the refined SPI set for each of the sustainability dimensions.
3 SUSTAINABLE BUILDING RATING SYSTEMS

Sustainable building rating systems (also called green building rating systems or sustainability rating systems) that were developed to assist in the management of "green" building projects have a vital role in informing on progress in sustainability practices (Siew et al. 2013). Rating systems are qualitative tools that deal with sustainability performance of buildings by providing a set of performance criteria and scoring each building project based on those criteria. Rating systems examine the performance level or expected performance of a "whole building" and allow comparison of different buildings (Fowler and Rauch 2006).

Applications of rating systems are increasing worldwide and many tools have been developed for the environmental evaluation of the built environment, e.g. over 60 in the US (Economist 2007). The tools are not usually mandatory even though some jurisdictions have made them so (CEC 2014). The main focus of sustainability rating systems is on the environmental dimension of sustainability. Table 1 lists the well-known sustainable building rating systems around the world. In this paper, only the rating systems that are intended to be used internationally (LEED, LBC, BREEAM and SBTool) or in North America (Green Globes) have been selected for review.

<table>
<thead>
<tr>
<th>Rating System</th>
<th>Countries</th>
<th>Year of Launch</th>
<th>Organization(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEED</td>
<td>International</td>
<td>1998</td>
<td>US Green Building Council (USGBC), Canada Green Building Council (CGBC)</td>
</tr>
<tr>
<td>Green Globes</td>
<td>US and Canada</td>
<td>2002</td>
<td>Green Building Initiative (GBI), BOMA Canada, ECD Energy and Environment Canada</td>
</tr>
<tr>
<td>LBC</td>
<td>International</td>
<td>2006</td>
<td>International Living Future Institute</td>
</tr>
<tr>
<td>BREEAM</td>
<td>International</td>
<td>1990</td>
<td>Building Research Establishment (BRE)</td>
</tr>
<tr>
<td>SBTool</td>
<td>International</td>
<td>1996</td>
<td>International Initiative for a Sustainable Built Environment (iiSBE)</td>
</tr>
<tr>
<td>CASBEE</td>
<td>Japan</td>
<td>2001</td>
<td>Japan Green Build Council (JaGBC)</td>
</tr>
<tr>
<td>Green Star</td>
<td>Australia</td>
<td>2003</td>
<td>Green Building Council Australia (GBCA)</td>
</tr>
<tr>
<td>ESGB</td>
<td>China</td>
<td>2006</td>
<td>Ministry of Housing and Urban Rural Development of China (MOHURD)</td>
</tr>
<tr>
<td>BCA-GM</td>
<td>Singapore</td>
<td>2005</td>
<td>National Environment Agency</td>
</tr>
<tr>
<td>HK BEAM</td>
<td>Hong Kong</td>
<td>1996</td>
<td>BEAM Society</td>
</tr>
</tbody>
</table>

3.1 Leadership in Energy and Environmental Design (LEED)

USGBC developed the Leadership in Energy and Environmental Design (LEED) rating system by using a coalition of construction industry practitioners, decision makers, contractors, owners and manufactures. LEED is one of the widely adopted rating systems worldwide. Over 148000 square meters of building space are daily certified by LEED in 147 countries. As of January 2015, nearly 50000 construction projects have registered and are participating in LEED (equal to over 800 million square meters of building space). This system is a voluntary, market-driven and consensus-based system that verifies green buildings. LEED was intended to be used for different building types, by which solutions to the green design, construction, use and maintenance of buildings can be identified and implemented. The latest LEED version (v.4) provides the following rating systems that address various project types (USGBC 2015):

- Building Design and Construction (LEED BD+C). Applies to new construction and major renovation projects;
- Interior Design and Construction (LEED ID+C). Applies to projects that are a complete interior fit-out;
Building Operations and Maintenance (LEED O+M). Applies to existing buildings that are undergoing improvement work or little to no construction;

Neighborhood Development (LEED ND). Applies to new land development projects or redevelopment projects; and

Homes (LEED-H). Applies to single family homes, low-rise multi-family (one to three stories), or mid-rise multi-family (four to six stories).

The performance of a building is assessed through a set of performance credits (points) (Castro-Lacouture et al. 2009). In fact, LEED assigns weighted credits to a building project based on a number of performance categories. For example, LEED for New Construction and Major Renovations addresses seven performance categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation in Design, and finally, Regional Priority (USGBC 2009). The total score is obtained by summing up the credits achieved in each performance category. For example, the total score can add up to a maximum of 110 points and 136 points for commercial projects and homes, respectively. Depending on the project type and earned score, each project is rated and awarded one of the four levels of certifications below (USGBC 2015, Kubba 2010):

- **Platinum**: 80 points and above
- **Gold**: 60–79 points
- **Silver**: 50–59 points
- **Certified**: 40–49 points.

Since the year LEED was launched, despite the reported benefits, several researchers and construction experts have argued its limitations. Some literature investigated the aspects of green versus sustainable building in LEED and concluded that the LEED rating system does not explicitly consider the socio-cultural and economic issues of buildings and mostly addresses the short term aspects rather than global and long term goals of sustainable building (Coleman 2004). According to Newsham et al. (2009), even though LEED certified buildings used 18-39% less energy per floor area, 28-35% of them used more energy compared with their conventional counterparts. In addition, they argued that there is little correlation between the real energy performance and certification level of LEED buildings. In another publication, it was shown that, on average, greenhouse gas emissions are not reduced in the use phase of LEED buildings due to no energy reductions in their operations (Scofield 2009). Ahn (2007) stated that, in addition to the many advantages of LEED buildings; however, the construction cost of green buildings is significantly higher than traditional buildings. Furthermore, it was shown that more capital is required depending on the level of LEED certification, from certified to platinum (Kats 2003).

### 3.2 Green Globes

The Green Globes system was intended mainly to assist construction practitioners and owners to self-assess their building performance (Kubba 2010). Green Globes is well recognized in North America and is endorsed by many states and provinces. For example, it has been used by the federal government of Canada in recent years. In addition, Green Globes and LEED were recommended by the US General Services Administration (GSA) for the construction projects of the US federal government (ECD 2015).

Green Globes is an interactive and affordable tool that enables building environmental design, operation, and management. The system provides a web-based self-assessment Yes/No/NA-type questionnaire-based package that comprises a protocol, rating system, and easy-to-use interactive guidance to assist the integrated design process implementation (i.e., goal and scope definition to construction documents) (Green Globes 2015, Smith et al. 2006). In addition, it provides market recognition of the environmental attributes of buildings by using third-party verification. Green Globes is available to be used in the following construction areas (ECD 2015):

- Existing Buildings;
- New Construction/Significant Renovations; and
- Commercial Interiors (i.e., office fit-ups).
Green Globes for existing buildings was developed based on six environmental performance categories: Project Management, Water, Energy, Resources, Emissions and Indoor Environment. For new buildings, the tool uses the same performance categories adding the seventh one: Site Impact. The total number of points listed in the seven categories is 1000.

It was discussed that although Green Globes is similar to LEED in terms of structure, Green Globes is more comprehensive and includes additional aspects, such as adaptability and durability. However, Green Globes does not address some aspects that are included in some other sustainability rating systems, such as project performance strategies and innovations (Kubba 2010).

3.3 Living Building Challenge (LBC)

According to ILFI (2015), the Living Building Challenge (LBC) is a building rating system that provides the most advanced sustainability criteria that can be used to measure the sustainability of buildings. LBC requires the highest and stricter standards in sustainable design and performance of buildings, and can apply to any type of building and any shape, size, and location including new, existing, single/multi-family residential, governmental, educational, and medical buildings, among others. LBC uses seven performance categories (Petals): Place, Water, Energy, Health and Happiness, Equity, Beauty, and Materials. Petals comprise of twenty mandatory Imperatives.

LBC certification is awarded based on the actual performance of projects (rather than the modeled or anticipated performance). Thus, projects are evaluated at least twelve months after the operational phase starts. However, through a preliminary audit, a number of Imperatives can be examined after construction. The latest version of LBC (v.3.0) was launched in 2014 (ILFI 2014).

LBC is significantly different from the other rating systems. Wang et al. (2012) pointed out that buildings need to meet all of the design and operations strategies of LBC to be certified, which may result in user dissatisfaction. In fact, LBC is a “all-or-nothing” not a point-base system. Nevertheless, other rating systems such as LEED and Green Globes need a minimum number of points (credits) in order to award a base level of certification, i.e., the more points achieved leads to higher levels of certifications.

3.4 Building Research Establishment’s Environmental Assessment Method (BREEAM)

The Building Research Establishment’s Environmental Assessment Method (BREEAM) was developed in 1990 for environmental evaluation of any type of new and existing buildings. BREEAM rating system is widely used in the world. According to BRE (2015), since it was first launched, two million projects have registered for performance evaluation and currently 425,000 buildings have been awarded BREEAM certificates. Construction practitioners (e.g., engineers, developers, managers) demonstrate the level of environmental performance of their building projects by applying this flexible, clear, and easy to use scoring system. BREEAM rates various types of building project including (BRE 2011):

- Commercial Buildings (offices, shopping centers, restaurants);
- Public Buildings (schools, universities, hospitals, museums, libraries, law courts); and
- Multi-residential Buildings (residential care homes, residential college/school, military barrack).

Ten environmental categories such as water consumption, energy consumption, materials, health, transport, waste, etc. and forty nine sub-categories are dealt with by BREEAM to promote life cycle sustainable buildings. Depending on the earned score, each building project is awarded one of the six levels of assessment (score percentage) as listed below (BRE 2011):

- Outstanding: 85%
- Excellent: 70%
- Very good: 55%
- Good: 45%
- Pass: 30%
- Unclassified: <30%
Compared to the straightforward approaches used in other rating systems (e.g., LEED), a complex algorithm is applied by BREEAM in order to evaluate the environmental performance of a building (Gu et al. 2006). The literature argued that one of the main differences between BREEAM and other sustainability rating tools is that the evaluation in BREEAM is based on absolute values while in others, such as LEED, scores are achieved based on improvements in design (Lee and Burnett 2008).

### 3.5 Sustainable Building Tool (SBTool)

The Sustainable Building Tool (SBTool), formerly known as Green Building Tool (GBTool), is an international rating system for evaluating not only green building issues, but also the sustainability performance of building projects. SBTool was developed based on various construction experts’ viewpoints and can be adopted in different regions with different building types (residential and commercial), environmental condition, economy, and cultural values. Accordingly, the scope and criteria can be modified (iiSBE 2015, Ruiz and Fernández 2009, Cole and Larsson 2002). According to Lee and Burnett (2005), SBTool is “the most comprehensive environmental assessment framework for building that explicitly includes the core elements of sustainable development”.

SBTool covers different life cycle phases of new and existing building projects. This system offers two distinct evaluation modules, one is used in the pre-design phase of site assessment, and the other is used in the design, construction and occupancy phases of buildings. The two modules are then combined to assess and rank building projects (Larsson 2012).

Due to its complex framework, SBTool may be difficult to use. According to Fowler and Rauch (2006), because of the flexibility inherent (in the application of SBTool), using SBTool needs more technical knowledge than other rating tools.

### 4 JOURNAL AND CONFERENCE ARTICLES

As mentioned earlier, the second source category was journal and conference papers. Several articles were found during the search period which can be grouped into two source sub-categories. The first sub-category encompassed those papers that a limited number of SPIs have been used to perform life cycle analyses such as LCA. In this type of papers, there were no SPI lists provided or discussed. The second sub-category included those papers that were mainly about SPIs and they provided appropriate sets of SPIs for one or more sustainability dimensions.


### 5 RESULTS AND ANALYSIS

In this section, the results of the content analysis are presented. First, the selected sustainable building rating systems and journal/conference articles were reviewed to develop a preliminary list of sustainability criteria related to each sustainability dimension (TBL). Regardless of different criteria naming styles used by different sources and also the frequency of each criterion, in this step, all of the criteria were included in the list. Second, the main ideas (concepts) that each of the above SPIs addressed were investigated and the similar SPIs that had different names but the same meaning were merged. A total number of 43 SPIs were found related to the environmental dimension. In the cases of the economic and social dimensions, 22 SPIs and 19 SPIs were identified, respectively.

The next step was to further modify the SPI list. As this study aimed to develop the main sustainability performance criteria, some of the SPIs were integrated and combined together to make the preliminary
list shorter. For example, “public transportation access”, “bicycle storage and changing room”, and “adequate parking capacity” were considered as sub-criteria, thus integrated into a new main criterion named “alternative transportation”. As another example, “reused content in building”, “recycled content in building”, and “waste collection and recycling” were combined to form a new main SPI named “construction waste management”.

The final step was to narrow the list down by identifying the frequency of each SPI in the reviewed literature. Since the sustainable building rating systems were developed based on many academic and industry experts’ opinions, more attention was paid to the rating systems than journal/conference articles. To refine the SPI list, in this paper, the instructions below were applied to select the most important SPIs:

- **Environmental Dimension**: If a SPI is used in more than 50% of the rating systems (i.e., 3 out of 5 and more), the SPI is selected regardless of its frequency in the second source category (i.e., journal/conference articles). If not, the frequency count in all references, including the rating systems and articles, should be more than 50% (i.e., 10 out of 20) in order for a SPI to be selected.

- **Economic and Social dimensions**: Since rating systems were mainly developed to address the environmental performance, if the frequency count of a SPI in all references, including the rating systems and articles, is more than 20% (i.e., 4 out of 20 and more), the given SPI is selected.

Table 2 summarizes the refined sets of SPIs for all TBL as well as frequency counts of each SPI. Using the method explained above, 16 SPIs were eventually selected as the most significant SPIs related to the environmental dimension of sustainability. A total number of 9 SPIs and 12 SPIs were identified as the most commonly used criteria for buildings life cycle economic and social performance assessment, respectively.

6 DISCUSSION

Sustainability rating tools are mainly based on qualitative assessment of buildings. Therefore, criteria used in these tools can be vulnerable to wide interpretation by users (assessors). In addition, there are different performance categories and criteria used in sustainable building rating systems. For example, LEED was developed based on Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation in Design, and finally, Regional Priority; however, Green Globe’s performance categories are Project Management, Water, Energy, Resources, Emissions and Indoor Environment, and Site Impact. Accordingly, the criteria under each category were different. Furthermore, each sustainability rating tool has its own scoring criteria (weighting scheme) that can generate different performance scores for a given building. Even though there are many similarities between the various sustainability rating systems, there is a lack of full consistency due to the above mentioned reasons.

There are many published standards, reports and articles that address the environmental performance of buildings. For example, most of the current sustainable building rating systems were mainly intended to be used for buildings’ environmental performance evaluation. Therefore, numerous environmental performance criteria were developed and provided in the literature. The criteria in Table 2 show the environmental SPIs have the higher counts. Almost all of the reviewed rating systems in this study have emphasized the environmental SPIs proposed in Table 2. The next highly mentioned criteria are the economic SPIs that were mostly found in the second reference category, i.e., journal and conference articles. However, Table 2 shows lower counts of social performance criteria in both reference categories.

It should be mentioned that some references, such as LEED, provide some criteria that are mainly environmental indicators but they are indirectly related to the economic and social dimensions of sustainability. For example, “indoor air quality” is an environmental SPI that can lead to “health, comfort and well-being of occupants”, thus it has social impacts as well. As another example, using “regional (local) materials”, “renewable materials”, and “renewable energy” can save a considerable amount of money during the life cycle of buildings. However, fewer direct economic and social criteria were found in the reviewed rating systems.
Table 2: Proposed SPI sets for buildings

<table>
<thead>
<tr>
<th>Environmental SPI</th>
<th>Count: rating systems</th>
<th>Count: articles</th>
<th>Total count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site selection</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Alternative transportation</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Site disruption and appropriate strategies</td>
<td>5</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Renewable energy use</td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Energy performance and efficiency strategies</td>
<td>3</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Embodied energy</td>
<td>5</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Water and wastewater efficiency strategies</td>
<td>4</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Regional (local) materials</td>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Renewable materials</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Construction waste management</td>
<td>4</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Low impact/unhealthy/forbidden materials</td>
<td>4</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Greenhouse gas emissions</td>
<td>5</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Indoor air quality</td>
<td>5</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Daylighting and viewing comfort</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Thermal comfort</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Acoustic (noise) comfort</td>
<td>3</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Economic SPI</th>
<th>Count: rating systems</th>
<th>Count: articles</th>
<th>Total count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and construction time</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Design and construction costs</td>
<td>2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Operational costs</td>
<td>2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>2</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>End of life costs</td>
<td>2</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Durability of the building</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Return on investment (ROI) and related risks</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Flexibility</td>
<td>1</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Integration of supply chains</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Social SPI</th>
<th>Count: rating systems</th>
<th>Count: articles</th>
<th>Total count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health, comfort and well-being of occupants</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Influence on the local economy</td>
<td>-</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Functionality and physical space usability</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Aesthetic options and beauty of the building</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Construction workforce health and safety</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Community disturbance</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Influence on local social development</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Cultural and heritage conservation</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Affordability</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Safety and security</td>
<td>3</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>User acceptance and satisfaction</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Neighborhood accessibility and amenities</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
As noticed during this study, sustainability performance criteria can be qualitative or quantitative. Many of
the criteria developed by the reviewed references are qualitative criteria and there are no clear methods
for quantifying them, although there have been advances made in the development of quantitative tools.
For example, LCA and LCC are capable of evaluating the life cycle environmental and economic
performance of buildings, respectively. However, there is no standard social life cycle assessment tool
available. Accordingly, there is a growing need for developing comprehensive and standard evaluation
systems for assessing all TBL of building, i.e., life cycle sustainability assessments (LCSAs).

7 CONCLUSION

During the last few years, there was a paradigm shift in the construction industry due to natural resources
limitations. Therefore, more attention is being paid to decrease the environmental impacts of the built
environment. However, it is not adequate to only protect the environment and ignore the socio-economic
impacts of construction projects. In fact, sustainable construction strives to find a balance between the
three primary sustainability dimensions, i.e., environmental, economic and social (TBL). Therefore, to
have a sustainable building all TBL should be addressed sufficiently. A comprehensive method to
address this need is a life cycle sustainability assessment (LCSA) framework, by which all TBL
performances are assessed during the life cycle of a building.

In order to assess the life cycle sustainability performance of buildings (using a LCSA framework), it is
necessary to identify significant indicators of all the sustainability dimensions. In this paper, the most
commonly recommended criteria were identified using a content-analysis based literature review. A broad
list of building sustainability performance indicators (SPIs) were collected, modified, combined and refined
to form final TBL-SPI sets, i.e., environmental, economic and social SPI sets. For assessing the
environmental performance of buildings, 16 SPIs were identified as the most significant SPIs. For the
economic and the social dimensions of sustainability, a total number of 9 SPIs and 12 SPIs were
identified as the most commonly used criteria, respectively.

This paper provides a deeper insight into sustainability in construction by providing the frequently used
sustainability criteria in different publications, including the sustainability rating tools and other published
references. The findings can help construction stakeholders, such as decision makers, policymakers,
clients, developers, contractors, engineers, architects, and designers in the development of sustainable
construction. The proposed TBL SPI sets can be applied in the design and construction phases of
buildings’ life cycle. In addition, they can be used as a generic reference list in order to assess after
construction the extent to which buildings are sustainable.

Since the refined environmental, economic and social SPI sets consist of both qualitative and quantitative
criteria, future research will need to investigate methods to measure and integrate them using appropriate
LCSA frameworks. It should be mentioned that this paper is part of an ongoing comprehensive research
project currently being conducted by the authors regarding the life cycle sustainability of off-site and on-
site construction methods. Therefore, the developed SPI sets will be used in a LCSA framework to
comparatively assess the sustainability of modular and conventional buildings.

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FORECASTING BREAKAGE RATE IN WATER DISTRIBUTION NETWORKS USING EVOLUTIONARY POLYNOMIAL REGRESSION

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Abstract: The economic, social and environmental impact of water main failures impose great pressure on utility managers and municipalities to develop reliable rehabilitation/replacement plans. The annual number of breaks or breakage rate of each pipe segment is known as one of the most important criteria in condition assessment of these pipelines. A model is developed in this research to predict the annual number of breaks in water pipes. The developed model utilizes Evolutionary Polynomial Regression (EPR), which is an intuitive data mining technique. The model is applied to a case study to test its effectiveness. The case considers the water distribution networks of in the cities of Doha in Qatar; Montréal, Moncton and Hamilton in Canada. The results indicated that the developed models successfully estimated the breakage rate for the city of Montréal and the number of breaks for the city of Doha with a maximum coefficient of determination of 88.51% and 96.27% respectively. This demonstrates the accuracy and robustness of the developed models in forecasting the number of breaks and breakage rate in water distribution networks.

1 INTRODUCTION:

The Canadian Infrastructure Report Card 2012 (CIRC 2012) shows municipal drinking-water networks ranked “Good: Adequate for now”. Despite this overall rating, 15.4% of water distribution systems in Canada were ranked “fair” to “very poor” that can cause a total cost of $25.9 billion for replacement of the pipes. The “fair”, “poor” and “very poor” condition would be interpreted as deterioration beginning to be reflected, nearing the end of useful life and no residual life expectancy respectively (CIRC 2012). According to this report, 86 Canadian municipalities recorded a total of 719,630 km of water pipelines containing distribution pipes (≤350 mm diameter) and transmission pipes (>350 mm diameter). Based on the expertise’s viewpoint one of the most popular techniques in finding the leakage location in the water pipes is joining the pole to pipes. Therefore the approximate failure place can be discovered by hearing the leak sound. Obviously, this method is insufficient, inaccurate and sometimes cost consuming. According to the CIRC 2012, a considerable percentage of municipalities in Canada do not have complete data of buried infrastructures including water and sewer pipes. While, it is clear that testing, inspection and evaluating of the physical specification of pipes requires large amount of financial reserves, it can be more profitable if the prediction models develop based on the limited historical data instead of real physical data. Recently, a data-mining technique titled Evolutionary Polynomial Regression (EPR) was developed by Giustolisi and Savic. The EPR can be categorized as Grey Box Technique and is performed in two stages: 1) search for the best model using Multi-Objective Genetic Algorithm (MOGA), and 2) parameter estimation for the model using Least Square Method. This type of regression generates several symbolic expressions that are understandable by specialists and professionals, based on various independent variables. The main objectives of this study are: 1) estimate the number of breaks of water mains based on the pipe age to reconstruct the historical databases using regression; 2) develop failure rate prediction models using Evolutionary Polynomial Regression; and 3) develop deterioration curve of water mains with respect to the pipe age using sensitivity analysis.

2 PREVIOUS STUDIES:

Several researchers considered many factors that affect the deterioration of water mains and pipe failure. Stone et al. (2002) categorized these factors in two groups, namely; static and dynamic. The
characteristics of static parameters (e.g., diameter, length, soil type, pipe material, etc.) do not depend on the time, but dynamic factors (e.g., age, cumulative number of breaks, soil corrosivity, water pressure, etc.) change over time. Osman and Bainbridge (2011) tried to identify the effect of time-dependent variables like pipe age, temperature and soil moisture on the deterioration of water pipes. In addition, InfraGuide. (2003) classified the deterioration factors of water pipes into three main categories, namely; physical (e.g., pipe material, pipe wall thickness, pipe age, pipe diameter, type of joints, pipe installation, etc.), environmental (pipe bedding, trench backfill, soil type, pipe location, etc.) and operational (internal water pressure, leakage, water quality, O&M practices, etc.). Several researchers such as Berardi et al. (2008), Xu et al. (2011), Arsénio et al. (2014) and Kutylowska (2015) examined the impact of physical parameters on the water pipes failure. The most frequent explanatory variables in these studies are age, diameter, length and material of the pipe. Some others tried to add more parameters from various categories (environmental and physical) as the independent variables in order to improve reliability of the models. For example, Wang et al. (2009) and Shirzad et al. (2014) took into the consideration the operational factors like hydraulic pressure and burial depth in addition to physical factors. Asnaashari et al. (2013) considered soil type as the environmental factors, as well as the physical ones. Jafar et al. (2010) employed the pipe characteristics (physical), hydraulic pressure (operational), soil type and pipe location (environmental) as the inputs. Moglia et al. (2008) utilized corrosion rate, wall thickness, internal pressure and external loads as the inputs; while, typically corrosion rate is the output in the most of the previous studies.

During the last three decades, researchers introduced different models to predict the condition of the water pipes for a reliable infrastructure management system using various methodologies. The deterioration and water pipe failure prediction models could be classified into six categories; namely, deterministic, statistical, probabilistic and some advanced mathematical models such as artificial neural networks (ANN), fuzzy logic and heuristic. Recently, several efforts have been made to develop deterioration and pipe failure prediction models. A summary of the most prominent ones is shown in Table 1. The EPR does not require large data sets for training and unlike ANN, it enables recognition of correlations among dependent and independent variables. As such it is not a “Black-Box” technique, but it is classified as a “Grey-Box” technique that can provide insight into the relationship between inputs and output. The process of development and selection of EPR contains engineering knowledge that allows the user to understand the generated equations and the correlation between variables involved.

<table>
<thead>
<tr>
<th>Authors (Year)</th>
<th>Model Classification</th>
<th>Methodology</th>
<th>Output Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berardi et al. (2008)</td>
<td>Statistical</td>
<td>Evolutionary Polynomial Regression</td>
<td>Pipe Deterioration</td>
</tr>
<tr>
<td>Wang et al. (2009)</td>
<td>Statistical</td>
<td>Five Multiple Regression Models</td>
<td>Annual Break Rates</td>
</tr>
<tr>
<td>Li et al. (2009)</td>
<td>Probabilistic</td>
<td>Monte-Carlo Simulation</td>
<td>Remaining Useful Life</td>
</tr>
<tr>
<td>Wang et al. (2010)</td>
<td>Statistical</td>
<td>Bayesian Inference</td>
<td>Deterioration Rate</td>
</tr>
<tr>
<td>Jafar et al. (2010)</td>
<td>Artificial Neural Networks</td>
<td>Genetic Programming and Evolutionary Polynomial Regression</td>
<td>Deterioration Rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rate of Failure (ROF) and Transition State (TS)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ANN and Multi Linear Regression</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ANN and Support Vector Regression (SVR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ground Movement Estimated by Radar Satellite Data</td>
</tr>
<tr>
<td>Asnaashari et al. (2013)</td>
<td>Artificial Neural Networks</td>
<td>ANN</td>
<td>Failure Rate</td>
</tr>
<tr>
<td>Shirzad et al. (2014)</td>
<td>Artificial Neural Networks</td>
<td>Analysis of pipeline conditions with satellite data</td>
<td></td>
</tr>
<tr>
<td>Arsénio et al. (2014)</td>
<td>Statistical</td>
<td>Artificial Neural Networks</td>
<td>Failure Rate</td>
</tr>
<tr>
<td>Kutylowska (2015)</td>
<td>Artificial Neural Networks</td>
<td>ANN</td>
<td></td>
</tr>
</tbody>
</table>

2.1 EVOLUTIONARY POLYNOMIAL REGRESSION:

The Evolutionary Polynomial Regression (EPR) technique was first presented by Giustolisi and Savic (2006). The technique utilizes the huge potential of conventional numerical regression techniques and
the strength of Genetic Algorithm in solving optimization problems (Xu et al. 2011). Later, this approach was used by other researchers in several fields. Savic et al. (2006) and Ugarelli et al. (2008) used EPR to model the sewer pipe failures. Several researches were conducted using EPR in different engineering fields. Berardi et al. (2008) and Xu et al. (2011) applied the EPR to develop deterioration models for water distribution networks. Rezania et al. (2008) utilized the EPR methodology to evaluate the uplift capacity of suction caissons and shear strength of reinforced concrete deep beams. Elshorbagy and El-Baroudy (2009) compared the EPR and Genetic Programming to develop the prediction model of soil moisture response. Guistolisi and Savic (2009) tested the EPR-MOGA (An improved EPR) to develop groundwater level prediction model based on monthly rainfall. El-Baroudy et al. (2010) utilized the EPR to develop the evapotranspiration process then compared efficiency of Evolutionary Polynomial Regression to Artificial Neural Networks (ANNs) and Genetic Programming (GP). Markus et al. (2010) applied EPR, ANNs and the naive Bayes model to forecast weekly nitrate-N concentrations at a gauging station. Ahangar-Asr et al. (2011) applied EPR to predict mechanical properties of rubber concrete. Fiore et al. (2012) used EPR to provide the predicting torsional strength model of reinforced concrete beams.

Evolutionary Polynomial Regression is data-driven technique and can be classified as a grey box method according to the color coding classification system categorizes mathematical models based on the existence of necessary information into three groups; white box models, black box models and grey box models (Giustolisi 2004). The process of creating the symbolic expressions contains two stages: in the first stage the EPR tries to find the best model structure using Multi-Objective Genetic Algorithm (MOGA). Then, the appropriate values for constant are estimated using Least-Squares optimization (LS) (Berardi et al. 2008). In the EPR_MOGA, seven assumed structures of expression are available and the best case according to the prior knowledge about the nature of the output can be selected by the user. In this study the following equation was chosen:

\[ Y = a_0 + \sum_{j=1}^{m} a_j \cdot f(X_1)^{ES(j,1)} \cdot \ldots \cdot f(X_k)^{ES(j,k)} \cdot \ldots \cdot f(X_k)^{ES(j,2k)} \]

Where, \( X_k \) is the \( kth \) explanatory variable, \( ES \) is the matrix of unknown exponents that should be defined by the user, \( f \) is inner function selected by the user (can be no function, logarithm, exponential, tangent hyperbolic, secant hyperbolic), \( a_j \) are unknown polynomial coefficients, \( m \) is the number of polynomial terms and \( a_0 \) is the bias term. It must be remarked that, the zero value should be considered in the matrix of exponent to make the EPR able to remove some variables, which are not powerful enough to predict the output, from the returned expressions.

During the modelling phase by EPR, it tries to return several equations based on accuracy and parsimony of the models. The model parsimony can be implemented by optimizing the number of terms, the number of independent variables, or both strategies. Each of these options can be selected by the user. Furthermore, the user can force EPR to generate the equations with only positive value of constant coefficients \( (a_j > 0) \). Also, the maximum number of terms in every equation in each run can be specified by the user. In addition, the normalization (if required) can be accomplished by EPR, therefore, the user just needs to identify the range in which the inputs or output should be scaled. The EPR can develop model to forecast the output based on either one input or several inputs, in other words it can construct Multi Input Single Output (MISO) and/or Single Input Single Output (SISO) models. It should be noted that, the limited missing data point can be recreated using linear interpolation by EPR; thus, the model can be developed with an incomplete historical database. During the generating symbolic expressions, if the EPR cannot find appropriate combination of terms containing \( f(x) \) (as an inner function), it deselects this function. The effectiveness of fitness of developed models was measured by Coefficient of Determination (CoD) equation as follows (Berardi et al. 2008):

\[ \text{CoD} = 1 - \frac{\sum_n (\hat{y}_{\text{exp}} - \bar{y}_{\text{exp}})^2}{\sum_n (y_{\text{exp}} - \bar{y}_{\text{exp}})^2} = 1 - \frac{n}{\sum_n (y_{\text{exp}} - \bar{y}_{\text{exp}})^2} \cdot \text{SSE} \]

Where \( n \) is the number of samples, \( \hat{y} \) is the value that predicted by the model, \( y_{\text{exp}} \) is the actual amount of the historical data and \( \text{SSE} \) is the sum of squared errors.

3 RESEARCH METHODOLOGY:

Fig. 1 shows the developed research methodology. It started by presenting a comprehensive literature review to investigate the deterioration and pipe failure prediction models. In the second step, the relevant data were collected from two different municipalities; City of Doha in Qatar and City of
Montréal in Canada. The database of the city of Montréal contains an inventory of pipes’ information and the related bursts. However, the number of breaks was not available in the database of the city of Doha. Lack of such data prevents working with EPR because this technique takes into account the number of breaks or breakage rate as a dependent variable in order to develop a pipe failure prediction model. Therefore, it was necessary to estimate the number of breaks for the city of Doha from similar infrastructure databases. Thus, the number of breaks for the city of Doha was estimated using two databases such as: Moncton and Hamilton. Several attempts were carried out using different regression models to predict the number of breaks of water mains based on the pipe’s age. The model that provides large number of data points as well as the best R-Square was used to predict the pipe bursts for city of Doha. The third step, the model implementation, the databases were cleaned and classified into homogeneous groups based on age and diameter of the pipes. It means that all pipe segments of each class have the same value of age and diameter. Also, all missing data points were removed from the databases. At this point, data sets of Montréal and Doha are ready to be analyzed using EPR_MOGA_XL. In this study, two different scenarios were implemented; the first one considered the number of breaks as an output and the other one assumed that the dependent variable is the breakage rate (Breaks/Length (Km)/Age (Yr)). Finally, the sensitivity analysis was carried out for both cases to develop different deterioration curve and to identify the effect of each variable on the breakage rate.

Figure 1 Research Methodology

4 DATA COLLECTION:

In this study, four sets of data from various municipalities were used, namely; city of Moncton, city of Hamilton and city of Montréal in Canada and city of Doha in Qatar. The city of Moncton, Hamilton, Montréal and Doha own 517 km, 1,891 km, 70 km and 4,682 km of water distribution networks respectively (SOIR, 2005, KAHRAMAA Report). The physical characteristics of water pipes in different databases are generic. In fact the results obtained using the Hamilton and Moncton data were very close. In view of this finding and the insufficient data collected from Doha, it was required to use the model developed based on Hamilton and Moncton to predict the number of breaks in Doha. Estimation of number of breaks was implemented by applying regression analysis using data sets of Moncton and Hamilton. Three different models were developed. In the first two models the data of each city was used separately, while, in the third one the combined data for both cities was utilized. In each model the data was clustered into different groups based on the pipe age. The breaks per length (m) was calculated for each age-class by computing the average of number of bursts. Several attempts were conducted to reach the best model using different types of databases. Since, in the database of Doha, there are not pipes older than 33 years, it was not necessary to keep the pipes with the age of 34 and more, therefore they could be deleted in the new inventories. Finally, the model
which provides large number of data points and gives the best performance based on the Coefficient of Determination ($R^2$), was chosen to estimate the number of breaks for the city of Doha.

Fig. 2 shows the result of regression (based on the No. of Breaks per Length (m)) of Moncton, Hamilton and mixing of both cities, respectively. The equation of each inventory and determined $R^2$ are shown in Table 2. It can be seen that the developed models of Moncton and both Cities are acceptable; while, the one that belongs to city of Hamilton is not promising enough to be used in Doha. Then, number of breaks per length that obtained from these equations should be multiplied by length of related pipe segments to calculate the estimated number of breaks of Doha’s database.

The completed database of Doha, including the estimated number of breaks, and Montréal data set was filtered before applying with EPR. Each of them comprises several factors: Table 3 shows the collected variables for both inventories. The units of age, length, diameter, depth of laid and pipe elevation are year, Km, mm, m and m respectively in collected data. For cleaning and organizing databases, several steps performed. Some segments with having either the missing pipe information or inconsistent data were totally removed from databases. The qualitative variables such as pipe type and soil type were translated to numerical ones. For example, if there are four different types of soil, each number from 1 to 4 was assigned to a specific soil type. It is noteworthy mentioning that the maximum number was assigned to the hardest pipe type; in other words, the harder the material, the larger the allocated number and the vice versa. As it was mentioned before, there are two different scenarios in considering the output in the current study; number of breaks and breakage rate. The breakage rate of each segment should be calculated by dividing number of breaks by age (or observation years) and length (km) of the pipe. Finally, two databases were classified into homogeneous groups based on age and diameter of the pipe. A detailed discussion about classification is presented in model implementation section.

<table>
<thead>
<tr>
<th>Different Databases</th>
<th>Equations</th>
<th>R-Squared (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moncton</td>
<td>$y = 3E^{-05}x^2 - 0.0003x$</td>
<td>83.31</td>
</tr>
<tr>
<td>Hamilton</td>
<td>$y = 1E^{-06}x^3 - 0.0001x^2 + 0.003x - 0.0032$</td>
<td>31.09</td>
</tr>
<tr>
<td>Mixing of Both Cities</td>
<td>$y = 6E^{-06}x^2 + 0.0004x + 0.0026$</td>
<td>68.20</td>
</tr>
</tbody>
</table>
5 MODEL IMPLEMENTATION:

5.1 EPR SETTINGS:

In the database of Montréal, the following factors were considered as independent variables; pipe length, diameter, pipe type and age of the pipe. Whereas, inputs in Doha data set were pipe length, diameter, thickness, pipe type, age, pipe elevation and depth laid. Also, the settings which are followed were same for both cases. Nomination of exponents were limited to [-2, -1.5, -1, -0.5, 0, 0.5, 1, 1.5, 2] in which the positive and negative value represent the direct and inverse relationship between dependent and independent variables and their amounts show how significant the inputs are. The maximum number of terms in each expression was three and the bias term was considered as zero. In the Regression Method tab, the Least Square parameter estimation was forced to search for just positive value of $a_j$ as a coefficient. The exponential was selected as the inner function. EPR rounded the output to the nearest integer number if the classification is selected as the Modelling Type. Thus, in the scenarios in which the breakage rate was assumed as a dependent variable, Statical Regression should be chosen for considering the output as a real number. The range of variables was constrained to [0.01, 1] for scaling all inputs and output data. The “GA” is the number of generation and depends on several attribute such as number of independent and dependent variables, number of terms and exponents, and was selected as 40 based on the previous experience. There are three different choices in Optimization Strategy; namely, \( \min(a_j, SSE), \min(X_i, SSE) \) and \( \min(a_j, X_i, SSE) \). Among them the \( \min(X_i, SSE) \) was selected. Maximization of the parsimony and the accuracy of the model caused by minimization of \( a_j \) and \( X_i \) respectively.

<table>
<thead>
<tr>
<th>Table 3 Collected Data for Each City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factors</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Pipe Length</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>No. of Breaks</td>
</tr>
<tr>
<td>Pipe Type</td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>Observation Period</td>
</tr>
<tr>
<td>Functional Impairments</td>
</tr>
<tr>
<td>Pipe Elevation</td>
</tr>
<tr>
<td>Depth Laid</td>
</tr>
</tbody>
</table>

* Estimated by Other Databases

5.2 CLASSIFICATION:

Once, the process of cleaning and reconstruction was conducted, pipe segments were classified into several homogeneous groups based on age, diameter and pipe material. In the database of Doha there were only three nonmetallic pipes out of 1599 pipes, which were removed. Thus the classification of Doha was based on only age and diameter. The following equations were used to group the data:

\[
A_{\text{class}} = \frac{\sum_{\text{class}}(L_p \cdot A_p)}{L_{TA}}, \quad D_{\text{class}} = \frac{\sum_{\text{class}}(L_p \cdot D_p)}{L_{TD}}
\]

Where, \( L_{TA} \) and \( L_{TD} \) are the total length of pipes with the same age and diameter respectively. Also \( L_p, A_p \) and \( D_p \) are length, age and diameter of each segment in the group. Thus, there are several categories with the same class of age, diameter and material for each inventory. It should be mentioned that the other features of pipe (such as thickness, length, etc.) can be utilized as grouping criteria in different studies. But in this research age was selected for classification to take into account the indirect effect of time-varying solicitation on water mains. Because as an engineering point of view, the higher the duration of solicitation, the higher the chemical and mechanical harmful effects (caused by soil condition, traffic loads, etc.) on pipes (Berardi et al. 2008). Furthermore, the other equivalent attributes in each database can be calculated by different mathematical functions (such as
sum, average, etc.). In the database of Montréal, the length and the number of breaks of each class were computed by summing corresponding ones of each pipe segment. Likewise, in the Doha database, the same calculations were performed for the length and the number of breaks; while, the other variables such as pipe elevation and burial depth were calculated by computing the average of related features of pipes in that group.

6 ANALYSIS OF RESULTS:

In this study, two databases; the city of Montréal and the city of Doha were utilized to forecast the number of breaks (for the city of Doha) and the breakage rate (for the city of Montréal) using EPR. Among all symbolic expressions that were developed by EPR, the best one was chosen based on the fitness to the historical data and parsimony of the equation. Tables 4 and 5 show different pipe burst prediction models for the city of Montréal and the city of Doha with their corresponding R-Square respectively. It can be seen that in both cases the expressions accuracy is increased when equations get more complicated. It can be understood from Tables 4 and 5 that the age of the pipe has a direct impact on the breakage rate as well as the number of breaks. In addition, the equations describing the number of breaks for the city of Doha has higher coefficient of determination than the equations describing the breakage rate for the city of Montréal.

Table 4 shows twelve breakage rate prediction models that were generated by applying the EPR with database of Montréal. It can be seen that equations 5 considers the age, length and diameter of pipes and has a coefficient of determination of 79.58%. In equation 6, the material of pipes was added to the model which improves the coefficient of determination by 5.71%. While, the coefficient of determination increased from 85.29% to 88.51% from equation 6 to 12, the models became more complicated. Thus, in this study, equation 6 was selected to be the best one to describe the pipe breakage rate as it has the acceptable coefficient of determination with reasonable number of variables.

Table 5 shows the twelve symbolic expressions that were generated by EPR to estimate the number of breaks for the City of Doha. It can be seen that age, length and diameter of the pipes are the most commonly used variables for estimating the number of breaks while depth laid and pipe elevation has been introduced in only the last five equations. It can be notice that as the age of pipes increases the breakage rate increases. However, when the diameter of the pipes increases the breakage rate decreases. It can be remarked that equation 2 has a coefficient of determination of 94.33%. However, it only considers the length and the age of the pipe. In order to test the sensitivity of the prediction model by changing the inputs, model number 9 was chosen as it considers all variables that has a significant effect on the pipe bursts.

Figure 3 and 4 show the Pareto graphs of different models based on Montréal and Doha result respectively. In these graphs each point represents one returned equation and vertical axes shows the number of selected inputs while the horizontal axes demonstrate the fitness of models (1-CoD).

7 SENSITIVITY ANALYSIS:

In this study, the sensitivity analysis was performed to identify the effect of each variable on the pipe bursts when the water pipes get older. Figures 5 to 9 show the deterioration curves for the city of Montréal and the city of Doha. Figures 5 and 6 illustrate the breakage rate for the city of Montréal for different pipe diameters and pipe lengths respectively while keeping all other inputs as constants. The value of these constants were considered as the average of that variables in the database. Figure 5 and 6 show the effect of pipe diameter and pipe length on the breakage rate. The breakage rate of pipes with different diameter has increasing trend as the pipe become older. It is clear from the Figure 5 that the bigger the diameter of the pipes, the higher the value of breakage rate. In addition, Figure 6 shows the breakage rate of pipes with various length are increased when the pipes get older. The same analysis was carried out for city of Doha. As it was mentioned before the equation 9 of database of Doha was used to develop graphs including different deterioration curves. Figure 7, 8 and 9 show the sensitivity analysis for length, depth laid and pipe elevation respectively. It is confirmed in these graphs that, the number of breaks is increasing while the pipes are aging.
rate of the water pipes. As it was confirmed by previous studies, the most critical factors that affect
analysis was implemented to identify the effect of each factor on the number of breaks and breakage
fitness was measured by Coefficients of Deterministic. Then, the results were analyzed and sensitivity
Doha and Montréal. For each attempt several symbolic expressions were returned by EPR and their
data sets were utilized in different parts including city of Doha, Montréal, Moncton and Hamilton. In
this paper. The setting of EPR_MOGA software was explained in details. Four different aggregated
The process and specifications of Evolutionary Polynomial Regression technique were described in
8 CONCLUSION:
The process and specifications of Evolutionary Polynomial Regression technique were described in
this paper. The setting of EPR_MOGA software was explained in details. Four different aggregated
data sets were utilized in different parts including city of Doha, Montréal, Moncton and Hamilton. In
the database of Doha, the number of breaks of pipelines was not available. Therefore a regression
model developed to predict the number of breaks based on the pipe age. This was performed using
city of Moncton, city of Hamilton and mixing of both cities. The EPR was applied with databases of
Doha and Montréal. For each attempt several symbolic expressions were returned by EPR and their
fitness was measured by Coefficients of Deterministic. Then, the results were analyzed and sensitivity
analysis was implemented to identify the effect of each factor on the number of breaks and breakage
rate of the water pipes. As it was confirmed by previous studies, the most critical factors that affect
deterioration of water pipes are age, length, diameter and material. Finally, for each data set, one

Table 4 Produced Equations by EPR for Montréal database and related CoD

<table>
<thead>
<tr>
<th>Symbolic Expressions</th>
<th>CoD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Breaks=1.1493 A0.5 L</td>
<td>90.66</td>
</tr>
<tr>
<td>2- Breaks= 1.8169×10^6 A0.5 L</td>
<td>94.33</td>
</tr>
<tr>
<td>3- Breaks= 3.3795×10^6 A0.5 L</td>
<td>94.99</td>
</tr>
<tr>
<td>4- Breaks= 1.146 A0.5 L + 1.7317×10^5 A2 ln(\frac{1}{\tau^2})</td>
<td>95.21</td>
</tr>
<tr>
<td>5- Breaks= 0.0066601 ln(D0.5) + 1.1721 A0.5 L + 1.6884×10^6 A^2 ln(\frac{1}{\tau^2})</td>
<td>95.87</td>
</tr>
<tr>
<td>6- Breaks= 1.4624×10^6 A0.5 L + 2.0317×10^6 A2 ln(\frac{1}{\tau^2})</td>
<td>95.58</td>
</tr>
<tr>
<td>7- Breaks= 3.4001×10^6 A0.5 L + 2.4526×10^6 A^2 ln(\frac{1}{\tau^2})</td>
<td>95.7</td>
</tr>
<tr>
<td>8- Breaks= 3.2060×10^6 A0.5 L + 2.8169×10^6 A^2 ln(\frac{1}{\tau^2})</td>
<td>95.91</td>
</tr>
<tr>
<td>9- Breaks= 3.4191×10^7 A0.5 L + 3.453×10^5 A^2 ln(\frac{1}{\tau^2})</td>
<td>96.02</td>
</tr>
<tr>
<td>10- Breaks= 3.4559×10^7 A0.5 L + 3.5792×10^6 A^2 ln(\frac{1}{\tau^2})</td>
<td>96.1</td>
</tr>
<tr>
<td>11- Breaks= 3.817×10^7 A0.5 L + 3.5748×10^6 A^2 ln(\frac{1}{\tau^2})</td>
<td>96.27</td>
</tr>
<tr>
<td>12- Breaks= 3.822×10^7 A0.5 L + 3.5775×10^6 A^2 ln(\frac{1}{\tau^2})</td>
<td>96.05</td>
</tr>
</tbody>
</table>

8 CONCLUSION:
The process and specifications of Evolutionary Polynomial Regression technique were described in
this paper. The setting of EPR_MOGA software was explained in details. Four different aggregated
data sets were utilized in different parts including city of Doha, Montréal, Moncton and Hamilton. In
the database of Doha, the number of breaks of pipelines was not available. Therefore a regression
model developed to predict the number of breaks based on the pipe age. This was performed using
city of Moncton, city of Hamilton and mixing of both cities. The EPR was applied with databases of
Doha and Montréal. For each attempt several symbolic expressions were returned by EPR and their
fitness was measured by Coefficients of Deterministic. Then, the results were analyzed and sensitivity
analysis was implemented to identify the effect of each factor on the number of breaks and breakage
rate of the water pipes. As it was confirmed by previous studies, the most critical factors that affect
deterioration of water pipes are age, length, diameter and material. Finally, for each data set, one
predicting model was selected to be used by utility managers and decision makers of Water Distribution Networks.

Acknowledgement:

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References:


COMPARATIVE ANALYSIS OF EXISTING BUILDING INFORMATION MODELLING (BIM) GUIDES

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Abstract: The current approach to development of building information modelling (BIM) guides has catered to each specific client in a unique way. There has been no universal standard format or standardized content employed in the development of these guides from one organization to the next. Conversely, many organizations have pioneered the development of their guides to support the need for standardized methodologies in developing and deploying BIM capability within their organization and/or supported by industry deliverables. Further, published BIM guides around the world define similar or the same terms and concepts in unique ways (and vice versa). The BIM guides project is the first project to leverage existing publications within an open process of consensus standardization, in pursuit of harmonization of concepts, definitions, terms and the organization of how this content is delivered. It uses a review template to capture common metadata fields for comparative analysis within a database. A database of BIM guide information can inform on real-world procedures and requirements from industry. Guidelines are for the user, and this project gives insight and direction to those needing, using and creating BIM guidelines. It is hypothesized that this approach will deliver guides more efficiently, contribute to BIM adoption and standardized use within industry and provide a needed baseline from which the end-user can effectively build their knowledge, skills and abilities.

1 INTRODUCTION

In the construction and facilities industries, clients and professionals currently need to perform or outsource a major amount of work to review existing BIM guide documentation in order to develop their own version of a BIM guide for their company or organizational needs. The process of reviewing, analysing and drafting guide documents is labour-intensive and results in parallel or duplication of effort without value added to the achievement of standard procedures or best practices. Recognizing the opportunity for greater efficiency through harmonization of efforts, a group of experts working collaboratively under buildingSMART International launched the “BIM Guides Project” to determine if and how standards and the standards developing process can aid in improving the process of creating, implementing and using BIM guide documentation.

The project’s goals when initially established included publishing a publicly accessed database of pre-defined and user-defined search criteria and then using these results to make recommendations on an international framework for BIM guidance documentation. Additional questions the project seeks to answer include: Can the plethora of global BIM Guides be reverse-engineered down to a few pioneering documents? What are the roots to today’s foliage of guidance documentation? What published documents are used in popularity, and thus becoming de-facto industry standards? What are the common elements of BIM guidance documentation across the majority of publications? Where are there gaps in
existing BIM guidance documentation? How can new concepts in standardized applications be used to the benefit of BIM guidance development?

1.1 Definitions
For the purposes of this project, "Guides" refer to any documentation that has been published to support the end-user in applying standardized processes, procedures or technical requirements in Building Information Modeling (bSI BIM Guides Project Team 2014.).

1.2 Current Guidelines Development Process
The current process of developing BIM guidelines typically involves one or all of the following steps:
- duplication, modification and/or addition of content to an existing guide;
- compilation of existing content within a new organization of information (table of contents); and
- development of original content.

It takes a lot of time for someone to get up to speed on all major guide publications, as they consider each for content, organization of content, and scope. The results vary in quality, applicability to the ‘real-world’ and achievement of the client’s objectives.

Overall, most clients and consultants will agree with the adage of “not wanting to re-invent the wheel” when it comes to BIM standards and best practices. If information can be available, the general consensus is that this content would be welcomed and leveraged for greater industry use. That said, issues of intellectual property and a general comfort level of openly sharing content developed continues to lead to clients or consultants, willingly or forced, to develop guideline and other standard or best practice documents independently and often uniquely.

1.3 An Industry Project to Benefit from Academic Rigour
This project identifies a gap in the current ability to achieve consensus and consistency on BIM guide content. This gap varies from country to country, but exists everywhere nonetheless. This is evident by the amount and variety of guides publically available. Although not initiated as a research project, this industry-identified project recognizes the role that the academic process can bring to achieving rigour in the methods and outcomes, including substantiating results and recognizing value. Future work is anticipated and encouraged within academia in collaboration with this project team to bring best value to industry.

2 BACKGROUND
The BIM Guides Project started out of a recognized need during the delivery of the United States’ National BIM Standard, version 3 (NBIMS-USv3). At that time, there was little to no known literature available that provided a way to categorize or classify content of and within guides. Specific focus on comparing guidelines was first introduced by a work group within FIATECH, but limited in scope to focus only on the AutoCodes project (FiatechAutoCodes), and then left to this project to take further.

The BIM Knowledge Content taxonomy (BKC) (Succar 2013) has since been identified and should be reviewed for relevancy in the metadata fields captured within the database via the review template. Identification of the noteworthy BIM publications (NBP)’s concept and metrics (Kassam 2013) also provides opportunity to fine-tune the review template for metadata capture that can assist in supporting existing research areas and overall industry needs.

A standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose (International Standards Organization 2015). Building off of existing guide content to achieve standardized parts, methods and terms would support greater efficiency in BIM adoption and use. Recognizing that a guide document needs flexibility to achieve its purpose, where trying to standardize on
too much is not useful or realistic, the project has set its ultimate goal to achieve a framework with sample language and agreed terminology/concepts for easy population of content.

3 METHODOLOGY

The project uses a template approach as the key method to establishing a baseline of common fields, or metadata, about the majority of BIM guide documentation available globally. A template approach is defined as the review of a document captured in a commonly defined template in order to provide a method for comparison of disparate document content. This metadata capture provides the ability to search across document content and make comparisons. The culmination of the analysis places the document in a chart comparing content and scope, where all guidance documentation can be related from a high-level. The choice to use a wiki was based on the capacity to create a searchable compendium of reviews of all known BIM standards, guidelines, and best practices. The Wiki format makes it open to the worldwide BIM community.

Prior to this project there were no real efforts to harmonize BIM guides, whether at a national or an international level. Given the number of established and implemented BIM guides we cannot start over and propose one common international guideline. But harmonization of the content can be accomplished on multiple levels:

1. The first level is to harmonize or map the understanding of its field of application and aimed users. Human interpretation is required to tease out the metadata. The result is being able to query across documents.
2. The second level is mapping content (mainly by chapters) to a common table of contents. The result is the establishment of a common structure or framework, either to aid in comparison or to use when creating new guides.
3. The third level is harmonizing or mapping definitions. Also referred to as searching for keywords, the level of effort to identify and harmonize terminology is significantly greater than the first and second levels. All three levels contribute to the made-to-measure concept of building out guides with consistent or standard terms, definitions and structure.

Figure 1 below illustrates the project's 3-level concept:
The goals of the project include:

- support a common framework for BIM guides based on the results of the project;
- promote BIM guide content that employs open BIM based file exchanges and processes; and
- deliver a product application of the database tool for public consumption and use.

3.1 Developing a Matrix for Comparative Analysis

The initial approach was to intuitively identify common categories of information type, based on expert experience within the project team, and to plot that content against an implementation level. Captured in Table 2: Guide Mapping Matrix, the comparative analysis hypothesis was that as content within existing standards and guidelines documentation was mapped to this matrix, awareness, consent and agreement on what (level of) content belongs where along the implementation continuum would begin to form from intuitively interpreting the results and recognizing trends or patterns.

Table 2: Guide Mapping Matrix

<table>
<thead>
<tr>
<th>Categories of Information vs. Implementation Level*</th>
<th>Standards</th>
<th>Contracts (&amp; Technical Specifications)</th>
<th>Business Processes (By Role, etc.)</th>
<th>Tools, Technology, Modelling Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Framework</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>National Framework</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Owner Organization Guides/ Manuals</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Facility Managers/ Operators</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Trade-Related/ Associations</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Project/ Company- Related Use</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Software- Related Use</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

*Guides are qualified by scope and mapped to this matrix; multiple boxes can be checked

3.2 Review Template for Common Metadata Fields

The review template was created to capture these common metadata fields, thus providing the method by which to compare guides at a comprehensive level. Overall the capture and completion of a review of a guide document is not intended to be a labour-intensive or exhaustive exercise. Recognizing that BIM guides are so diverse in their content, the intent was to capture overall scope and subject areas from a generalization perspective. Sections are completed from drop-down menus, with a comment field at the end of each section for manual text entry at the reviewer’s discretion for additional information or specificity.

The template splits content into two (2) sections, with multiple sub-sections:

- Part A: Document Overview (Intended Use and Audience)
  - Section 1 – Document Details
  - Section 2 – Intended Use and Audience
  - Section 3 – Document position by type and content (see Table 2 above)
- Part B: Document Content
  - Section 1 – Project Definition and Planning
  - Section 2 - Technical Specifications
Section 3 – Implementation Processes
Section 4 – Supporting Tools
Section 5 – Legal Aspects

The goal is to have each document reviewed three (3) times to ensure accuracy and completeness. Ideally, the document author or authoring organization representative completes one of these reviews. This approach is especially important for documents that require purchase, as users will only want to purchase documents if they can see that they are applicable to their effort.

3.3 Using the wikiX platform

It was determined that using a wiki would serve the database and public-access requirements best. NOTE: This wiki does not host the source documents under review. A link is provided to the source document within the review. Some source documents may require purchase. The database at the metadata level can be used to query guides for items such as general scope and audience, including drilling down to specific topics such as Level of Development, Project Execution Planning or COBie, for example.

3.4 Mapping to a Common Table of Contents

Parallel to the effort of trying to compare guides at an overall scope level, is getting down to the table of contents level (ToC). Mapping existing guides to a generic table of contents could be used when assembling from any BIM guidance document the sections within the database that are relevant to their organization or project. Developing a standardised TOC for the BIM Guides Wiki can provide a framework for users wanting to assemble their own customised guide based on content found in the guides included on the Wiki. This can contribute to harmonization of BIM guidance and, in turn, BIM practice.

3.5 Using Keyword Search Functionality

The third level of granularity is to achieve functionality that supports keyword searches. This implies that the document content is accessible and set up to be able to be searched at the keyword level. Alternatively, keywords can be tagged to the document by human interpretation that are not already captured at the metadata or table of contents levels. Likewise, this functionality must be completed in conjunction with how the buildingSMART Data Dictionary (bsDD) is used and in support of harmonization of terms and concepts.

3.6 The Made-to-Measure Concept

The made-to-measure concept is a logical extension to having a database of i) standardized terms, ii) a standardized structure, and iii) access to existing content that can be used with appropriate citation. The idea of being able to have a tool that builds out a BIM guide based on these three levels of available content is theorized to deliver industry efficiency and repeatability in administering BIM guides for project use. Likewise, this kind of tool does not detract from organizations needing organization- and/or project-specific content within their guide(s). The focus is on delivering common content in a common way. This concept is already being leveraged in at least two (2) countries: buildingSMART Norway’s BIM Manual efforts and known activity through buildingSMART Korea. (Note: Both chapters have participants on this project team. The project does not necessarily have the goal to create another, similar tool if an existing tool can be leveraged for the needs of the project.)

3.7 Copyright and intellectual property

A licensure letter and accompanying project prospectus document was identified as necessary to engage with document authors and authoring organization on the subject of copyright. The goal of the project is to leverage existing content for mass consumption via a standardization process. It is imperative that authors maintain their IP over existing content. Therefore, a requirement within the project is to ensure that accurate referencing is enabled when content is re-used and that content authors understand and agree to how their content can provide benefit to industry adoption and use of BIM.
3.8 Using the buildingSMART Data Dictionary (bSDD) to harmonize terminology

The buildingSMART Data Dictionary (bSDD) stores concepts with associated definitions to house a common ontology for the building and construction industry (buildingSMART International 2014a.). The open international data dictionary is a service based on [the] IFD Standard (ISO 12006-3) which allows users, architects, engineers, consultants, owners and operators on one side and product manufacturers and suppliers on the other from all around the world to share and exchange essential product information (buildingSMART International 2014b.). Although not the traditional use of the bSDD, the BIM Guides Project is currently exploring how the bSDD will be used to support this context.

The bSDD group has been engaged and steps have been taken to identify the following:

a) understanding and usage of the bSDD (general)
b) choice in how the bSDD is used affects the outcome (project-specific)
c) the processes for defining, inputting and using standard content in the bSDD
d) the harmonization process of content, pre- or post-input to the bSDD
e) a BIM guide project interface that accesses the bSDD in the background
f) pilot projects that can show proof of concept

3.9 ISO/TS 12911:2012 – Framework for building information modelling (BIM) guidance

ISO/TS 12911:2012 establishes a framework for providing specifications for the commissioning of building information modelling (BIM) (International Standards Organization 2012). The design intent behind the technical specification is to deliver structured, computable and therefore testable requirements, including how these requirements cascade down the contractual chain. The contractibility and checking functionality is predicted to be the key to the next generation of the standard.

The concept is to provide a framework that stands above any guide, taking a generic view. It is more ambitious than just a table of contents. It is meant to be used to deliver documents small in size, aimed at one particular deliverable, with multiple documents put together into a handbook for any particular project. The clause layout makes them computable: 1. Applies; 2. Select; 3. Except; 4. Require.

The overall structure divides the content into 3 Framework sections as shown in Table 1 below:

<table>
<thead>
<tr>
<th>Framework Section*</th>
<th>Level of Responsibility</th>
<th>Topic</th>
<th>Description</th>
<th>Application Example (UK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic</td>
<td>Principals</td>
<td>Outcomes (Outputs)</td>
<td>Intended Deliverable from BIM</td>
<td>Employer Information Requirements (EIR)</td>
</tr>
<tr>
<td>Management</td>
<td>Design Management</td>
<td>Controls</td>
<td>Management of BIM</td>
<td>Project Execution Plan (PxP)</td>
</tr>
<tr>
<td>Implementation</td>
<td>Design Team</td>
<td>Inputs (Data)</td>
<td>Operational Requirements</td>
<td>Digital Plan of Work (DPoW)</td>
</tr>
</tbody>
</table>

*Table developed by author to harmonize content and verbal descriptions of content

Under the three (3) framework sections, three (3) levels of guidance are to be established:
A. International
B. National or Regional
C. Project- or Facility-specific

ISO/TS 12911 was not on the radar of any of the experts within the team when this project began. A goal within the project was to use the comparative analysis to inform a framework for BIM guidance at the
international level. Currently, ISO/TS 12911 has been brought to the team’s attention as definition of said framework. Therefore, the team has efforts underway to continue to evaluate the applicability of ISO/TS 12911 to this body of work. Current discussion includes accepting this body of work as a technical standard of a technical standard compared to the fundamental definition of what a guide is.

4 DISCUSSION

Harmonization of content (and concepts) when coupled with end-user consensus is a powerful tool to achieving standards and best practices that are respected and used within industry practice. It is not the project’s goal or vision to see one single guide as a standard. Instead, the project team sees value in focusing on key parts that can benefit from the standardization process. The idea is to have a tool available for creation of BIM guidance documentation based on standard terms and structure, with access to sample content referenced from existing sources. In doing so, a “standardized” approach can be taken to align all the various activity and achieve a compendium of (searchable) best practices without diminishing the need for guides to be localised.

Prior to this effort there was no single place to go for this information nor has there ever been an established set of criteria, or methodology, for the comparative analysis of guide documents. It is wasteful for practitioners to attempt to read and digest all the available material each time they wish to validate previous work accomplished. Likewise, it is unreasonable to expect those looking for guidelines for a specific purpose to adopt an existing document without assessing its suitability relative to ‘what is out there’.

The project could help answer the following questions:
• How do you know what guidelines and best practices have been developed throughout the world related to Building Information Modelling?
• Some of these guidelines are based on previous efforts; what is their relationship to them?
• How do you ensure that new initiatives are taking advantage of previously accomplished work?
• What International Standards are in place, and which ones have an impact on BIM?
• How can you align your work efforts with best practices already in place?
• How do you ensure you are not reinventing the wheel when developing a new business practice?

The challenge with this project is identifying sufficient funding and resources to achieve the goals. Alignment to existing research cells, terminology groups and educational curriculum development would help broaden its reach and refine its implementation.

4.1 Highlighting BIM as a Process

This project is a way of building up standard parts and best practices based on industry use and acceptance. What it also does is highlight BIM as a process. The purpose of guides is to direct and inform the end-user on tasks, deliverables, processes and practices. Through review of guide content and then building a purpose-specific guide, BIM as a process is highlighted.

4.2 Client-specific needs

A strength of the project is the goal to engage directly with authoring organizations as well as to provide a tool for them, and industry at large, to use. It is expected that this project will help raise awareness, provide an educational role, and be a guide in itself for industry’s uptake and standardization around BIM terms, concepts, processes and frameworks.

That said, it should be explicitly recognized that each client has specific needs. By providing a framework and harmonized concepts and definitions, the client is free to tailor their guide to their needs in a standardized way. As the project is launched and we are better able to gauge industry uptake, we can better determine where specific value is being achieved (or not) and develop additional functionality accordingly.
Authors and authoring organizations in support of this project can expect the following benefits:

- added visibility to their organization and published guide(s);
- harmonization of content across global BIM guides, including terms and definitions;
- informs future versions of their organization’s BIM Guide documentation;
- contributes to standards development; and
- supports industry adoption of BIM.

4.3 End-user acceptance

A guidance document has to be user-friendly. User-friendly means easy to use, operate and understand. A certain level of standardization as outlined in this project can help to produce guides that are more user-friendly and predictable. End-users typically have to follow a different BIM guide for every different client or even project. Having guides that follow a standardized structure and employ the same definition of terms would make it easier on the end-user and would support end-users delivering the BIM aspects of their projects more consistently across the board.

4.4 Showcasing the use of open standards

The project team have discussed and agreed that under the banner of buildingSMART International, “the home of open BIM”, showcasing the use of open standard end deliverables should take precedence to proprietary-focused guides. Whereas there is value in BIM guides with proprietary deliverables outlining important process changes and collaboration methods, there is also a need to recognize milestone deliverables versus final project deliverables in terms of open standards. It’s not always a clean cut, and it’s important to recognize that disparity continues to exist around the world on the functionality and usability of Industry Foundation Classes (IFC) deliverables without also including the originating platform files. Certainly, needing to highlight uses of IFC as the final deliverable are needed to dispel the myth that IFC and open standards don’t work.

4.5 The need for a degree of standardization within guidelines

Although there will always exist discussion around the ‘degree’ to which standardization is important or practical, certainly a basic requirement is to achieve greater consistency and compatibility between guidance documents.

As mentioned, there is a sweet spot to hit between the flexibility required for clients to define their unique requirements and all end-users having a baseline standard to work from. It seems logical that any end-user would accept an easier way of working.

4.6 Guidelines use as a medium for education

At a minimum, guidelines have an opportunity to link to further discussion on topics relative to the end-user level of competency and experience. They are informative, descriptive and cater to a specific audience for a specific need.

Guidance documentation can serve a needed role in the following areas:

- help owners/clients define their needs;
- communicate corporate and/or project requirements; and
- educate industry (or other members of the client organization) on BIM processes, deliverables, technology requirements, among others.

5 CONCLUSION

Within the construction and facilities industries, each client feels they do things differently. And they do – to a degree. But doing things differently without attempting to identify commonalities and standard pieces does nothing to improve overall industry productivity. Likewise, authoring organizations, in pursuit of their
own guide, often would like to build off existing ‘de facto standard’ content, but don’t have access to a database or tool that does this.

This project is a unique opportunity for industry to be engaged in the process of standardization. It leverages existing content being used as ‘de-facto’ standards, and sets out to achieve harmonization of concepts, terms, definitions and the overall structure or framework that guidance documentation is delivered within. What is exciting about it is the level to which industry can be engaged and learn from the process, with an eye to making achievements in efficiency and productivity.

Acknowledgements

This project has been developed out of the work started in the US-NBIMS Planning Committee (Chris Moor, Former Chair of NBIMS), and specifically within the Product Development Subcommittee (Susan Keenliside, Former Chair of NBIMS-PDS), supported by Deke Smith (Former Executive Director, buildingSMART Alliance). The NBIMS-PDS had already begun to do reviews using the template approach, and it was within the PDS that this work was recommended to be elevated to the bSI forum for international participation. The Process Room group adopted the methodology used by the NBIMS-PDS and agreement was made to move ahead with the guideline reviews and create a wiki to support it at the buildingSMART International Technical Summit Process Room meetings in Munich, Germany, in October 2013, and taken on by Sylvain Marie (VTREEM, France). The current bSI BIM Guide Project team includes (alphabetical order by first name) Deke Smith (United States), Ghang Lee (Republic of Korea), Jan Karlsheoj (Denmark), Mark Baldwin (Switzerland), Neil Greenstreet (Australia), Nick Nisbet (United Kingdom), Steen Sunesen (Norway), Susan Keenliside (Canada), Sylvain Marie (France), and Tomi Henttinen (Finland). Thanks to the NBIMS-US PDS members that contributed to the original project: Alan Redmond, Andrew Baranowski, Andy Smith, Chris Moor, Dominique Fernandez, Igor Starkov, Jason Reece, Jeffrey Ouellette, John Grady, John Messner and Monte Chapin. Special thanks to those who participated independently or as past-members of the team: Ingo Kittel, Zeynep Aydin.

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HOW WELL DID A MULTI-STAKEHOLDER MANAGEMENT FRAMEWORK FOR REMOTE SITES MODEL THE REALITIES ON AND OFF-SITE OF A SCOTTISH HIGHLANDS INFRASTRUCTURE MARINE PROJECT - REFLECTIVE CASE STUDY

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Abstract: The next 20 years will see inward investment of up to £100 billion in construction (and energy) projects in northern Scotland, particularly in the Highlands and Islands. The majority of these projects will take place in locations which are, to a greater or lesser extent, remote. However the performance of many remotely-sited projects across the world highlight the need for more effective management strategies and models. The multi-stakeholder management framework for remote site projects, developed by Kestle (2009), synthesised production and sociological design and management approaches, and has already been tested and validated on Antarctic, humanitarian aid and post-disaster reconstruction projects globally. Participants for this research were designers, construction, and project managers involved on a commercial scale marine infrastructure project in the Scottish Highlands. Semi-structured interviews were conducted and the findings analysed to establish and reflect on whether the framework modelled the realities on this remote site project, and actually provided the value-added sought by the multi-stakeholders involved. The findings suggested that the stakeholders’ value criteria expectations were indeed met, and that the management framework did reflect the realities of designing and managing this particular remote site project.

1 INTRODUCTION

Design and construction processes have become more complex and fragmented over the last few years, resulting in an increasing need for a shared and early understanding of the project objectives amongst the stakeholders. What is valued in the project, significantly impacts upon how and when decisions are made on design/construction issues. In the design management field the integration of those who have knowledge that contributes to the design, construction and management, is critical to developing and achieving value on projects. The added dimension of remote site projects, increases the complexity, and makes early decision-making; knowledge integration; logistical implementation planning absolutely critical and central to the potential success, or failure, of the project. The project team has to not only address the traditional management problems, but also those that specifically occur as a result of the remote locations of these often environmentally, and politically sensitive sites (Kestle, 2009).

The selected project for the this reflective case-study was the Ullapool pier improvement project, as it met the majority of Kestle (2009) typological criteria for remote sites, and aim was to utilise the Kestle (2009) management framework to establish and reflect on how well it modelled the realities of designing and managing an innovative infrastructure marine project in the remote Scottish highlands.
2 THE BASIS OF THE KESTLE (2009) MANAGEMENT FRAMEWORK

The development of the conceptual design management model (for remote sites), was in part a response to a call by design management researchers Koskela et al. (2002) for example, for research collaborations that improved the discipline of design management, and provided a solid conceptual foundation. Similarly, Winter et al. (2006) observed that “theories about practice can also be used as theories for practice”. In particular it was suggested that future research needed to focus on ‘in the field realities’ and offer practitioners realistic and contemporary management frameworks, that helped deal with the complexity issues of projects in the ‘midst of practice’ and recognised that an interdisciplinary approach was useful.

The conceptual model by Kestle (2009), was originally informed at the exploratory stages, by the key concepts and principles of design management and lean design management literature, and developed in conjunction with a typology for remote site projects (Kestle and London, 2002). The latter involved investigations into three historical project case studies on remote sites in Australia (Kingfisher Bay eco Resort), New Zealand (Tongariro National Park huts and ski lodge sites), and the Ross Sea Region scientific bases in Antarctica. The end result was a theoretical conceptual model which highlighted the factors or drivers that needed to be considered in the development of a conceptual design management model for remote sites (Kestle, 2009). Those factors were value generation, knowledge integration, process integration and timely decision-making, and were arrived at by contextualising the typological descriptors for remote sites, identifying the contributions made by the sociological and production oriented worldview literature, and in turn became the synthesis described by the four factors/drivers for the theoretical model.

Conceptual Design Management Model for Remote Sites (Kestle, 2009)

'Value Generation' - refers to the value that the client and stakeholders place on the project outcomes, and will vary according to the differing clients’ and stakeholders’ expectations of the projects, and these can vary not only between stakeholders but also between client groups.

'Knowledge Integration' - is concerned with capturing and integrating the specialist knowledge of all those personnel involved on a particular project, prior to and during the project phases. This suggests that key personnel be involved with any pre-briefing, pre-planning, and in the regular monitoring and review of the planning and operational stages, as the project progresses. Specialist knowledge is required to ensure the best solutions and results, despite frequently working with non-negotiable timelines.
‘Process Integration’ - involves the timely and cost-effective co-ordination and planning of a range of processes across the total project, such as planning methodology, logistics, information management, and the management of design/production interface. Logistical planning and implementation is complex, as well as critical in post-disaster response and recovery coordination.

‘Timely Decision Making’ - refers primarily to financial and design decisions, which are critical to the successful management of collaborative international projects. These decisions are made within the context of frequently non-negotiable windows of buildability timeframes, fixed or controlled budgetary constraints, and/or health and safety concerns.

The (doctoral) design management model for remote sites by Kestle (2009), has now been used for a few years as a management framework/tool on a range of multi-stakeholder international projects to gather data from in-field personnel and compare the in-field realities with the designers’ and managers’ pre-construction stage design and management planning for the project, in order to add to learnings from these remote site and often environmentally sensitive projects.

Researchers Salvatierra et al. (2010), recently noted that the concept of value varies across time, is context dependent, is relative/comparative, and very subjective, and tends to be restricted to just achieving value for end-users and clients, rather than society as a whole. Salvatierra et al. (2010), also referred to research by Ballard (2006) who was working on a model of project definition with a value generation perspective and which gives importance to the stakeholders’ perspective of value.

The stakeholders’ involvement is considered a key element in generating value, therefore it is important to underline the contribution of Emmitt et al. (2004), where the concept of value was divided into ‘external value’, which is the client/customer value, the value that the finalised project should have achieved, and the ‘internal value’ achieved by, and between the delivery team. The Kestle (2009) management framework, and the research work by Kestle published in Emmitt (2012), referred to adding-value, and that the integration of a team with knowledge contributing to planning, design, construction and management, was critical to developing and achieving value on projects for the client and stakeholders.

3 METHODOLOGY

The decision to undertake a reflective case study of the ‘Ullapool harbour pier/berthing improvement’-a marine infrastructure project in the Scottish highlands, was made on its perceived ability to resonate with the Kestle (2009) management framework and provide data and insights into how well the framework resonated/fitted with this multi-stakeholder remote site project.

The qualitative data were collected using semi-structured interviews with 5 selected participants and these were later codified, and analysed to identify whether and how the stakeholders’ added-value expectations had been met, and if the management framework did in fact reflect the realities of designing and managing this particular remote site marine infrastructure project.

Participant selection for this research was made on the basis of the participants’ roles and disciplines, and whether they played a management role, and/or were key players on the Ullapool Harbour Pier Improvement project in the Scottish highlands. The selected participants were stakeholders, designers, construction managers and project managers. The aim of the participant selection, and subsequent qualitative semi-structured interviews with them in September 2014, was to try and establish the participants’ perceptions and realities of their first-hand experiences in the design office, and in-the-field, and how the project ran, on reflection, and whether and how value was added for the various stakeholders. The interviews ran for a minimum of an hour and thirty minutes per participant, using the ethically approved open-ended interview questions (refer Appendix A). The interviews were conducted within the context of the participants’ official roles on the project. This involved exploring the management approaches, the challenges at the pre-planning and operations stages, the reflections and learnings from the project in Part A, and seeking detailed participant responses to the relevancy of the four key factors of the Kestle (2009) management framework to this particular project in Part B.
4 RESULTS AND REFLECTIONS

4.1 Overview of the case study project

The project, located in the northwest Scottish highlands was initiated by the clients/stakeholders (Ullapool Harbour Trust, Stornaway Port Authority and CEMAL (Caledonian Maritime Assets Ltd)/CalMAC - Caledonian, Macbrayne ferries), as a result of a decision to increase ferry passenger capacity between Stornaway and Ullapool, and which involved the commissioning of a new 13000 tonne, 115m long ferry for delivery in late 2014. The new ferry weighed 50% more than the existing ferry, and was15m longer. There was originally only one pier, and one linkspan at Ullapool, whereas there were already two piers at Stornaway, hence the decision by the various Port and Ferry service stakeholders to extend the current Ullapool pier by 35m, and call for interested marine infrastructure designers to compete for the appointment to design and manage the tendering of the project.

4.2 Key factors for consideration and resultant design challenges

The Ullapool pier and berthing improvement project was designed, consented and tendered in the period from 2010 till 2013. Factors for consideration included the fact that winds are often over 25knots. This fact had previously meant 1/3 to 1/2 of existing ferry sailings being cancelled, so the capacity of the new pier extension thrusters needed to be increased for when winds are over 25 knots to help the ferry when reversing into the extended pier. The berthing velocity needed to be 0.2m/s, as the energy absorption of the current pier of 3500 ton displacement, could not resist the 6054 tonne displacement of the new ferry. Hence new and innovative 8m long fenders, known as ‘parallel motion fenders’ were designed and installed on the pier extension. According to the interviewed participants, energy absorption is absolutely critical when designing piers. The design of the fenders had to be undertaken first before any of the other considerations were addressed, and the fenders were only to be attached once the caisson was installed at the Ullapool pier. The thickness of the caisson walls was critical as well, too light it would fail under hydrostatic pressures, too heavy and it might sink.

4.3 Stakeholder criteria and consequent impacts on the type and installation of the pier extension structure

Avoiding disruptions to the use of the harbour by ongoing ferry passenger services, cruise ships, fishermen, tourists, and avoiding disruptions to tour bus operations, and local residents’ and businesses, was absolutely pivotal to meeting the stakeholders’ value criteria/added expectations of the project. Therefore, after several piling options were considered, the decision was taken to increase the budget to facilitate the construction of a 35x14mx15m high caisson off-site, some 140miles/230 km away at Greenock, Glasgow and float it north along the coast to the Ullapool pier over a 2.5 day period. This called for design, construction and logistical innovations, to ensure that the right design solution, safe delivery and installation at Ullapool. The risks were significant, on reflection, according to the participants, given the fact that this off-site prefabrication and delivery approach was a first, the dramatic off-shore coastline to be navigated, the unpredictable weather, challenging spring tides, and the constant risk of capsize of the 4000 tonne caisson that consisted of 12 cells filled with water ballasting to weigh it down sufficiently for the trip to the pier site. When the caisson was floated in a fenderless state to the pier, there were on average 5.5m tide changes.

4.4 Management Frameworks, Pre-planning, Operations, and Communications

In summary, neither the designers, nor contractors operated a hierarchical management framework. Instead teamwork, partnership, a no-blame organisational culture, and an open-company approach was the norm. The resultant pier improvement project personnel were a team of informed, included and acknowledged staff, sub-contractors, and clients/stakeholders. Significant pre-planning was a constantly held view by participants of how and why the project succeeded in meeting stakeholder expectations. Pre-planning by the designers and contractors included extensive, thorough, albeit exhaustive detailing of every element, component, pre-fabrication process, operational logistics, installations, coordination of trades at the pier and foreseeing harbour-use contingencies. Communications were collaborative,
inclusive and regular during all of the design and operational stages. All the design and construction staff were expected to be quick problem-solvers and deal with any problems immediately. Daily communication meetings were held between the client, designers and contractors once site work commenced, resulting in positive progress, open frank discussions and collaborative decisions, resulting in a very positive work environment and best end product. Staying on top of the details was suggested as another reason for the success of this (and other) project(s), and was a commonly held view amongst the participants’

4.5 Reflective Analysis of the (Part B) management framework factors’ findings

a) Value Generation

The clients and stakeholders non-negotiable value criteria were that this project had to be completed by August/September 2014, for the new ferry service to potentially commence late 2014, and that there be minimal disruption to ferry schedules, any and all harbour users, tour operators and local residents.

In addition, the Ullapool pier improvement project had to be well project managed, timing and keeping to budget was also absolutely critical for client/stakeholders. All of these criteria were met, and the ongoing feedback from clients/stakeholders as work progressed, and as it completed have been very positive on all counts. The off-site caisson decision was the right one as was the decision to award the contracts to the successful designers and contractors who paid significant attention to pre-planning, detailing, logistics and an inclusive non-hierarchical team approach. The resultant was a project that met all of the stakeholders’ and client’s value criteria – no disruptions to harbour users, met the strict timelines and was definitely fit for purpose.

b) Process Generation

This project was all about forward planning and logistics from a process integration perspective - building the 35x14x15m high caisson off-site at a considerable distance (230km) from the pier site, and then also ensuring that the pier was ready to receive the caisson. The work platform was very tight (35x14m), with 4 very different contractors there at any one time, including teams of divers, grit blasters, concrete pumpers, and crane operators. A total team involvement, including the designers, clients, designers, contractors, sub-contractors, caisson prefabricators et al from day one, and even before day one, was obviously key to the successes achieved within the very tight 6 month construction timeframe, embracing specialised design and construction innovations, and logistical risks.

c) Specialised Knowledge Integration

The fact that the designers and contractors’ had previous specialist pier experience, even though the caisson approach was a first for them. Apart from the prefabrication of the caisson, the project utilised local people, local knowledge/solutions, and local networks proved invaluable for this project from the stakeholders’ perspective. Specialist knowledge was definitely needed though on this site, for example, previous and detailed knowledge of ground conditions under the future caisson position, ballasting specialists were essential, divers experienced in attaching anodes to the steel piles and thence to the caisson, painting and concreting below water, and the need for very specialised marine specific IT knowledge. Early contractor and sub-contractor involvement with local knowledge across all or most of the tasks was invaluable on this project. Achieving demanding ‘tolerance controls’ under water for caisson work was a significant lesson learned for future projects according to the participants.

d) Timely/Critical Decision Making

The start time in January 2014 was a difficult time of the year to start such a project, being winter, and northern Scotland. However, according to the participants the extensive pre-planning meant that everything went as planned in terms of the caisson and foundation aspects of the project. Funding constraints meant that monies had to be spent by the end of March, so working through some of the worst months weatherwise, with limited daylight was a real challenge at times. Deferring end-budget to
end-summer might help future projects. However, in future a new challenge for infrastructure projects is that consents have to be in place before any funding is sought. Decisions were always made cooperatively and collectively between on-site and off-site personnel, and were always unambiguous in terms of the tight construction times and tides, creating trust, buy-in and best solutions. Delegated authority was key. Workable tides only ever occurred 3 times/fortnight, which together with strong seasonal winds created pressure points on the project that had to be met, no question. This was particularly important, as it significantly affected decisions around when diving operations could be undertaken, especially painting, anode attachments, and concreting activities best conducted at those lower tide levels.

4.6 Overall reflections, learnings and relevance of the model to the focus project in the Scottish highlands

The client/stakeholder representative provided feedback at daily meetings with the on-site including the designers, and this at times included off-site staff as well. This in their view resulted in clear and timely communications throughout the project, and avoided potential misunderstandings and programming holdups. In terms of the pre-planning, it was noted by the participants that the designers, client, stakeholders, the potential contractors and sub-contractors were meeting regularly around the table. At these meetings the potential contractors were made aware that they had to provide a method in their tender for the caisson, rather than for piling, and had to demonstrate and explain how they planned to mitigate disruptions to all the harbour users. The caisson approach was a new experience and challenge for those who had been involved with previous pier construction, so it carried a modicum of risk and the chance for innovation as well. The resultant design, logistics and construction methodology worked well according to the stakeholders and the participants interviewed. The caisson was floated into position in June 2014, and the completed project handover was 25th September 2014, meaning the project was on-budget and well ahead of the scheduled ferry delivery time in late 2014.

The participants all commented that the four factors did in their view model the key aspects of the design and management on and off-site for this project, and when undertaking a multi-stakeholder remote site projects. Participants were quick to identify ways in which the process integration, value generation, specialist knowledge and timely/critical decision making applied to this and other remote site projects that they had been involved on, and often answered giving some in-depth examples. They found the semi-structured interview research process very useful in terms of offering them a chance to reflect on their experiences and identify the areas of reassurance around their on and off-site practices, and the lessons learned from the Ullapool pier improvement project. One of the commonly held views amongst the participants in terms of best practice management of the project, was how well the collaborative approach involving all the on-site and off-site staff, and stakeholders had worked, both before and during the construction stages.

5 CONCLUSIONS

The objective of this research was to establish and reflect on how well the Kestle (2009), multi-stakeholder management framework for remote site projects modelled the realities/experiences on and off-site, and added value for the stakeholders in terms of their expectations and requirements, on the Ullapool pier improvement project in the Scottish Highlands. The methodology undertaken involved conducting semi-structured interviews with designers, stakeholders, construction and project managers on the pier project, in September 2014 as the project concluded, and was handed over to the client/stakeholder representatives. The findings suggested that the reasons for the project achieving the stakeholders goals and a value-added result resided in the extensive pre-planning, thorough detailing, quick problem-solving, and working collaboratively at all times across all the players, before and during the construction stages, therefore keeping everyone informed on a regular often daily basis. In addition, specialist knowledge of pier design and construction, local labour, local networks, and the local challenges (such as tides and weather, ground conditions), were invaluable to the success of this project being delivered to budget, to stakeholder criteria, and well ahead of schedule in readiness for the new ferry at this remote site location in the Scottish Highlands.
Acknowledgements

Thanks go to Kate Hayes in Scotland for contacting a selection of potential participants to be a part of this particular research paper.

References


Appendix 1

INTERVIEW SHEET

Part A
The focus of this part of the interview is on the official role that you play(ed), from a management/managed perspective.

Name of Interviewee                                                         Date
Name of the Project

Q1
In your role (and your official capacity) as ............................................ on this project, please identify
a) Your job description, briefly, in terms of your key responsibilities on this project, and how they may have changed during the course of the project.

b) If there were changes during the course of the project, how did these impact on your role and/or on the project overall

Q2
(a) What in your official role, were the main (management) challenges that arose during the project. Please answer this question as concisely as possible, under the bulletted headings below.

• Management framework and approaches,
• Pre-planning and detailed planning stage(s)
• Operations stage
• Communications
• HR
• Funding
• Other challenges
(b) Recommendations / lessons learned for future projects

Part B
The next few questions are related to the exploratory conceptual design management model/framework developed by Kestle (2009) for multi-stakeholder international remote site projects.

Please find a copy of the model/framework attached to this questionnaire, as we would like to test some of those ideas with you relative to this particular project.

Q3
In terms of this Project in particular, and your role on that project, please comment on:

a) Value Generation – (the value that the client/stakeholder places on the particular site and the project, and the value various roles add to the outcomes)

• what are/were the clients value criteria,
• what are/were the stakeholders value criteria
• how do you know or measure the effectiveness of your role on this project
• are there any rules-of- thumb that you intuitively apply(ied)
• how and what type of feedback do you get/ have you received from clients
b) Knowledge Integration - (a combination of relevant specialist knowledge across IT, design briefing, pre-planning/early contractor involvement and at the construction/operational stages)
• specialist on-site construction knowledge expectations/challenges
• IT for remote site coordination challenges
• are there gaps in the specialist knowledge that you are aware of in your area of involvement on the project, and if so what
• how is what you have learned on this project passed on to others during the course of the project, and for future projects
c) Process Integration
• logistics and site accessibility challenges
• design and the production interface challenges construction/operational planning/methodology
• alternative procurement strategies
• what methods or approaches do you employ to achieve your goals and fulfil your role
• how have you improved/added value to this approach, or to the system(s) used
• what role does HR play, or could it play (staff training /upskilling)
d) Decision Making
• how are the decisions made – and are they decentralised or centralised
• what are the expected performance criteria expectations on staff and their accountability
• are there limited operational windows, and if so when and why do they occur
• what are some of the economic constraints (are there tight/impossible budgets?) and how are budgets maintained
• how are any environmental sustainability sensitivities of the site, and likely impacts addressed and managed

Q4 Other comments, that you consider may be relevant to this research
CHALLENGES AND OBSTACLES FACING TENDERERS ADOPTING E-TENDERING IN THE PUBLIC SECTOR OF THE CONSTRUCTION INDUSTRY IN EGYPT

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Abstract: The construction public sector in Egypt, like most countries in the world, is tendering its projects through the traditional paper-based tendering procedure, which has many weaknesses including bureaucracy and lack of transparency. Due to the considerable volume of projects tendered each year, it was essential to study the possibility of implementing another more efficient mechanism “E-Tendering” that overcomes the drawbacks of the paper-based tendering procedure. This on-going research examines the readiness of the construction industry in Egypt to adopt E-Tendering for public tenders and provides recommendations to improve its uptake. This paper provides a model of the barriers, challenges and concerns of the Egyptian tenderers towards accepting and adopting E-Tendering. This is accomplished through extensive review of the literature together with expert identification and analysis. 19 challenges are highlighted and categorized into 4 categories: security challenges, user acceptance and staff resistance, accessibility issues and legal barriers. These challenges are then examined and ranked with respect to their importance by a panel of academic and industry experts to reflect the Egyptian public tendering context. The most important highlighted barriers are the SMEs access difficulties, the expected technical malfunctioning of the portal, the reluctance/resistance to change and the breach of confidentiality of information. These findings present a cornerstone in the development of a framework that presents practical solutions to the success of E-Tendering for the construction public projects in Egypt.

1 INTRODUCTION

The construction industry in Egypt is one of the most active and dynamic sectors of the economy. It accounts for 7% of the Gross Domestic Product (GDP) and by the year 2015, the investments in this sector are expected to reach US$7.3 billion (General Authority for Investment and Free Zones [GAFI] 2014). Unfortunately, a number of research have shown that bribery and corruption are rampant in the construction sector worldwide according to Transparency International’s 2002 to 2011 Bribery Payers Index (BPI) (Hardoon and Finn 2011). Concerning Egypt, the European Bank for Reconstruction and Development (EBRD) has published a report in 2013 containing a review of its public procurement practices. The report highlights that companies in Egypt face a high risk as the procurement process is burdened with lack of transparency, bureaucracy, ineffective monitoring and review mechanisms together with unethical public procurement officials (Business Anti-Corruption Portal 2013). Moreover, it is argued that the traditional paper-based tendering process in Egypt is full of inefficiencies (EBRD 2013). It is also worth noting that according to the Canadian Construction Association (CCA), in a typical construction
project, the cost of tendering to a client accounts for up to 5.85% of the total cost of a project (Hore et al. 2007).

Consequently, it is imperative to find a more efficient mechanism to replace/complement the traditional paper-based tendering processes of the construction public works in Egypt in order to reduce the considerable cost of tendering, save lots of money wasted due to the inefficiencies of the traditional tendering, increase transparency, and reduce corruption in the public sector. The proposed solution is the adoption of E-Tendering.

2 E-TENDERING IN CONSTRUCTION

2.1 Definition and processes of E-Tendering

According to the Royal Institute of Chartered Surveyor (RICS 2007), the basic principles of traditional tendering are preserved in E-Tendering while enhancing the way of communication through finding an alternative medium through which the tender documents and information are exchanged. This medium is further defined by Amarapathy et al. (2013) as E-Tendering portals that are “secure dedicated websites, specifically set up for the exchange of information and tender documents electronically over the internet”. The ultimate goal/objective of E-Tendering as clarified by Amarapathy et al. (2013) is a complete shift from paper-based manual tendering, to fully automated electronic means of communication. This would significantly decrease or even eliminate paper handling, speeding up interaction and communication between the different parties involved, and hence increases productivity and efficiency (Seah 2004). Technically, the E-Tendering concept/process combines a number of processes that take place before the award of the contract. It mainly involves E-Notification, E-Access, E-Submission, E-Evaluation, and sometimes E-Awarding.

2.2 Advantages/Benefits of E-Tendering

Kajewski and Weippert (2004) cited the NSW Government and Department of Commerce highlighting the benefits that construction professionals and governmental departments/agencies could gain when implementing Electronic Tendering processes. These benefits and advantages are grouped in 3 categories: General Perspective, Industry perspective and Government perspective.

General Perspective: streamlines the entire tendering process; provides secure and improved access to tender documents; makes it easier for businesses to obtain tender documentation and to submit an offer online on time as the postal system is no longer needed (Lavelle and Bardon 2009); maintains an audit trail of all communication (RICS 2007); virtual elimination of errors due to strict process (MERX 2014); ability to automatically eliminate noncompliant bids, hence saves time (MERX 2014); saves money and time as the electronically submitted tenders are downloaded in a suitable form that facilitates evaluation without requiring the client’s representatives to re-enter the data manually.

Industry perspective: increases tender opportunities, competitiveness and promotes transparency; provides easy and fast access to private and public tender information; facilitates remote accessibility to the tendering system which improves access for geographically isolated industry practitioners/organizations (Amarapathy et al. 2013), and hence assures fairness regardless the tenderers’ geographical area (MERX 2014); reduces the cost of printing and copying which saves time and resources (Lavelle and Bardon 2009).

Government perspective: better value for the money of the taxpayers; increases effectiveness and efficiency; standardizes the tendering processes across the government; promotes E-Government initiative; environmentally friendly due to a predominantly paperless process, so no waste generated (RICS 2007).

In addition, Lavelle and Bardon (2009) demonstrated additional benefits for E-Tendering such as the reduction in administration processes via providing one single source of information. Consequently, duplication of documents does not occur and any revisions to the documents are kept track of and notified to the tenderers as audit trail/log is provided through the system. Moreover, Tindsley and Stephenson (2008) indicated that E-Tendering can provide full automated assessment with computerized analysis, hence, fairer and faster evaluation of the tenders submitted. Also, the system could automatically identify incomplete or unusual entries, thus reduction in communications and faster analysis
as well. Furthermore, according to the International Data Corporation (IDC) (2013), EU public contracts
tendered electronically and processed with electronic submission were 13% lower on average than public
contracts traditionally tendered.

3 RESEARCH AIM AND SCOPE OF THIS PAPER

In many developing countries, E-Tendering is regarded as unnecessary and unfeasible given the number
of social, cultural and economic barriers that are expected to hinder its implementation. So this on-going
research investigates the readiness of the construction industry in Egypt to adopt E-Tendering and
provides recommendations for its implementation.
The scope of this paper is limited to the identification of the barriers, challenges and concerns of the
tenderers towards accepting/adopting E-Tendering in Egypt.

4 RESEARCH METHODOLOGY

Since this is an exploratory research in nature, qualitative approach is adopted in identifying from the
literature a list of the most common challenges that influence the tenderers' acceptance/adoption of E-
Tendering worldwide. These challenges are then categorized in 4 categories: Security Challenges, User
Acceptance and Staff Resistance, Accessibility Issues and Legal Barriers. The list of identified challenges
is then presented in a form of a survey questionnaire to a panel of 15 knowledgeable experts in the field
of tendering in Egypt in semi-structured interviews. The experts were required to mark/check on a 5-scale
Likert item the probability/likelihood that a tenderer considers the challenges as obstacles against the
adoption of E-Tendering in Egypt. The survey output is analyzed using the adjusted relative importance
index to identify and rank the highest obstacles against the tenderers. Hence, the sampling design used
is non-probability sampling and more specifically purposive sampling. The expert interviews are
conducted since their expertise and experience add more depth to the research taking place. The panel
of experts is composed of academic and industry professionals, which included consultants and
contractors. The experts are selected based on their expertise in the field of tendering in Egypt and based
on the criteria and they carried out/participated in more than 50 tenders.

5 THE IDENTIFIED CHALLENGES/CONCERNS OF THE TENDERERS

The preliminary findings for the barriers, challenges and concerns of the tenderers are grouped in the
following 4 categories: security challenges, user acceptance and staff resistance, accessibility issues, and
legal barriers. These challenges/barriers were developed and grouped after extensive review and
analysis of the literature in order to identify the barriers hindering the adoption of E-Tendering.

5.1 Security Challenges

- Document tampering i.e. when a person makes unauthorized and unfair modifications to the tender
  (Eadie et al. 2010).
- Problems with data integrity after reassembly - possibility of inaccurate, incomplete, corrupted data
  after reassembly (Davila et al. 2002).
- Confidential documents getting leaked to competitors (Davila et al. 2002).

5.2 User Acceptance and Staff Resistance

- High investment costs to adopt and maintain E-Tendering with no substantial benefits realized
  (Samuelson 2008).
- Reluctance/Resistance to change i.e. general attitude that old ways of doing things have worked well
  throughout the years and changes are unnecessary (Olukayode and Adeyemi 2011).
- Unethical investors and corrupted officials will fight to continue with the traditional paper-based
  tendering which is full of leaks (fear of potential loss of bribery) (Mastor et al. 2006).
- Automation is a threat to the employees' jobs.
• E-Tendering is more time consuming than traditional tendering.
• E-tendering is an additional workload with no compensation/reward.
• Lack of leadership/upper management support (Eadie et al. 2010)

5.3 Accessibility Issues

• Fear of using non-compatible software with the client/consultant system hence tender submission could get rejected "noncompliance" (Samuelson 2008).
• Irregular electric power supply will affect the E-Tender processes especially the tender submission (Olukayode and Adeyemi 2011).
• A fear that a technical malfunctioning of the portal could cause disturbance to the electronic submission of the tenders.
• Poor telecommunications infrastructure will affect the E-Tendering processes (Olukayode and Adeyemi 2011).
• E-Tendering requires high speed expensive internet services.
• A large portion of the Small Medium Enterprises "SME’s" especially in Upper Egypt are computer illiterate hence will face difficulty to apply, prepare and submit tenders electronically.
• The contractors will bear the costs and responsibility of copying and printing the drawings for the subcontractors.

5.4 Legal Barriers

• Complex, time consuming and onerous regulatory procedures (IDC 2013).
• Problems with proof of intent of the tenderer (Eadie et al. 2010).

6 THE CONDUCTED SURVEY QUESTIONNAIRE

After being introduced to the list of identified challenges from the literature, the experts were asked to check/mark on a 5-scale Likert item, the probability/likelihood that a tenderer considers the challenges presented in the list as obstacles against the adoption of E-Tendering specifically in Egypt. In addition, the experts were asked to identify more challenges/barriers if any.

The scale consisted of the following 5 points:

<table>
<thead>
<tr>
<th>Scoring Number</th>
<th>Scoring Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score 1 - Strongly Disagree</td>
<td>The challenge will strongly motivate tenderers to accept E-Tendering</td>
</tr>
<tr>
<td>Score 2 - Slightly Disagree</td>
<td>The challenge will slightly motivate tenderers to accept E-Tendering</td>
</tr>
<tr>
<td>Score 3 – Neutral</td>
<td>The challenge will neither motivate nor prevent tenderers from accepting E-Tendering</td>
</tr>
<tr>
<td>Score 4 - Slightly Agree</td>
<td>The challenge will slightly prevent tenderers from accepting E-Tendering</td>
</tr>
<tr>
<td>Score 5 - Strongly Agree</td>
<td>The challenge will strongly prevent tenderers from accepting E-Tendering</td>
</tr>
</tbody>
</table>

It is debatable whether the distance between each response in a 5-scale Likert item is equal or not since numerous research provided different conclusions as highlighted by Holt (2014). In this research, the Likert items are symmetric (5-scale) and interval in nature, hence the difference between each response can be considered equal in distance (Holt 2014).
6.1 Data Analysis

The survey output is analyzed using the adjusted relative importance index (RII) to identify the rank (relative importance) of each barrier/challenge hindering the uptake of E-Tendering in Egypt in order to address and tackle them. The adjusted RII equation used in this research is shown in Eq.1 (Holt 2014).

\[ \text{Adjusted percent equation} = \text{RII } \% \text{ adjust} = 125\times\left(\frac{\sum P_i}{N\times n}\right) - 25 \]

RII = Relative Importance index

RII % adjust = Relative Importance Adjusted Percent using scale (Rmin=1 to Rmax=5)

\( P_i \) = Participant’s rating of the barriers/challenges hindering the uptake of E-Tendering

\( N \) = Total number of experts

\( n \) = Highest attainable rating for one trial = 5

The above equation yields “the true percentage for scales where Amin = 1 and, achieve unity (i.e. 0-100 per cent)” as shown below (Holt 2014).

- The minimum rating is RII % adjust = 125\times[15\times1 / 15\times5] - 25 = 0
- The maximum rating is RII % adjust = 125\times[15\times5 / 15\times5] - 25 = 100

Initially, 5 experts were only selected to conduct this survey questionnaire, but since there was variance in the data they provided and each expert added valuable information to the research, it was essential to conduct more expert interviews in order to reach the point where the data converges i.e. limited variance and hence good coverage of the research in consideration. As highlighted earlier, the final number of interviewed experts is 15.

6.2 Results and Discussion

The below table shows that all the experts agree that 16 challenges (RII above 3 or above 50\%) out of the 19 identified from the literature can be considered as obstacles against the widespread adoption of E-Tendering in Egypt; whereas 3 challenges (RII below 3 or below 50\%) are considered a motivation to the tenderers in Egypt. It is important to note that no more barriers were identified by the experts other than the ones that were provided in the list of preliminary challenges provided to them.

The highest challenges against the widespread adoption of E-Tendering in Egypt are the SMEs access difficulties (RII\% = 88.33\%), the expected technical malfunctioning of the portal (RII\% = 86.67\%), the reluctance/resistance to change (RII\% = 80\%), the breach of confidentiality of information (RII\% = 76.67\%), the electronic signature problems (RII\% = 76.67\%) and the document tampering (RII\% = 75\%).

<table>
<thead>
<tr>
<th>Challenge/Concern</th>
<th>RII Adjusted Percent</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMEs Access Difficulties</td>
<td>88.33%</td>
<td>1</td>
</tr>
<tr>
<td>Technical Malfunctioning of the Portal</td>
<td>86.67%</td>
<td>2</td>
</tr>
<tr>
<td>Reluctance/Resistance to Change</td>
<td>80.00%</td>
<td>3</td>
</tr>
<tr>
<td>Confidentiality of Information</td>
<td>76.67%</td>
<td>4</td>
</tr>
<tr>
<td>Signature Issues</td>
<td>76.67%</td>
<td>4</td>
</tr>
<tr>
<td>Document Tampering</td>
<td>75.00%</td>
<td>6</td>
</tr>
<tr>
<td>Lack of Support</td>
<td>73.33%</td>
<td>7</td>
</tr>
<tr>
<td>Irregular Electric Power Supply</td>
<td>70.00%</td>
<td>8</td>
</tr>
<tr>
<td>Poor Telecommunications Infrastructure</td>
<td>70.00%</td>
<td>8</td>
</tr>
<tr>
<td>Software Non-Compatibility Issues</td>
<td>68.33%</td>
<td>10</td>
</tr>
<tr>
<td>Challenge</td>
<td>RII%</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>Corruption Seekers</td>
<td>66.67%</td>
<td>11</td>
</tr>
<tr>
<td>Subcontractors Dependency on Contractors</td>
<td>65.00%</td>
<td>12</td>
</tr>
<tr>
<td>Bureaucratic Regulatory Requirements</td>
<td>61.67%</td>
<td>13</td>
</tr>
<tr>
<td>High Speed Expensive Internet Services</td>
<td>60.00%</td>
<td>14</td>
</tr>
<tr>
<td>E-Tendering High Investment Cost</td>
<td>55.00%</td>
<td>15</td>
</tr>
<tr>
<td>Data Integrity</td>
<td>51.67%</td>
<td>16</td>
</tr>
<tr>
<td>Time Consuming</td>
<td>35.00%</td>
<td>17</td>
</tr>
<tr>
<td>Additional Workload</td>
<td>33.33%</td>
<td>18</td>
</tr>
<tr>
<td>Automation Job Threat</td>
<td>28.33%</td>
<td>19</td>
</tr>
</tbody>
</table>

Shown below is a detailed analysis of each of the challenges together with its corresponding RII adjusted percentage.

1. **SMEs Access Difficulties (RII% = 88.33%)**

There is a great concern that the small and medium enterprises will be unable to participate in the E-Tendering processes especially that smaller enterprises in Egypt are probably computer illiterate and lack the basic needs (computer, internet, etc.) which are necessary for the participation in the E-Tendering processes.

2. **Technical Malfunctioning of the Portal (RII% = 86.67%)**

Given the fact that Egyptians lack trust in any governmental provided service, there is a strong fear that the portal could malfunction (i.e. broken links, service unavailability, slow page load,…) especially during the submission of the tenders. Furthermore, if technical malfunctioning of the portal occurred and it was impossible for the tenderers to submit their tenders, many will be suspicious and will file claims of corruption against the entity running the portal especially that Egyptians nowadays believe in conspiracy theories.

3. **Reluctance/Resistance to Change (RII% = 80%)**

This is a very strong cultural trait in the Egyptians and humans in general. It is always perceived that if old ways of doing things are good, there is no need for going the extra mile and doing something unconventional (i.e. moving to paperless processes) to the norms is unnecessary.

4. **Confidentiality of Information (RII% = 76.67%)**

The experts have a great fear that the confidential data sent to the government personnel before the deadline are prone to breach and leak to other competitors even if the tenders were password protected. This stems from a number of reasons, mainly, that the corrupted people will always find a way and that hackers are unstoppable as they always infiltrate through finding vulnerabilities/weaknesses in the system.

5. **Signature Issues (RII% = 76.67%)**

Most of the experts do not accept putting their handwritten signatures on a document and sending it online (i.e. electronic signature) since their signatures could be copied and pasted on other documents by unethical government personnel or unethical competitors.

6. **Document Tampering (RII% = 75%)**

Almost all the experts agree that sending tender documents online is not safe since their data could be altered/modified by unethical government personnel or by hackers who could infiltrate into the system.
7. Lack of Support (RII% = 73.33%)

The interviewed experts believe that in Egypt the upper management of the companies would not support adopting E-Tendering. This stems from the fact that most of the upper management figures are old people that are not used to have a computerized system; they do not know how to run an electronic system nor have the time to learn it. In addition, it is also important to note that the decision-making figures of the companies, before submitting their tender envelopes to the client, make last second changes (addition or reduction of a certain percentage) to their tenders. Mainly, this happens because they want to make sure no one knows the submitted tender price especially that they fear the presence of corrupted personnel in their companies who could inform their competitors of the submitted tender price. Consequently, these decision-making figures, in case they will not be capable of using the E-Tendering system (i.e. due to complexity, computer illiteracy, etc.) will never trust an employee to deal with a system on their behalf without their full control and awareness.

8. Irregular Electric Power Supply (RII% = 70%)

Unfortunately, there is irregular power supply nowadays in Egypt especially during summer time and this is expected to continue for few more years. The electricity goes down without any notice, for different durations, and in different areas unequally. Consequently, most of the interviewed experts (more than 70%) believe that this irregular electric power supply could disturb the tendering process especially if the tenderers were unable to submit their tender responses before the deadline due to electricity shortage. It is important to note that not all the tenderers have an Uninterruptible Power Supply (UPS) and also the UPS have time limit capacity.

Moreover, sometimes, when there is electricity shortage, the landlines (internet) stop working. Hence, the usage of a UPS will not help in submitting the tender online; unless a USB internet modem is used in addition to the UPS.

9. Poor Telecommunications Infrastructure (RII% = 70%)

This is one of the very important challenges that need to be carefully addressed by the government since most of the experts believe that there is a serious problem with the network of telecommunications in the different governorates in Egypt, which will seriously impact the adoption of E-Tendering. It is argued that some areas do not have internet services at all in Egypt.

10. Software Non-Compatibility Issues (RII% = 68.33%)

Given the fact that the tender response will be electronic/softcopy, not a hardcopy, most of the experts believe that a problem of software non-compatibility between the tenderers' computers and the computer of the client will arise, which will seriously affect the submitted tender documents. In other words, the documents sent from the tenderers, will not open on the computer of the tender evaluators due to software non-compatibility issues (different software, different version of the software, etc.).

11. Corruption Seekers (RII% = 66.67%)

In Egypt, although most of the plans proposed by the different governments are always important to be implemented, one of the major problems that hinder their implementation is that that there is always a strong resistance from within the governmental entities in order to not adopt such plans that could have major impact on the unethical personnel working in the different entities. Also, this problem aggravates when such proposed plans impact negatively the unethical investors and the illegal tycoons who control the market and who would exert all the necessary efforts to halt such plans.
12. Subcontractors Dependency on Contractors (RII% = 65%)

Most of the experts believe that always the subcontractors depend on the contractors in the transmission of the tender documents; in other words, there is no difference in the transition from traditional paper-based to electronic tendering. The experts believe that this dependency negatively affects the contractor as he loses both time and cost.

13. Bureaucratic Regulatory Procedures/Requirements (RII% = 61.67%)

All the experts stress on the fact that the bureaucratic regulatory procedures required by the government are a major reason that makes the Egyptian tenderers uninterested, unwilling and unable to participate in governmental tenders. Almost one-third of the experts believe that the introduction of E-Tendering will not have any positive impact to solve these bureaucratic requirements (the problems will persist in both traditional and electronic tendering). Another third believe that E-Tendering will actually make the process more complex (especially for the proof of intent and authentication of the tender documents - signature) and the last third believe that E-Tendering will make the process much easier (especially concerning the discovery of the tender opportunities and the submission of the tender documents).

14. High Speed Expensive Internet Services (RII% = 60%)

Most of the experts believe that E-Tendering does not require a high speed internet services in order to have smooth operations, however, a number of experts (27%) expect that small tenderers will face difficulties and will have to subscribe in higher bundles than the ones they use.

15. E-Tendering High Investment Cost (RII% = 55%)

Almost 50% of the interviewed experts agree that there is a high investment cost needed in order to operate/function adequately on the E-Tendering Portal. This investment cost includes buying new computers, specific software, licenses, hiring competent personnel, training sessions, etc.

16. Data Integrity (RII% = 51.67%)

Problems with data integrity, which includes possibility of inaccurate, incomplete or corrupted data after reassembly since the tender response is not sent as a hardcopy, is only perceived by 27% of the experts as a challenge/obstacle towards the adoption of E-Tendering. On the other hand, some experts argued that whenever there are problems with the submission of a tenderer, they get contacted by the client representatives to clarify the ambiguities/unclear data in their tender response.

17. Time Consuming (RII% = 35%)

27% of the interviewed experts believe that E-Tendering is more time consuming than the traditional tendering and hence this will be an obstacle against its adoption by the Egyptian tenderers.

18. Additional Workload (RII% = 33.33%)

27% of the interviewed experts believe that E-Tendering is an additional workload since they expect that, after finishing their tender response, they will be required to fill in different forms in order to comply with the tender electronic submission; hence, wasting time without compensation/reward. Furthermore, all the experts affirm that structuring the tender documents in Egypt is too hard to be accomplished.

19. Automation Job Threat (RII% = 28.33%)

Automation of the tendering processes is only perceived by 27% of the experts as an obstacle towards the adoption of E-Tendering since the automation of the processes will have a negative impact on a limited number of jobs within the company (i.e. the secretaries, the drivers, etc.).
7 FUTURE RESEARCH DEVELOPMENT

The next step of this research is to develop a set of recommendations to tackle the obstacles and concerns perceived by the experts. Then verification and validation to the recommendations and solutions should be accomplished.

The verification will examine whether or not the proposed solutions and recommendations are applicable and doable technically. The verification should be accomplished qualitatively through introducing the recommendations to a panel of experts from different fields (computer experts, construction engineering experts, finance experts, etc.).

The validation will tackle the effectiveness of the proposed solutions to address the concerns of the Egyptian tenderers. The effectiveness of the developed recommendations should be validated quantitatively through introducing them to a bigger sample that represents the whole population of the construction industry practitioners to examine whether or not the presented solutions will address their concerns. The sample should include different construction professionals (project managers, quantity surveyors, designers, etc.) and different construction entities (contractors, subcontractors and suppliers).

8 CONCLUSION

This research provides an identification of the barriers, challenges and concerns that are expected to face the Egyptian tenderers when the government reveal its plans of the full adoption of E-Tendering. Further to thorough examination of the literature, 19 challenges were identified and categorized in 4 categories: security challenges, user acceptance and staff resistance, accessibility issues and legal barriers. Then 15 semi-structured interviews with academic and industry experts were conducted and the qualitative analysis showed that 16 challenges (RII above 50%) out of the 19 identified from the literature can be considered as obstacles against the widespread adoption of E-Tendering in Egypt; whereas 3 challenges (RII below 50%) are considered a motivation to the tenderers in Egypt.

Furthermore, the highest challenges against the widespread adoption of E-Tendering in Egypt are the SMEs access difficulties (RII% = 88.33%), the expected technical malfunctioning of the portal (RII% = 86.67%), the reluctance/resistance to change (RII% = 80%), the breach of confidentiality of information (RII% = 76.67%), the electronic signature problems (RII % = 76.67%) and the document tampering (RII% = 75%).

This research is a cornerstone in the development of a framework that aims to identify and address the barriers, challenges and concerns of the Egyptian tenderers towards the adoption of E-Tendering, hence improving the uptake of E-Tendering specifically for the construction public works in Egypt.

References


Abstract: Indoor Environmental Quality (IEQ), being one of the main pillars of sustainability, stretches its effect far beyond ensuring a pleasant environment for the occupants to live in. In fact, IEQ plays a major role in defining the level of productivity within organizations. Recent studies acknowledge the link between IEQ and employees' overall satisfaction at work, and in turn, productivity. The ultimate goal of an ongoing research project is to propose and validate a decision making tool that optimizes office buildings renovation projects based on maximizing occupants' satisfaction with the IEQ conditions at their workplace, and in turn, maximizing their productive time. The first step in this direction requires an understanding of the relationship between IEQ and productivity. This is achieved in this paper through a survey of corporate employees, which provides a correlation between the level of IEQ in an office setting and the overall level of satisfaction with the workplace. The latter is, in turn, correlated with the level of occupant productivity at work, as measured by the amount of productive time. The paper concludes with an empirical model based on statistical regression analysis, depicting the relationship between IEQ satisfaction and productive time.

1 INTRODUCTION

The overarching objective of any for-profit firm is to maximize profitability. The cost of employees is considerably larger than any other cost incurred in running most businesses. In fact, the cost of employees is more than 130 times the cost of energy in a typical workplace, and is 85% of the total costs incurred in a typical office building (Annika et al. 2013). Hence, to ensure a profitable operation, the benefits associated with the employees' productivity must outweigh the associated costs. In fact, a slight increase of 0.1% in employee productivity - by enhancing Indoor Environmental Quality (IEQ) factors such as occupant comfort and satisfaction - can yield a dramatic increase in profitability (Singhvi et al. 2005).

IEQ is defined as "a generic term used to describe the physical and perceptual attributes of indoor spaces. These include the indoor air quality and the thermal, acoustic and visual properties of the environment, as well as various characteristics of the furnishings, facilities and fitouts" (Newton et al. 2009). Fifteen different IEQ factors define the indoor environmental quality of a workplace; these are: thermal comfort, air quality and ventilation, amount of light, visual comfort, noise level, sound privacy, amount of space, visual privacy, ease of interaction, comfort furnishing, adjustability of furniture, colors
and textures, building cleanliness, workspace cleanliness, and building maintenance (Kim and de Dear 2012). Each of these factors has a unique impact on the physical and mental well-being of the occupants.

The main hypothesis tested in this study is the existence of a relationship between productive time and occupants’ satisfaction with IEQ conditions at the workspace. The relationship is said to exist due to the proven influence of the different IEQ factors on the well-being of the occupants, which, in turn, influences the level of productivity. The level of performance of the IEQ factors at the workplace is indicated via the self-assessed satisfaction levels reported by the occupants, and the level of productivity is estimated by measuring the productive time. Accordingly, the first null hypothesis tested in this study is:

\[ H_0 : \text{The level of productive time does not correlate with the level of satisfaction with the IEQ conditions at the workplace.} \]

The literature includes several studies that offer quantitative post-occupancy evaluation of the correlation between employee productivity and satisfaction with the workplace. However, the results of these studies differ widely due to the different approaches used for measuring satisfaction and productivity. The purpose of this study is to redevelop this relationship using a new method that targets the possible gaps spotted in previous studies. This method includes estimating productivity through measuring productive time, a more quantifiable parameter to assess. Satisfaction with IEQ is measured by self-assessing the level of satisfaction with each of the factors of IEQ, and then aggregating the assessments to estimate the level of overall satisfaction with the IEQ at the workplace, while taking into consideration the different level of influence of each IEQ factor on the overall satisfaction at the workplace.

In the next section, a literature review on IEQ is presented and related to the well-being, satisfaction, and productivity of building occupants. The third section presents the objective and the methodology adopted in this paper to test the existing relationship between productive time and occupant satisfaction, taking into consideration the spotted gaps in the literature. The fourth section begins with testing the hypothesis of this relation, and ends with a regression curve that raises a concern regarding extremely low satisfaction levels. The paper concludes by comparing the results with those of previous studies.

### 2 LITERATURE REVIEW

This section presents a literature review on the correlation between post-occupancy IEQ and the following three conditions: Occupants’ well-being, overall satisfaction, and level of productivity at the workplace. Based on the reviewed literature described in this section, the relationship among the three mentioned conditions can be depicted as schematized in Figure 1.

The four factors of IEQ, nature of work, psychological environment and space management, do not equally influence physical and psychological status; however, all four play a role in influencing occupants' satisfaction level, which, in turn, influences their level of productivity. It is important to note that the direct causality between all these factors as presented is only a simplified representation that is yet to be ascertained and validated, since the existing relationship among these factors is of high complexity.
2.1 IEQ Conditions and Occupants’ Well-Being

IEQ conditions at the workplace can have physical and psychological implications on the employees. Many studies examined the health implications of each of the 15 IEQ factors on occupants’ well-being (Singh 2009, McGrory 2012). As summarized in Table 1, many of the implications are common across several IEQ factors. This shows the complexity of the relationship between IEQ conditions and occupants well-being.

Table 1: IEQ and well-being (Kumar and Fisk 2002, Balazova et al. 2008, Mardex 2004)

<table>
<thead>
<tr>
<th>IEQ Factor</th>
<th>Health Impact (Physical and Psychological)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Comfort&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Fever, chills, fatigue, attention drift, dizziness and nausea</td>
</tr>
<tr>
<td>Air Quality and Ventilation&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Asthma/chest tightness, respiratory allergy, fever/chills, dizziness, nausea, headache, eye/nose/throat irritation, fatigue, dry or itchy skin, lowered cognitive performance</td>
</tr>
<tr>
<td>Amount of light</td>
<td>Depression, dizziness, nausea, fatigue, headache</td>
</tr>
<tr>
<td>Visual comfort</td>
<td>Depression, Stress, headache, fatigue</td>
</tr>
<tr>
<td>Noise level</td>
<td>Stress, headache, fatigue, lowered cognitive performance</td>
</tr>
<tr>
<td>Sound privacy</td>
<td>Attention drift, lowered cognitive performance</td>
</tr>
<tr>
<td>Amount of space</td>
<td>Stress, fatigue, headache</td>
</tr>
<tr>
<td>Visual privacy</td>
<td>Attention drift, lowered cognitive performance</td>
</tr>
<tr>
<td>Ease of interaction &amp; IT</td>
<td>Stress, tension, attention drift, misconception and miscommunication</td>
</tr>
<tr>
<td>Comfort furnishing</td>
<td>Muscle aches, de-motivation</td>
</tr>
<tr>
<td>Adjustability of furniture</td>
<td>Muscle aches, de-motivation, stress</td>
</tr>
<tr>
<td>Colors and textures</td>
<td>Depression, fatigue, stress, headache</td>
</tr>
<tr>
<td>Building cleanliness</td>
<td>Stress, de-motivation</td>
</tr>
<tr>
<td>Workspace cleanliness&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Eye/nose/throat irritation, dry or itchy skin, respiratory allergy, lowered cognitive performance, stress, de-motivation, headache</td>
</tr>
<tr>
<td>Building maintenance</td>
<td>Can lead to any of the above</td>
</tr>
</tbody>
</table>

<sup>a</sup> Canadian Centre for Occupational Health and Safety (http://www.ccohs.ca)
2.2 IEQ Conditions and Occupants’ Overall Satisfaction with the Workplace

Several studies examined the relationship directly between IEQ factors and occupants’ overall satisfaction at the workplace (Agha-Hossein et al. 2013, Frontczak et al. 2012). Of particular interest is Kim and de Dear’s work, which goes a step further in relating IEQ to satisfaction by giving weights to the IEQ factors. Kim and de Dear (2012) present a tool that allows for quantifying the level of occupant satisfaction with the IEQ conditions in the workplace by breaking it down into its 15 factors and applying the weighted effect of each factor on the overall resulting satisfaction level. Some of these 15 factors, named Proportional Factors – such as air quality, amount of light and sound privacy, have a direct relation with the overall satisfaction; i.e. as the level of perceived satisfaction with these IEQ factors increases or decreases, the level of overall satisfaction increases or decreases respectively, each with a different magnitude. Other IEQ factors, named Basic Factors – such as temperature, noise level and amount of work space, have a non-direct relation with the overall satisfaction. When such factors are perceived negatively, they inflict a negative effect on the overall satisfaction, while perceiving them positively barely adds to the overall satisfaction; quoting, “it is not easy to impress occupants with IEQ”. This classification indicates that every IEQ factor affects the overall satisfaction of the occupants differently, depending on their type and on how well they perform at the workplace. Some have linear relation with the overall satisfaction, while others do not. For this reason, it is highly important to include the weights of the IEQ factors while quantifying the overall satisfaction at the workplace.

2.3 IEQ Conditions and Occupants’ Productivity

Productivity, being the essential organizational outcome, forms the main indirect economical benefit of IEQ enhancements. As shown in Figure 1, IEQ is among the four main factors that describe the overall satisfaction and comfort of employees at their workplace, which in turn affects their level of performance and productivity at work. Enhanced indoor environments in office buildings have a positive correlation with occupants’ satisfaction, yielding higher levels of well-being, which, in turn, positively correlates to productivity. The approaches followed in analyzing the relationship between productivity and IEQ can be categorized into three methods. The first method consists of qualitatively analyzing IEQ investments and yielding benefits. A detailed conceptual relation presented by Seppanen and Fisk (2003) show that health and productivity are highly improved when proper measures are taken to enhance IEQ conditions. The second method, such as the one used by Wyon (2004), relies on statistical techniques to examine the effect of IEQ conditions on productivity. This method analyzes the effect of each IEQ factor independently. For example, air quality is among the IEQ factors that could highly affect office work performance by up to 9%. Despite the fact that segregating the many IEQ factors simplifies the analysis, the sum of their individual effects on performance would not be equal to the combined effect of all factors acting together. The third method looks at IEQ as a whole as opposed to analyzing the effect of individual IEQ factors on productivity independently. Oseland (2004) found a linear relation between productivity and both, environmental and facility factors at the workplace. However, Oseland’s measuring of productivity was based on two self-assessed questions which ask the respondents about the effect of the facility and the environment on their productivity, along with several other questions of which are concerned with downtime such as waiting for lifts, walking between buildings, and other similar questions that might not link to IEQ conditions specifically. Moreover, the IEQ factors were not weighted while calculating the overall satisfaction, such as the case with Kim and de Dear’s study.

Contrarily, Somers and Casal (2009) proposed a nonlinear U-shaped relation between productivity and satisfaction. No explanation was reported regarding this unexpected relation: as satisfaction increases, productivity decreases for the lower levels of satisfaction. Artificial Neural Networks were used to model nonlinearity. Job performance measurements of the employees were taken from the organization’s formal performance appraisal process and reflected supervisor ratings of employee job performance. Beside the possible inaccuracy and bias associated with such productivity measuring techniques, the sample was limited to nurses and psychiatric technicians drawn from a university medical center. Despite the limited sample of this study, it presented the possibility of having nonlinear relationships between IEQ and performance, and hence productivity, which could negate the generalization of Oseland (2004)’s findings.
It is important to note that all of the three methods described in this section use similar means for measuring job performance and productivity level. Productivity is measured by either self-assessments or by simulating office activities (typing, proof-reading, addition, etc.) Self-assessments are not quite accurate primarily due to the lack of reliable benchmarks. Moreover, being aware of the fact that they are being studied, occupants’ might report biased self-assessments of productivity. Simulating office works, on the other hand, includes uncountable tasks to be properly measured. In addition, some tasks might not always be affected by the level of IEQ satisfaction, depending on the difficulty of the task at hand. This makes it challenging to quantify job performance and productivity, and highly lowers the accuracy of the results. Moreover, simulating office work would inevitably include bias since, again, the studied sample is aware of being observed. Another important point is the fact that adding or averaging productivity measures for the sampled employees might be misleading. The level of output for the same state of satisfaction might significantly vary from one employee to another, depending on their nature of work, experience, psychological or physical status, etc.; thus employees with low satisfaction might have outputs equal to or higher than that of satisfied employees.

The best way to attain valid measures is by studying employees’ productivity level at their own offices, while performing their routinely tasks, and without being aware of a direct assessment of their abilities (Haynes 2008). Such a technique has rarely been used in a job performance versus job satisfaction study due to being practically infeasible. This fact is due to the complexity of controlling the many possible combinations of IEQ conditions if analyzed as a whole, difficulty of measuring irregular day-to-day tasks, and difficulty in studying the productivity of employees while at work without having biased results. Due to the complexity in objectively measuring the level of productivity on all its aspects, this paper focuses on productive time related to IEQ conditions. Non-productive time, in this context, is defined as the working time wasted by not being productive due to poor IEQ conditions specifically, subtracted from the total working time of an employee. Measuring productive time rather than productivity could give lower estimates since IEQ conditions might have an effect on productivity parameters other than productive time, such as task productivity: the amount of work done during productive time. However, the level of influence of IEQ per se on task productivity is very difficult to quantify due to the complexity of other influencing factors, and could include biasness since it directly assesses the performance of the individuals who are aware of being tested. Instead, and by asking the employees about the time lost due to external factors or due to causes out of their control, all related to IEQ, they are more likely to reply with objective and more accurate estimates, since erring seem to have neutral influence on their benefit. Moreover, measuring time rather than productive work is a much easier task to do. Several peer-reviewed questionnaires present in the literature measure productivity by focusing on quantifying productive time, such as the Migraine Work and Productivity Loss Questionnaire (MWPLQ), and the Health and Performance Questionnaire (HPQ).

3 METHODS

In order to examine the null hypothesis [1] and further investigate the potential relationship between occupant satisfaction with the IEQ and productive time, a survey questionnaire consisting of three sections was proposed. The first section gathers demographic information related to the respondent. The second section measures time lost during working hours due to poor IEQ conditions as self-assessed by the occupants via expressing their level of satisfaction with IEQ conditions. The aim is to quantify the working-hours lost without performing productive work due to IEQ related causes. Productive time is measured by a set of questions adopted in part from previous productivity-related questionnaires, such as Work Productivity, Work Productivity and Activity Impairment General Health Questionnaire, QQ Instrument, etc. The questions were modified to portray IEQ-related lost time at work. This section directs respondents towards estimating their time lost due to poorly performing IEQ factors or related physical and mental problems faced at work. The third section of the questionnaire directs the respondents into self-assessing their level of overall satisfaction towards their workplace using the same questioning and scaling technique used in Kim and de Dear (2012)’s study, including the weighted parameters presented for the different IEQ factors to estimate an accurate level of overall IEQ satisfaction. Table 2 discloses a few sample questions from the questionnaire, as shown in their related sections.
Table 2: Sample questions from survey questionnaire

<table>
<thead>
<tr>
<th>Section</th>
<th>Question</th>
<th>Measure/Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section I</td>
<td>How long have you been working at your current workplace?</td>
<td>Years &amp; Months</td>
</tr>
<tr>
<td>Section I</td>
<td>Your job description includes occupying your office for an average of:</td>
<td>Days a week &amp; Hours a day</td>
</tr>
<tr>
<td>Section II</td>
<td>During the past week, how many days have you left work early due to being tired or depressed, and not feeling like dealing with the poor environmental conditions at your workplace as indicated in Questions 1 and 2?</td>
<td>Days</td>
</tr>
<tr>
<td>Section II</td>
<td>During the past 12 months, how many times have you felt that your workplace environment made you sick or too tired to work that you took a sick-leave (allergic, migraine, prolonged nausea, etc.)?</td>
<td>Times</td>
</tr>
<tr>
<td>Section III</td>
<td>How satisfied are you with the noise level in your workspace?</td>
<td>Scale 1 to 7</td>
</tr>
<tr>
<td>Section III</td>
<td>How satisfied are you with the temperature in your workspace?</td>
<td>Scale 1 to 7</td>
</tr>
</tbody>
</table>

The responses of the survey were used to compute three parameters out of each questionnaire: *Longevity, Percent Productive Time and Percent IEQ Satisfaction.*

- **Longevity:** Question 1 of Section I asks participants about their time spent at their current workplace. Longevity in this context does not imply the number of years of employment, but merely the number of years spent at the currently occupied office, which might be much less than the total years of employment.

- **Percent Productive Time:** Question 2 of Section I through Question 15 of Section II of the questionnaire are used to calculate the respondent’s percentage of utility of their potential productivity. For example, a *Percent Productive Time* of 70% means that the respondent is, on average, wasting 30% of their working time. This is calculated by summing up the time lost due to the several IEQ-related impediments at the workplace that hinder the respondent from being productive. The lost time due to each of the impediments is self-assessed by the respondents by responding to Section II of the questionnaire. The summed lost time is subtracted from the total working-time supposed to be spent at the workplace; yielding *Productive Time*.

- **Percent IEQ Satisfaction:** Section III of the survey questionnaire is used to calculate the percentage of satisfaction of the respondent with the IEQ conditions, which influences their level of overall satisfaction with the workplace. In total, 15 questions, each relating to one of the 15 IEQ factors, ask the respondent to self-assess their perceived level of satisfaction towards the related IEQ factor on a scale of 1 to 7, similar to that used in Kim and de Dear’s study (2012). The responses are then accumulated after being factored by the weighted influence effect of each IEQ factor, as proposed by Kim and de Dear, to yield the overall IEQ satisfaction at the workplace. A *Percent IEQ Satisfaction* of 80% means that the respondent is 20% short of being completely satisfied with the IEQ conditions at the workplace. This also means that the IEQ conditions are contributing to the overall satisfaction 80% of what they could at an ideal situation.

The total sample size included 102 participants divided among offices of six organizations of different types: engineering, pharmaceutical, banking, industrial, governmental, and educational; each of which completed between 15 and 20 questionnaires. The aim behind selecting different types of organizations
was to include a various combination of white-collar employees working on different types of office-work tasks, to generalize the validity of the tested relationship. A total of 20 hard copies of the questionnaire were kept at the lobbies of each of the consenting organizations, and the employees were invited to fill them in; voluntarily and anonymously. The gathered data were then checked against random responses and any outliers using the ROUT method. The ROUT method in brief attempts to fit the regression model to the data where outliers have little impact. Then, it detects the points that are far enough from the predicted model, basing its prediction on a predefined false discovery rate. The remaining data is then statistically analyzed to reveal the descriptive statistics of the three parameters, longevity, percent productive time and percent IEQ satisfaction, of the studied sample. To study the null hypothesis, a bivariate (Pearson) correlation is carried out on the resulting data, testing the proposed relationship between productive time and overall satisfaction with IEQ conditions at the workplace. The next natural step after testing the null hypothesis is to further investigate this relationship by trying to infer a statistical regression model that relates the two parameters. The obtained regression curve is then validated by comparing the results of this survey with those of Oseland (2004)’s and Somers and Casal (2009)’s statistical regression models, since these two models address the same problem, yet yield possibly contradicting results; the latter claims a linear relation, while the former presents a nonlinear U-Shaped regression curve.

4 RESULTS

4.1 Data Analysis

One response out of the 102 was eliminated since it was found to have been filled arbitrarily; the calculated lost time was greater than the reported total working hours per day. For the remaining responses, and using the previously described calculations, each questionnaire was reduced to a coordinate point (Percent IEQ Satisfaction; Percent Productive Time). Two outliers were filtered out of the data set using maximum False Discovery Rate of 1% (Motulsky and Brown 2006). For the remaining responses (total of 99), the three variables are statistically summarized in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
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<tbody>
<tr>
<td>Percent Productive Time</td>
<td>99</td>
<td>68.6</td>
<td>30.8</td>
<td>99.4</td>
<td>72.6</td>
<td>14.9</td>
</tr>
<tr>
<td>Percent IEQ Satisfaction</td>
<td>99</td>
<td>97.8</td>
<td>2.2</td>
<td>100</td>
<td>54.3</td>
<td>23.9</td>
</tr>
<tr>
<td>Longevity</td>
<td>99</td>
<td>11.9</td>
<td>0.1</td>
<td>12</td>
<td>3.1</td>
<td>2.9</td>
</tr>
</tbody>
</table>

- **Percent Productive Time:** The percent productive time mean of the sampled employees is 72.6% with a standard deviation of 15.0%; i.e. on average, employees are performing their jobs at 72.6% of their ability. The minimum recorded time productivity is 31%, while the highest is about 99%. This suggests that employees tend to utilize their productive time at a wide range of levels, depending on several parameters, among which, the level of IEQ satisfaction.

- **Percent IEQ Satisfaction:** The percentage of satisfaction with the IEQ conditions averages to 54.3%, with a standard deviation of 23.9%. The levels of satisfaction with the IEQ seem to range across the whole 100% scale, with a minimum of 2.3%, and a maximum of full satisfaction.

- **Longevity:** The longevity mean of the sample is approximately three years. The logical explanation for this apparently low number goes back to the first question of the survey, which states: “How long have you been working at your current workplace?” The aim of this study is to measure the level of satisfaction of the employees with the IEQ conditions of their currently occupied office. Since many employees throughout their employment tend to get transferred from one workplace to another due to
several reasons; getting promoted, moving to a new office building, department switching, etc., the average longevity is as low as three years.

Table 4: 2-Tailed Pearson correlation test

<table>
<thead>
<tr>
<th>Percent Productive Time</th>
<th>Pearson</th>
<th>Percent IEQ Satisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Productive Time</td>
<td>1</td>
<td>.56**</td>
</tr>
<tr>
<td>Sig.</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Percent IEQ Satisfaction</td>
<td>.56**</td>
<td>1</td>
</tr>
<tr>
<td>Sig.</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>N</td>
<td>99</td>
<td>99</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).

As summarized in Table 4, the bivariate (Pearson) correlation test shows that there is a statistically significant correlation between the two parameters, thereby enough evidence to reject the null hypothesis \( H_0 \). This result further confirms the findings of Somers and Casal (2009) and Oseland (2004).

4.2 Best-Fit Regression Curve

After performing the regression analysis on the collected data to find the best fit curve that would model the relationship between Percent Productive Time and Percent IEQ Satisfaction, the three regressions with the highest R-Square values are found to be the linear, quadratic and cubic curves. In addition to featuring the highest R-Square value, the cubic model offers a more logical fit especially for cases of high levels of satisfaction, since 100% productive time is practically infeasible as shown by the quadratic fit in Figure 2. Similar to the finding of Somers et Casal (2009), the relation between Productive time and Satisfaction with IEQ thus appears to be non-monotonic with a U-shaped cubic regression curve. As the satisfaction increases to 25%, the productive time drops from 70% to 60%. This value then increases at a slower rate to 95% as satisfaction increase until 100%.

![Figure 2: U-Shape cubic relation between productive time and IEQ satisfaction.](image)
4.3 Discussion

Despite the approach used in measuring satisfaction and productivity, which is validated by previous literature to have more accurate results in comparison to other approaches used in other studies, all three regression curves show relatively low R-Squared values. A possible cause behind this outcome is the fact that productive time and satisfaction level with the different IEQ factors had been self-assessed by the respondents, who could have estimated their lost time inaccurately, or reported their level of satisfaction based on the momentarily situation they were in at the moment of assessment, rather than responding in a general manner. Another cause could be due to the complexity of the relationship between IEQ conditions and occupants' comfort, well-being, satisfaction and productivity. This complex relation stretches far beyond the frame of this study, which relies on several assumptions that simplify this relationship to a quantifiable dimension. For example, feeling dizzy at work and not being able to be productive could be due to reasons that have nothing to do with IEQ, such as feeling ill or pregnancy. A third important observation spotted in Figure 2 that could be associated with the low correlation factors attained is the scatter plot for low values of IEQ Satisfaction (below 20%). The scatter plot at that region of the graph seems to lie randomly above all three regression curves, which could influence the best-fit curves into falsely depicting the relationship between very low IEQ satisfaction levels and productive time. Unlike the first two causes presented, this is not an error in estimation or bias in assessment, but could be a phenomenon that needs to be looked at more closely. If there is no correlation between Percent Productive Time and Percent Satisfaction for such low satisfaction levels, then the proposed model is not applicable for extremely low satisfaction levels, which should be excluded from its domain.

5 CONCLUSIONS

In this paper, the relationship between post-occupancy perceived satisfaction with the indoor environmental quality of office buildings and the self-assessed level of productive time of the occupants is tested. To the contrary of most reviewed studies, productive time rather than productivity per se is measured, linking it solely to poorly performing IEQ or related health problems. The level of IEQ satisfaction, on the other hand, is based on Kim and de Dear (2012)'s regression model, which takes into consideration the weighted influence of the IEQ factors on the overall satisfaction. A survey questionnaire was used to gather the sample data that links the level of productive time to the level of IEQ satisfaction at the workplace. Running a Pearson Correlation test on the gathered data shows a significant relationship. After the initial plotting of responses, a cubic U-shaped behaviour of the studied relationship is observed, similar to what Somers and Casal (2009) concluded. However, and after analyzing the causes behind this unexpected increase in productive time at lower levels of satisfaction, it appears that there might be no correlation between the two. This leads to the conclusion that the curve might not hold valid for such cases; an observation that calls for further studying the hypothesized relationship. The significance of this study is that it validates the existence of the relationship between occupant productivity and satisfaction at the workplace, presents a quantitative empirical model for the relation between productive time and IEQ satisfaction specifically, and presents a possible explanation to the counter-intuitive U-Shaped regression curve attained. Possible future work on this subject could focus on the relation between productive time and extremely low IEQ satisfaction levels. Future work could also address one of the limitations of this paper, i.e. its reliance on self-assessment methods of productive time as proxy for productivity. More direct measurements of productivity are needed to confirm the relationship between IEQ conditions and productivity.

Acknowledgments

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References


A COMPARISON OF GEOGRAPHIC INTERVENTION GROUPING METHODS FOR INFRASTRUCTURE INTERVENTION PLANNING ACROSS MULTIPLE NETWORKS

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Abstract: Interventions on infrastructure networks in municipalities cause disruptions to the service provided by the network that requires the intervention. They also cause disruptions to the service provided by other networks that have to be at least partially shut down so that the intervention can be executed. Due to these effects, there is substantial benefit to be obtained by grouping interventions on all networks that are spatially close to one another, i.e. work programs for spatially close networks should be developed together. This benefit is principally due to reduced interruption to services and reduced costs of intervention. The challenge of determining such combined optimal work programs is made more difficult as it requires quantification of the value of lost services, which depends on how different stakeholders value the services as well as how the services are interrupted. In this paper the difference between two methodologies to be used to develop work programs on spatially close infrastructure networks is shown: 1) a traditional methodology based on a grid-cell based grouping method, and 2) a methodology based on a combined topology / Voronoi cell / density based clustering of interventions. Both methodologies exploit recent developments in the area of critical infrastructures and GISs. The differences are illustrated by using both methodologies to determine combined work programs for five spatially close infrastructure networks (electricity, gas, water, sewage, roads) in a municipality with approximately 1'500 inhabitants. The advantages and disadvantages of each are discussed.

1 INTRODUCTION

Infrastructure networks (INs), such as electricity, gas, road, sewer, and water distribution networks are some of the main assets but also some of the main cost drivers of a municipality. Therefore, interventions on these networks should be carried out in a way that minimises the costs of intervention and the disruption of the service, i.e. an optimal work program (OWP) should be determined. Traditionally, the managers of each IN produce their own work programs. Example methodologies to find OWPs for single INs can be found in Fenner, Sweeting, and Marriott (2000), Miyamoto, Kawamura, and Nakamura (2000), Stillman (2003), Cardoso et al. (2004), Arthur et al. (2009), Dehghanian et al. (2013), Zayed and Mohamed (2013), Lethanh, Adey, and Sigrist (2014). These work programs are then discussed with those responsible for the other INs in order to reduce the impact on service disruption and costs by manually combining the work programs to create synergy effects. In this paper a case study on a dynamic geographic intervention grouping method is presented. This method can be used to take into consideration the structural and functional differences, as well as the different ways that the networks are typically monitored, in an automated way. The resulting work program is compared with the work program
from a static geographic intervention grouping method presented in Kielhauser, Adey, and Lethanh (2014), herein referred to as the traditional methodology.

2 METHODOLOGY

The concept of the herein presented dynamic neighbourhood methodology (DNM) is based on the concept of neighbourhood. The neighbourhood of object A is defined as the region around object A, where object B would be considered close if it lies within that region. The basic process for the DNM follows 7 steps, which are explained in the following sections and shown in Fig. 1.

![Methodology Flowchart](image)

2.1 Step 1: Determine Level 1 objects

In this process, objects with high priority (level 1 objects) are determined. In this paper, level 1 objects are defined as follows:

*Level 1 objects are objects, which are in such a state (e.g. failure probability, condition, age, level of service) that an intervention on this object is justified on its own, i.e. the decision to do an intervention is independent from other objects.*

In the first step of this process, triggers for selecting an object as a level 1 object are defined. These triggers are thresholds of one value or a combination of values of the object attributes. The attribute can be of the object itself, denoted as \( \zeta_n^i \) with the subscript \( n \ (n=1, \ldots, N) \) representing the object ID, and/or of the network, denoted as \( \xi_m^i \) with the subscript \( m \ (m=1, \ldots, M) \) representing the network ID. The superscript \( i \) denotes the level 1 objects. An example of the former is object condition. An example of the latter is change in network reliability. Then, objects are compared with the triggers by using a selector function \( f_i \). It is defined as a logical function, with \( f_i = 1 \) (true) when an object is selected, and 0 otherwise. This selector function is applied to a set of all objects considered (based on the boundaries of the physical area to be analysed and the jurisdiction of the manager) \( \delta_{i,n,m}^j \) in order to obtain the logical selection vector for the level 1 objects \( \bar{\delta}_{i,n,m}^j \):

\[
[1] \quad \bar{\delta}_{i,n,m}^j = f_i(\bar{\alpha}_{i,n,m}, \zeta_{n}^i, \xi_{m}^i)
\]

with \( \bar{\alpha}_{i,n,m} \) ... object vector consisting of all objects \( \alpha_{n,m}^i = (\alpha_{n,1}, \ldots, \alpha_{n,1}, \ldots, \alpha_{n,M}) \).
2.2 Step 2: Calculate Neighbourhood

This process is used to determine the neighbourhood of all level 1 objects being investigated. This is accomplished by determining the topological neighbourhood, the distance neighbourhood and the Voronoi neighbourhood. The first two of these neighbourhoods refer to objects in the same network, the last refers to objects that are in the spatial neighbourhood of the level 1 objects but are in different INs than the level 1 object. To better explain the used three different neighbourhoods, Fig. 2a shows an example network with 7 objects. Logical nodes (denoted with $\bullet$) are nodes that signify a join between two or more objects. Geometric nodes (denoted with $\circ$) are used to detail the object shape in between the endpoints (logical nodes). Lines with the same number are used to denote one object.

![Figure 2: Network definitions](image)

(a) Example network with objects 1-7  (b) Voronoi cells for network nodes  (c) Voronoi region for network element 1  (d) Voronoi region for network element 5

2.2.1 Topological Neighbourhood

The topological neighbourhood of an object is based on the topological distance, i.e. the number of objects between two logical nodes. In that sense, two objects are neighbours if the network distance between their closest logical nodes is below a certain threshold. For example, if the focus is on object 6 and the distance threshold is 1, then objects 1, 2, 5, and 7 can be considered to be in the same neighbourhood, as at most 1 object (namely 5) has to be crossed to reach them. Mathematically, neighbouring objects can be found as follows: Starting from the incidence matrix $C_n$ (i.e. a matrix describing which edges are connected to which nodes), all nodes reachable in a distance $k$ can be calculated by:

$$K_{n} = sgn(\sum_{i=1}^{m}((C_{n} \cdot C_{n} - \text{diag}(C_{n} \cdot \overline{I})))^k))$$

with $K_{n}$. … Reachability matrix of network $m$ for $k$ steps. Each element from $K_{n} = \lbrack k_{n,j} \rbrack$ shows if a node is reachable from another node with a maximum of $k$ steps. Combining those reachability matrices to a grand matrix gives the topological neighbourhood matrix $N_{c}$:

$$[3] \quad N_{c} = \begin{bmatrix}
    K_{i} & 0 & 0 \\
    0 & \ddots & 0 \\
    0 & 0 & K_{i}
\end{bmatrix}$$

2.2.2 Distance Neighbourhood

As the sizes of network objects can differ by orders of magnitudes (e.g. compare one valve with a 300m stretch of straight pipe), neighbourhoods can also be defined by distance along the network. This is an alternative neighbourhood definition, which only takes into account the physical distance of objects along the network. For this, an object is defined as a neighbour, if it can be reached within a certain distance along the network. For example, objects 3 and 5 are within a distance $d_{\text{travel}}$ of each other, as shown in
Fig. 2a, as their closest nodes are within a distance of $d_{travel}$. Mathematically, the shortest path between all logical nodes $q$ of all objects has to be calculated (or loaded from the database if available).

$$[4] \quad D_{m,q} = APSP_m(m, q)$$

with $D_{m,q} \ldots$ all logical node pairs distance matrix for network $m$, $APSP_m \ldots$ all node pairs shortest path algorithm for networks as described in Johnson (1977). The minimal distance between all object pairs is then the minimum of the minimal distances between each objects' logical nodes:

$$[5] \quad D_m = \min(dist(D_{m,q}, D_{m,q})) \quad q_m \in n_m$$

with $D_m \ldots$ minimal distance matrix for all objects in network $m$, $q_m \ldots$ logical nodes of network $m$, and $n_m \ldots$ objects of network $m$. Comparing this minimal distance matrix with a distance threshold $d_{im,m}$ for each network $m$ gives the neighbourhood matrix $D_{d,m}$:

$$[6] \quad D_{d,m} = D_m \leq d_{im,m}$$

Combining those distance matrices into a grand matrix gives the neighbourhood matrix $N_N$:

$$[7] \quad N_N = \begin{bmatrix} D_{d,i} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & D_{d,j} \end{bmatrix}$$

### 2.2.3 Voronoi Neighbourhood

Both topological and distance neighbourhood definitions have the prerequisite that all objects have to belong to the same network. To overcome this limitation, the neighbourhood can also be defined by Voronoi cells (Lejeune Dirichlet 1850). Figure 2b shows a Voronoi tessellation of the example network. Starting from a given set of core points $p_i$ (in this case: all network nodes, both logical and geometric), Voronoi cells $V_v$ consist of every point in space whose distance to $p_k$ is less or equal to any other core point $p_{j,k}$. A Voronoi region $R_i$ for one object is then the set of all Voronoi cells emanating from the nodes of that object (Fig. 2c,d). Combining those regions gives the set of all Voronoi regions $\tilde{R}_{n,m}$ for all objects $o_{n,m}$. This can be used to define the neighbourhood as follows: objects A and B are neighbouring, if object B touches object A's Voronoi region. The neighbourhood can then be defined as:

$$[8] \quad N_N = \tilde{R}_{n,m} \cap \tilde{o}_{n,m}$$

with $\tilde{R}_{n,m} \ldots$ Voronoi regions of objects $\tilde{o}_{n,m}$, $N_N \ldots$ neighbourhood matrix for Voronoi methodology and $\tilde{R}_{n,m} \cap \tilde{o}_{n,m} \ldots$ the dyadic geometric intersection between $\tilde{R}_{n,m}$ and $\tilde{o}_{n,m}$.
2.2.4 Neighbourhood combination

In the last activity of the dynamic neighbourhood calculation, all neighbourhoods are combined to a grand
neighbourhood by combining all neighbourhood matrices to the dynamic neighbourhood matrix \( N_D \):

\[ N_D = N_T \lor N_N \lor N_Y \]

with the symbol \( \lor \) denoting the logical "or", which only returns a value of "1" if at least one input is "1". In
words, two objects are neighbours if they are either topological, distance or Voronoi neighbours.

2.3 Step 3: Determine close objects

As next step, the so-called close objects are determined. Those objects are objects that are located in the
neighbourhood which is defined by the dynamic neighbourhood matrix \( N_D \). This process ensures that
only close objects, i.e. objects that are sufficiently near to level 1 objects are considered as level 2 objects
in the next step, where the object condition is compared against a threshold likewise to the determination
of level 1 objects. Mathematically, the whole process can be expressed in one equation:

\[ \delta_{n,m}^{C,D} = \left( (N_D \otimes \Delta_j) \cdot 1 \right) \rightarrow \delta_{n,m}^{C} \]

with \( \delta_{n,m}^{C,D} \) the binary variable vector indicating if object \( O_{n,m} \) is part of the close object set. The superscript
\( C \) denotes the close objects, the superscript \( D \) denotes the DNM, and the symbol \( \rightarrow \) denotes the
material non-implication, which is an operator that only returns a value of "1" if the first input is "1" and the
second input is "0". In this case: an object is only a close object for the DNM if the object is within the
same neighbourhood as a level 1 object but has not been already selected as a level 1 object.

2.4 Step 4: Determine Level 2 objects

In this subprocess, objects with lesser priority (Level 2 objects) are determined. In this paper, level 2
objects are defined as follows.

Level 2 objects are objects, which are in such a state (e.g. failure probability, age, level of service) that an
intervention on this object is not justified on its own but the synergies created by doing a combined
intervention with a level 1 object justify an intervention, i.e. the decision to do an intervention is dependent
on other proximate objects.

The selection process is similar to the one for level 1, just with different trigger values.

2.5 Step 5: Group objects

In this process, the level 1 and level 2 objects which have been identified in the previous steps, are
combined into intervention groups, i.e. sets of interventions that are executed together, using the
DBSCAN algorithm as described in (Ester et al. 1996). This algorithm takes the centroid point coordinates
of the objects requiring intervention and two values as inputs: 1) Eps - the maximum distance in which
two interventions should be grouped into one intervention group, and 2) MinPts - the number of
interventions, that form an intervention group. Then, the points are classified as either belonging to a
group or being single objects. If they belong to a group, then the interventions are included in the work
program as a group, otherwise it has to be discerned between level 1 and level 2 objects. Level 1 single
objects are also included in the work program as intervention, despite not being grouped, because per
definition level 1 signifies that an intervention is justified even without grouping, whereas level 2 objects
belonging to no group will be discarded. Mathematically:
[12] \( I_D = DBSCAN(\delta_i^j, \delta^H_{x, y}, \text{Eps}, \text{MinPts}) \)

with \( I_D \) intervention group matrix for the DBSCAN clusters. The cost of each group is the sum of the setup costs \( C_i \) for executing all interventions in group \( s_j \) and the unit costs without setup costs for each intervention on each object of each network \( c_{n,m} \) multiplied by its size \( u_{n,m} \).

\[ C_j = c_j + ((I_D \otimes (c_{n,m} \odot u_{n,m}) \cdot \bar{1}) \]

with \( C_j \) cost vector of intervention in all groups \( s_j \). The WP is simply the whole set of intervention groups, i.e. all rows of \( I_D \). The total costs are then simply the sum of the cost vector \( C_j \):

\[ C_{WP} = \sum_{j=1}^{J} C_j \]

### 2.6 Step 6: Rank groups

If there are constraints (e.g. budget constraints) and not all intervention groups can be included in the work program, a priority (related to the consequences that would be incurred due to service interruption if a failure occurred) is calculated so that the groups with the highest priority can be included in the work program. It is in this methodology based on two components: a) The object priority value, which relates to the object itself and its role in the network, e.g. for a sewer network object how many upstream objects will also be blocked if this object has to be blocked for maintenance, and b) a multiplicative factor related to the location, e.g. population density of the area with service interruption. Although this is multiplicatively connected with the object priority value, it is kept separate because the population density for example is not network dependent, whereas the object priority value is. Mathematically:

\[ W_i = (I_D \otimes (\lambda_{n,m}) \cdot \bar{1}) \]

with \( W_i \) priority vector of group \( s_i \), \( \lambda_{n,m} \) object priority vector based on object \( n \) and network \( m \), \( \lambda \) group priority vector based on group location, and \( \odot \) representing the element-wise multiplication of vectors. From there, the rank \( r_i \) of a group can be calculated:

\[ r_i = \text{rank(sort}(W_i|\text{desc.})) \]

This results in the group with the highest priority \( W_i \) having the lowest rank \( r_i \).

### 2.7 Step 7: Add group to constrained work program

The work program with constraints is constructed from the unconstrained work program: The groups included in the unconstrained work program are added one at a time to the constrained work program (i.e. a selection variable \( \lambda^g \) is changed from 0 to 1) starting with the group with the highest priority (i.e. where \( r_i = 1 \), then where \( r_i = 2, 3, \ldots \) etc.) and then the budget is checked. If the budget is not exceeded,
the group is kept and the group with the next highest priority is tried. This process is repeated until the
sum of the costs of the groups in the work program reaches the budget limit \( C_{lim} \): 

\[
\Lambda^e_g = 1 \text{ for } \sum_{k \subset N}^N C_i \leq C_{lim} \text{ or } 0 \text{ otherwise}
\]

with \( \Lambda^e_g \) the binary vector indicating inclusion in WP (1=yes, 0=no), \( C_{lim} \) the budget limit. The WP is the whole set of intervention groups \( I_D \) subsetted by the inclusion variable \( \Lambda^e_g \): 

\[
I_D^e = \left( I_D \otimes \Lambda^e_g \right)
\]

The total costs are the sum of the cost vector \( C_i \) times the inclusion vector.

\[
C_{\text{WP}} = \sum_{g=1}^{G} C_{i} \Lambda^e_g
\]

3 CASE STUDY

The DNM was used to determine a work program for five proximate municipal infrastructure networks. This work program was then compared with the work program generated using a traditional methodology Kielhauser, Adey, and Lethanh (2014). The advantages and disadvantages of each will be discussed.

3.1 Overview

The infrastructure networks (electricity, gas, roads, sewage, and water) used in this case study belong to a municipality with a population of ca. 1'500. The single network maps are shown in Fig. 3a – Fig. 3e.

![Network maps](image)

(a) Electricity  (b) Gas  (c) Roads  (d) Sewer  (e) Water

Figure 3: Network maps

The objects in the electricity, gas, and water networks were considered to be in one of 2 condition states, operational and not operational, the objects in the sewer network were considered to be in one of 5 discrete condition states, and the road objects were considered to be in a continuous-range condition state between 0 and 5 (Tbl.1). The thresholds for level 1 and level 2 are shown in Tbl. 2, the costs for the interventions (given in monetary units mu) in Tbl. 3.
Using steps 1-7, a work program (with a budget constraint of 200'000 mu) was calculated and compared to the WP obtained by using the method described in Kielhauser, Adey, and Lethanh (2014). To facilitate the comparison, the work programs will be referred to as WPD (with the D representing the DNM) and WPT (the T representing the traditional methodology). Tbl. 4 shows the results.

Table 4: Results

<table>
<thead>
<tr>
<th>Objects</th>
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<th>Avg. cost per Group</th>
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<tr>
<td></td>
<td></td>
<td>[mu]</td>
<td>287'387</td>
<td>71'847</td>
<td>71'847</td>
</tr>
<tr>
<td>WPD</td>
<td>6</td>
<td>4</td>
<td>874.5</td>
<td>874.5</td>
<td>874.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[mu]</td>
<td>288'672</td>
<td>72'168</td>
<td>72'168</td>
</tr>
</tbody>
</table>

This table shows that the traditional methodology selects 4 objects for the work program. A total amount of 861.6m will be renewed. With only 300'000 mu available, the total cost is 287'387 mu, which means a budget utilisation of 96%. The DMN selects 6 objects with a total length of 874.5m for the work program.
A total amount of 874.5m will be renewed. With total costs at 288'672 mu, the budget utilisation is also 96%. To be better able to compare the methodologies, we have used a proxy B which is the average amount of financial resources used to improve the age of the infrastructure, expressed as monetary units divided by the amount of removed age, multiplied by extent of the object. This indicator is based on the concept, that if it is assumed that an adequate level of service is always provided, the main goal of an infrastructure manager becomes the improvement of the infrastructure for the least cost. In this case, the best work program is the one that gives the highest improvement in the infrastructure provided for the least cost. For example, when a gas pipe is 70 years old and is replaced with a new identical pipe, it is considered to have improved the condition of the infrastructure by 70 years. When this is coupled with the costs to improve the condition, one gets the costs per time.

4 COMPARISON

One of the first things that can be seen by comparing the two methodologies is the difference between the numbers of interventions proposed. For the case study, this difference originates in a part of the network that is shown in Fig. 4. The left half shows the WPT, the right shows the WPD. The dashed line represents the boundary of a grid cell. The line weight represents the different levels (thick: level 1, medium: level 2, grey: no selection). For the WPT, it can be seen that within the grid cell, the level 1 object also triggers an intervention on the adjacent level 2 object, because it is in the same grid cell. For WPD, additionally, another object is included, as it is only at a topological distance of 1 from the level 1 object. This shows the main benefit of the DNM: as the neighbourhood is calculated dynamically from the network, such boundary situations can be taken into account in contrast to the traditional methodology.

As can be seen in Tbl. 4, the cost/improvement ratio B varies between the work programs. The work program determined using the DNM gives the best (i.e. lower) ratio (33.1 vs. 36.1). Therefore, the DNM performs better than the traditional methodology. This is due to the synergy effects created by the topological approach in contrast to the traditional approach.

5 CONCLUSION

In this paper, two methodologies to determine work programs for municipalities possessing multiple infrastructure networks were investigated and compared. In the investigated example, the methodologies were used to determine work programs for five infrastructure networks in a municipality with a population of ca. 1'500. It was found that the DNM for grouping objects in need of intervention within a network and on multiple networks leads to improvements over the traditional methodology. This demonstrated that the explicit consideration of the proximity of objects within multiple networks should be systematically done. It was found that the DNM leads to work programs that generated lower per unit improvement costs than the traditional methodology. This is because the traditional methodology relies on predefined grid cells, while the DNM dynamically calculates those from the individual network data.
Keeping this in mind, future research in this direction should include:

- the enhancement of the investigated methodologies to determine work programs using more direct consideration of the costs of service interruption
- the extension of the investigated methodology to determine work programs over multiple time periods
- the adaptation of the investigated methodology to take into consideration functional relationships between the objects within one network and within multiple networks, e.g. the effect on the amount of water flowing in a waste water network due to interventions being executed on a sewer network and a heavy rain fall occurring
- the enhancement of the investigated methodology to better take into consideration real world costs, i.e. more accurate representations of the variant and invariant costs involved with intervening on one or more networks, and on one or more objects
- the comparison of these methodologies with a real world situation to investigate the potential advantages and disadvantages of its use in practice

References

Abstract: As an approach to mitigate the harmful effects of Urban Heat Island (UHI), the use of glass cullet in the production of asphalt roof shingles has the potential to be employed as a cool roof strategy. The objective of this study was to test the hypothesis that the use of recycled glass cullet increases the solar reflectance index (SRI) without affecting the performance of asphalt roof shingles. In order to evaluate the feasibility of using recycled glass cullet in this new application, the engineering properties of glass cullet were investigated and compared to conventional aggregates used in the production of asphalt roof shingles. Laboratory shingle specimens were then prepared in order to measure solar reflectance properties and strength characteristics of conventional and recycled glass roof shingles. Results show that while the use of recycled glass cullet as a replacement to standard ceramic coated black roofing granules on the top surface of asphalt shingles increased the SRI, the addition of white pigment powder (anatase ultra-fine titanium dioxide [TiO₂] particles passing mesh #320) to the surface granules greatly improves the reflectance properties of the roof to a level that meets the cool roof threshold.

1 INTRODUCTION

With the continuous consumption of energy from non-renewable sources, many cities worldwide with a population that equals or exceeds 1 million people experience an increase in annual mean air temperature of 1-3°C when compared to its surroundings. Further, evenings can experience a difference as high as 12°C (USEPA 2014). This phenomenon is known as heat island effect. It is becoming increasingly intense as summertime temperatures rise due to global warming. The objective of this study was to evaluate the feasibility of integrating recycled glass cullet in the manufacturing of fiberglass roof shingles and to investigate the interactions that occur when recycled glass cullet is blended with traditional roofing materials. The impact of diverting materials from disposal and reusing Construction and Demolition (C&D) materials includes reduced extraction and consumption of virgin resources. Glass food and beverage containers can be recycled endlessly, and economic benefits of the reuse of glass include: cullet cost less than raw materials, reduces energy demand, prolongs furnace life, and creates 8 jobs for every 1,000 tons recycled (Glass Packaging Institute 2013). Environmentally, benefits include the reduction of emissions, energy consumption, consumption of raw materials, and waste ending in landfills. For every six tons of recycled container glass used, a ton of carbon dioxide, a greenhouse gas, is reduced (Glass Packaging Institute 2013).


2 BACKGROUND

Recycling of glass cullet can be categorized into two main groups: (1) new glass and bottle containers; and (2) other applications. Secondary recycling applications are categorized into eight main groups (Reindl 2003): (1) building materials; (2) concrete production; (3) construction aggregates; (4) industrial mineral uses; (5) building insulation; (6) asphalt paving; (7) remelt; and (8) others. While the recycling of glass cullet is beneficial in most applications, the performance of the product should not be compromised as compared to products prepared with virgin materials. Numerous advantages can result from the recycling of glass cullet: (1) reduced emissions and energy consumption during processing and manufacturing of virgin materials; (2) reduced consumption of virgin materials; (3) diminished consternation of public concerning emissions; (4) improved economic competitiveness of construction and manufacturing; and (5) reduced glass cullet disposed in landfills.

The most common roofing product is asphalt shingles, which account for approximately 85% of roofing products used in the residential sector in the US (Leavell 2006). A fiberglass roofing shingle is comprised of four major components: a substrate, asphaltic coating with mineral fillers, surface granules, and backdust. Conventional materials used to produce shingles include fiberglass matting as the substrate, air-blown asphalt as the coating material, and aggregates. Aggregates are classified by particle size as top surface granules, filler material, or backdust particles. Typical particle sizes are listed in Table 1. Materials most widely used as top surface granules include crushed slate, basalt, and trap rock (Pagen et al. 1986). Finer silt-sized granules are used as backdust, and ideal materials are non-cementitious minerals, such as mica flakes, talc, or sand (Bondoc et al. 1988). Examples of filler material include fly ash, recycled rubber, recycled shingles, fine grained carbonate rock, dolomite, trap rock, sand, stone dust, and limestone. Limestone has dominated the market due to its naturally occurring abundance, satisfactory performance, and positive reactions with asphalt as it does not make it brittle or loose granules (Leavell 2006).

<table>
<thead>
<tr>
<th>Shingle Component</th>
<th>Typical Particle Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral Filler Material</td>
<td>45µm - 150µm</td>
</tr>
<tr>
<td>Backdust Particles</td>
<td>75µm - 595µm</td>
</tr>
<tr>
<td>Top Surface Granules</td>
<td>595µm - 2,360µm</td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL PROGRAM

The objective of the experimental program was to evaluate the suitability of incorporating recycled glass cullet into the manufacturing process of asphalt roofing shingles and to test the hypothesis that the use of recycled glass cullet will increase solar reflective properties without affecting performance of asphalt roof shingles. Table 2 provides an overview of the experimental conditions, variables, properties testing, and ASTM specifications. The experimental program was divided in two phases. The first phase of the experimental program was to characterize the engineering properties of glass cullet in comparison to conventional materials used in producing fiberglass shingles. The engineering properties of interest included particle size distribution, specific gravity, absorption, void content, and soundness. The second phase consisted of preparing laboratory shingles in order to measure and compare the solar reflective properties and strength performance of conventional and recycled glass roof shingles. Conventional and recycled-glass modified fiberglass reinforced asphalt roofing shingles were prepared in the laboratory by varying the amount of glass cullet and conventional materials used in asphalt roof shingles, and acceptability was based upon the standard specifications described in ASTM D 3462.

3.1 Materials Description and Processing

Three sources of recycled glass cullet were collected from C&D processing plants. Each source was presorted by color and included one source of green glass and two sources of clear glass. Approximately
85% of the glass fragments received were larger than the maximum size aggregate (2.36mm) used in producing asphalt roof shingles and needed to be processed into a smaller size. With the use of a high performance mixer, the fragments were reduced, sieved, and fractionated into sizes used in the production of conventional shingle particle sizes, see Table 1. The ground glass cullet was then utilized in lieu of conventional mineral aggregates as surface granules, filler material, and backdust.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Number of Levels</th>
<th>Description</th>
</tr>
</thead>
</table>
| Type of Aggregate Location: Top Surface Granules | 4 | Green Glass
| Clear Glass #1
| Clear Glass #2
| Conventional Materials |
| Usage of Pigment | 2 | Included with Surface Granules
| Not included with Surface Granules |
| Phase I: Testing of Aggregate and Asphalt Binder | N/A | Particle Size Distribution (ASTM C136 & D422)
| Specific Gravity (ASTM C128)
| Absorption (ASTM C128)
| Void Content (ASTM C1252)
| Soundness (ASTM C88)
| Rotational Viscosity (ASTM D4402) |
| Phase II: Testing of Shingle Performance | N/A | Reflectance and Emittance (ASTM E903 & E408)
| Tear Strength (ASTM D1922) |

Conventional shingle aggregates were collected and included ceramic coated roofing granules for the top surface, high calcium limestone filler material, and crushed limestone (stone dust) as the backdust. The #11 grade top surface igneous roofing granules were coated with a black ceramic pigment and were comprised of pulaskite, which is variation of syenite with little or no quartz. The limestone filler material was a ground Calcium Carbonate product (96.7% CaCO₃) with 98% passing the U.S. Standard Sieve Mesh #50 (0.300mm) and 70% passing the #200 mesh (0.075mm). For the backdust, crushed limestone #10 was obtained, reduced, and then sieved to the required size and amount. Materials used to produce both conventional and glass modified shingles included air blown asphalt binder and fiberglass matting. The binder consisted of oxidized air-blown asphalt that is suitable for use as shingle coating. The fiberglass mat consisted of a non-woven web of glass fibers and served as the substrate for the shingle.

A white pigment powder was used in the fabrication of the asphalt shingles. To this end, the powder was mixed, saturated, and oven-dried with the glass surface granules prior to placement on the surface of the asphaltic coating. The powder consisted of 98% pure titanium dioxide (TiO₂) and was added at 8% by weight of the top surface granules. The anatase-based ultra-fine powder had a specific gravity of 3.9. The cool roof attributes of the modified shingle samples were evaluated with and without the addition of pigment powder.

### 3.2 Asphalt Shingle Preparation

In order to prepare fiberglass reinforced asphalt shingles in the laboratory, the process was divided into three steps: preparation of the formwork, preparation of the asphalt blends, and aggregate preparation. The preparation of the formwork included the thorough cleaning of an ample working surface for the
placement of a fiberglass mat substrate and then securing metal forms to ensure uniform dimension of the prepared samples. The prototype sample dimensions were 76mm x 76mm x 3mm.

Prior to pouring the asphalt binder in the prepared forms, all aggregates were weighted and fractionated to produce the samples described in Table 3. For the specimens that did not include pigments, the following weights were used per sample: 25 grams of top surface granules, 5 grams of backdust, and 23.4 grams of filler materials. The second embodiment consisted of the addition of the white (titanium dioxide) pigment powder to the surface granules. To include pigment powder, two grams of powder were mixed with 23 grams of surface granules, saturated with water, and then oven-dried.

The filler material was then uniformly mixed with 12.6 grams of liquefied asphalt binder for each sample, which was heated to 204°C. After mixing the filler material, 36 grams of asphalt coating mixture was reheated to become liquefied at 230°C. The asphalt coating mixture was then poured in the formwork of each shingle and then placed into the oven at 204°C for impregnation of the fiberglass. After one hour, the samples were removed from the oven and firm pressure was applied on the top surface granules in order to achieve 100% surface coverage. Upon cooling of the shingles, the forms were removed and the shingles were separated from the working surface by applying heat using a forced air heat gun. Finally, the backdust particles were applied to the back surface while keeping the underside heated.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Top Surface Material</th>
<th>Filler Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>Control 1: Ceramic Coated Granules</td>
<td>Limestone</td>
</tr>
<tr>
<td>X2</td>
<td>Control 2: Ceramic Coated Granules</td>
<td>Clear Glass 1</td>
</tr>
<tr>
<td>A</td>
<td>Green Glass</td>
<td>Limestone</td>
</tr>
<tr>
<td>B</td>
<td>Clear Glass 1</td>
<td>Limestone</td>
</tr>
<tr>
<td>C</td>
<td>Green Glass</td>
<td>Green Glass</td>
</tr>
<tr>
<td>D</td>
<td>Clear Glass 1</td>
<td>Clear Glass 1</td>
</tr>
<tr>
<td>C1</td>
<td>Green Glass and Pigments</td>
<td>Green Glass</td>
</tr>
<tr>
<td>D1</td>
<td>Clear Glass 1 and Pigments</td>
<td>Clear Glass 1</td>
</tr>
<tr>
<td>G1</td>
<td>Clear Glass 2 and Pigments</td>
<td>Clear Glass 2</td>
</tr>
</tbody>
</table>

3.3 Reflectance and Emittance Testing

The main purpose of using recycling of broken and waste glass cullet in the manufacturing of asphalt roofing shingle is to alleviate heating and cooling loads in buildings by reducing solar heat flux on the roof and heat island effects by increasing the reflectivity of the roof. To assess this ability, samples were exposed to a controlled light source from a spectrophotometer in order to measure solar reflective properties in accordance with the Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres (ASTM E903). Solar absorptance and reflectance were measured by using a spectroreflectometer with an absolute integrating sphere, 15°/h (Model: LPSR 200IR, AZ Technology). Measurements of emittance were produced by a spectrafire with an absolute ellipsoidal cavity, 15°/h (Model: TESA 2000, AZ Technology). Prepared samples for reflectance testing are presented in Table 3; sample dimensions were 76mm x 76mm x 3mm. To consider variability in reflectance and emittance measurements, two to six readings of three replicates were conducted.

Calculations of Solar Reflectance Index (SRI) under standard solar and ambient conditions are based on Approach II of the Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces (ASTM E1980). Based upon measurements of solar absorptance and thermal emissivity of the shingle samples, the SRI was calculated for three convective coefficients that correspond to low, medium, and high wind conditions at 5, 12, 30 W•m⁻²•K⁻¹, respectively:
3.4 Tear Strength Testing

To assess roof shingle tear strength, prepared asphalt shingles were tested using a pendulum tear strength tester according to the Standard Test Method for Propagation Tear Resistance of Plastic Film and Thin Sheeting by Pendulum Method (ASTM D 1922). Conventional and glass-modified shingles were compared to industry minimum strength performance standards as specified in Standard Specification for Asphalt Shingles Made from Glass Felt and Surfaced with Mineral Granules (ASTM D 3462). Tear strength was determined using a Thwing-Albert ProTear Electronic Elmendorf Tear Tester. Initial tear strength testing included sample types X1, C1, and D1 shown in Table 3. These samples were made using 36 grams of asphalt coating mixture as outlined in the aforementioned asphalt shingle preparation process. However, results were inconclusive due to the thickness of the shingle, which increased strength values beyond the testing capabilities of the Elmendorf Tearing device. To achieve measurable results, the procedure was modified to reduce the thickness of the shingle by using 20 grams of asphalt coating mixture.

4 RESULTS AND ANALYSIS

4.1 Particle Size Analysis

Table 4 illustrates the particle size characteristics of the three sources of glass cullet. Based on these characteristics, collected glass cullet sources appear to be well-graded. However, glass cullet sources are too coarse to be directly used in glass-modified asphalt shingles without processing. The glass cullet particle sizes were reduced with the use of a commercial grade blender with 101.6mm blades and were then fractionated into sizes suitable for use in roof shingles as top surface granules (2.36mm – 595µm), backdust particles (595µm – 75µm), and filler material (150µm – 45µm). The cumulative particle size distribution curves of the ground glass cullet are shown in Figure 1 (a to c) and are compared to the particle sizes of conventional aggregate used as top surface granules, backdust particles, and filler material. Results show that the laboratory grinding process effectively reduced the size particles of the recycled glass cullet and the nominal maximum aggregate size of the glass cullet, rendering it similar to conventional ceramic coated top surface granules at 2.36mm with 7.4 to 7.7% fines. The fineness modulus was calculated for each aggregate type, and glass sources and ranged from 2.59 to 2.78 whereas the markedly smaller conventional aggregate fineness modulus was 1.93.
Figure 1: Cumulative Particle Size Distribution Curve of (a) Top Surface Granules (b) Backdust Particles, and (c) Filler Material

Table 4. (a) Particle Size Characteristics of Recycled Glass Cullet Sources and (b) Comparison of Specific Gravity, Absorption, and Soundness of Conventional and Recycled Glass Cullet

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Green Glass</th>
<th>Clear Glass 1</th>
<th>Clear Glass 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Uniformity ($C_u$)</td>
<td>4.01</td>
<td>4.52</td>
<td>4.21</td>
</tr>
<tr>
<td>Coefficient of Curvature ($C_v$)</td>
<td>1.43</td>
<td>1.07</td>
<td>1.41</td>
</tr>
<tr>
<td>Fineness Modulus (FM)</td>
<td>5.63</td>
<td>5.34</td>
<td>5.63</td>
</tr>
</tbody>
</table>

4.2 Reflectance, Emittance, and Solar Reflective Index (SRI)

The mean solar reflectance and thermal emittance results are summarized in Table 5. In general, reflectance results were influenced only by the top surface material employed and were unaffected by the type of filler material used. Figure 2 shows the ceramic-coated roofing granules on the top surface of the conventional shingles and compares it to the shingles prepared with top surface glass granules, with and without the addition of white pigment powder. To measure the effectiveness of glass cullet as a top surface material, mean reflectance values were compared for samples with the same filler material. Samples A, B, C, and D include glass cullet as a top surface material, which resulted in an increased reflectance as compared to Samples E and F. The utilization of glass cullet as top surface granules
resulted in a mean reflectance range increase from 0.029 to 0.050. T-test statistical analyses with 95% confidence level were performed and showed significance for Samples E vs. A (P-value = 0.004), Samples E vs. B (P-value = 0.015), and Samples F vs. D (P-value = 0.0005).

Table 5. Results of Reflectance, Emittance, and Solar Reflective Index (SRI)

<table>
<thead>
<tr>
<th>ID</th>
<th>Material Composition</th>
<th>Solar Reflectance</th>
<th>Thermal Emittance at 300K</th>
<th>Convection Coefficient (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top Surface</td>
<td>Filler</td>
<td>Low</td>
<td>Med</td>
</tr>
<tr>
<td>X1</td>
<td>Control 1: Ceramic Coated Granules</td>
<td>Limestone</td>
<td>0.040</td>
<td>0.917</td>
</tr>
<tr>
<td>X2</td>
<td>Control 2: Ceramic Coated Granules</td>
<td>Clear Glass 1</td>
<td>0.036</td>
<td>0.917</td>
</tr>
<tr>
<td>A</td>
<td>Green Glass</td>
<td>Limestone</td>
<td>0.069</td>
<td>0.928</td>
</tr>
<tr>
<td>B</td>
<td>Clear Glass 1</td>
<td>Limestone</td>
<td>0.090</td>
<td>0.906</td>
</tr>
<tr>
<td>C</td>
<td>Green Glass</td>
<td>Green Glass</td>
<td>0.069</td>
<td>0.918</td>
</tr>
<tr>
<td>D</td>
<td>Clear Glass 1</td>
<td>Clear Glass 1</td>
<td>0.086</td>
<td>0.911</td>
</tr>
<tr>
<td>C1</td>
<td>Green Glass &amp; Pigments</td>
<td>Green Glass</td>
<td>0.263</td>
<td>0.917</td>
</tr>
<tr>
<td>D1</td>
<td>Clear Glass 1 &amp; Pigments</td>
<td>Clear Glass 1</td>
<td>0.254</td>
<td>0.921</td>
</tr>
<tr>
<td>G1</td>
<td>Clear Glass 2 &amp; Pigments</td>
<td>Clear Glass 2</td>
<td>0.275</td>
<td>0.933</td>
</tr>
</tbody>
</table>

(a) Green Glass (b) Limestone (c) Clear Glass 1 (d) Green Glass & Pigments (e) Clear Glass 1 & Pigments (f) Clear Glass 2 & Pigments
Although the increase was statistically significant, glass granules on the top surface alone do not meet the standards to be classified as a cool roof material. Samples C1, D1, and G1 represent the case in which a white pigment powder was added to enhance the reflectance performance of the glass-modified shingles. The addition of white pigment powder to the top surface granules resulted in a mean reflectance increase from 0.168 to 0.194 for the samples with glass cullet top surface granules. T-test statistical analyses with 95% confidence level were conducted and showed significance differences for Samples C vs. C1 (P-value < 0.001) and Samples D vs. D1 (P-value < 0.001). The overall mean increase in reflectance from conventional materials to top surface glass granules with pigments was 0.218. A t-test statistical analyses with 95% confidence level was performed and showed significant differences for Samples F vs. D1 (P-value < 0.001).

### 4.3 Tear Strength

Initial testing involved Samples X1, C1, and D1 so that ten constant radius measurements could be tested. However, the results of initial tear strength testing were inconclusive as no readings were obtained. Despite using the heaviest pendulum (6400gf) available for the Elmendorf device, the pendulum was unable to swing freely to tear the specimen, as the mass of the pendulum was supported by the sample. In order to decrease the strength of the shingle and to obtain useable readings, this test method was repeated by modifying the procedure to produce thin laboratory shingles. The amount of coating was decreased from 36 to 20 grams, which was the thinnest specimen achievable using the procedures outlined in the experimental plan. Results showed that the average tear strength for both conventional and glass-modified shingles was substantially greater than the minimum shear strength of 1,700gf recommended by ASTM D3462, and results of a one-way ANOVA showed no significant difference between means at a level of significance of 0.0885. It is recommended to develop assembly methods to decrease the thickness of the coating layer of the laboratory samples and to pursue the use of industrial manufacturing processes in order to further evaluate the effects of glass fillers on actual production samples.

### 4.4 Economic Evaluation of Glass Modified Asphalt Shingles

To perform a cost analysis of glass modified asphalt roofing shingles compared to conventional shingles, material costs for conventional aggregates and glass cullet as top surface granules and as filler material were estimated. Ceramic coated black roofing granules were quoted at $145-185 per ton and approximately $100 per ton for the uncoated headlap granules by Specialty Granules Inc. (SGI) and 3M Industrial Mineral Division. Because shipping and freight costs are so varied, the prices were given as free on board (FOB) at the granule manufacturing plant, where the buyer pays for all transportation costs. High calcium limestone filler material was quoted between $17-40 per ton by Lhoist North America and Great Lakes Calcium. The estimated price for recycled glass was provided by Strategic Materials Inc. and Dlubak Glass, and roofing granules were approximately $131-135 per ton and $150 per ton for filler material. However, if the market demand increases, the price for glass roofing aggregates could eventually compete with container cullet pricing and 15.8mm minus plate glass recycling at $78-100 per ton. The cost of obtaining white pigment powder at a rate of 8% by weight of the surface granules was $3.00 per pound.

According to the United States Department of Energy (USDOE), although cool asphalt shingles currently sell for up to $0.50 per ft² more than conventional asphalt shingles (USDOE, 2013), the cost increase associated with implementing recycled glass granules with pigments is approximately $0.112 per ft². Conventional ceramic coated granules, which are utilized at a rate of 0.50 pounds per ft², can be replaced by glass granules without the use of pigment powder for a cost reduction of $0.008 per ft² in material cost alone. Glass filler material at a rate of 0.46 pounds per ft² can be utilized at a cost increase of $0.03 per ft² in place of limestone filler material. However, since filler material had no effect on reflectance or emittance, it was not included in the economic analysis. According to the Department of Energy Cool Roof Calculator, the estimated savings associated with changing reflectance to 0.30 from a black roof for residential homes in Baton Rouge, LA is $0.061 per ft² per year, resulting in $91.50 savings per year for a
typical 1500 ft² residence (USDOE, 2014). With the annual savings achieved from increasing reflectance, the payback period to offset the increased cost of glass granules with pigments is estimated at 1.8 years, which is a relatively short period of time as compared to the service life of a residential roof.

5 CONCLUSIONS

Results show that glass cullet received from source recycling plants are generally coarse grained aggregate and therefore must be ground or crushed in order to be applied into the manufacturing process of asphalt roof shingles. Typical asphalt shingles are characterized by low reflectance, and results show that reflectance values were influenced only by the type of top surface aggregate utilized, and the type of filler material had no effect on reflectance values. The results show that a typical black ceramic coated asphalt shingle produced reflectance values from of 0.036-0.040. Replacing the top surface granules with green glass produced reflectance values of 0.069 and clear glass from 0.086-0.090. In order to achieve cool roof attributes, the addition of a white pigment mixed together with the top surface granules increased reflectance to 0.263 for green glass and 0.254-0.275 for clear glass.

Glass modified shingles were tested for durability by measuring resistance to tearing. Conventional and glass modified shingles exceeded the minimum standard for tear strength of 1700 grams and showed no significant differences between the means. Compared to a conventional black shingles, initial costs analysis shows only a modest increase in material costs of $0.112 per ft² to produce glass modified asphalt shingles with pigments, but annual savings of $0.061 per ft² per year in building energy consumption can be achieved through the increased reflectance. Based on the results of this study, it is concluded that glass cullet can be successfully blended with conventional materials to produce a sustainable asphalt shingle that has a solar reflectance of greater than 25% without compromising performance.

6 ACKNOWLEDGEMENTS

The author would like to acknowledge Ghesquiere Plastic Testing Inc. for providing tear strength testing, Lhoist North America for providing limestone filler material, BlendTec for providing a mixer, Strategic Materials Inc. for providing glass cullet, 3M Industrial Mineral Products for ceramic coated roofing granules, and the Louisiana Transportation Research Center (LTRC) for granting us access to their laboratories.

7 REFERENCES

THERMAL COMFORT ASSESSMENT THROUGH MEASUREMENTS IN A NATURALLY VENTILATED LEED GOLD BUILDING

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Abstract: Reductions in electric power consumption at the University of Washington are an established sustainability performance target. In order to meet this target, Leadership in Energy & Environmental Design (LEED) certification of buildings on campus is part of a long term plan for the University. It has been assumed that LEED certification will result in less power usage by occupants while improving indoor environmental quality. However, the related indoor environmental quality for these certified buildings has not been evaluated in situ. The primary objective of our study was to investigate the indoor quality assessment, more specifically in this paper, we discuss the thermal comfort of a LEED Gold building through both in-situ measurements of temperature, humidity, and occupant comfort surveys. Three measurement stations have been implemented in a low-rise retrofitted Student Union Building starting April of 2014: two in a food court or commercial kitchen environment and the other in a small office. Surveys to assess the comfort levels of both populations have been undertaken. The resulting data set is rich in terms of providing technical and nontechnical feedback on the thermal comfort of a LEED certified building. Preliminary findings indicate that thermal comfort parameters employed for heating, ventilation and air-conditioning systems control were not optimum in practice.

1 INTRODUCTION AND BACKGROUND

In 2009, University of Washington (UW) President Mark A. Emmert stated his intent to establish a climate-neutral campus having no net greenhouse gas emissions (University of Washington Climate Action Plan Oversight Team 2009). As part of a plan to accomplish this goal, over 216 smart meters have been placed on buildings on the Seattle campus to monitor energy consumption through the related Pacific Northwest Smart Grid demonstration project. Another major strategy adopted by the university is to require high-performance building standards (University of Washington Climate Action Plan Oversight Team 2009). As a founding signatory of the American College and University Presidents’ Climate Commitment, UW uses the United States Green Building Council’s (USGBC’s) Leadership in Energy & Environmental Design (LEED) rating system for all buildings on the UW campus. According to UW’s Environmental Stewardship and Sustainability Office, the number of LEED-certified buildings has increased from 15 in 2011 to 27 in 2013.

The newly renovated UW Husky Union Building (HUB) (i.e., the Student Union Building) received a LEED Gold rating. To achieve these goals, dramatic changes were made to the building. New mechanical, electrical, lighting, and audiovisual systems were brought into the building to replace antiquated systems, although half of the building’s more than 60-year-old superstructure was preserved (Bussard & Chan 2012,
“The University of Washington opens newly renovated husky union building” (2012). In addition, a series of sustainable elements were incorporated into the new HUB. For example, the newly designed atrium, the large expanses of glass, and supporting mechanical systems created a naturally illuminated and ventilated building. As a result, in principal, the indoor environment can be improved while energy usage is reduced. This led to the research question of this study: does the LEED-certified Gold HUB perform according to protocols established by agencies such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the Charted Institute of Building Services Engineers, and USGBC in terms of thermal comfort?

Studies about occupant and indoor environmental quality (IEQ) in green buildings have focused mostly on occupant surveys without investigating the on-site physical measurements of the indoor environment (Abbaszadeh et al. 2006, Altomonte and Schiavon 2013, Asmar et al. 2014) and mostly for office buildings (Radwan et al. 2013). This study takes into consideration both the subjective (occupant surveys) and objective (physical measurements) aspects of indoor environment in a LEED-Gold certified building. In addition, IEQ measurements for commercial kitchen environment were undertaken.

2 RESEARCH OBJECTIVE

The predicted energy performance of a building is based upon several assumptions about the indoor environment quality such as the indoor temperature, relative humidity, CO₂ levels, lighting and acoustics. In this paper, we present one segment of preliminary findings of a long-term investigation focused on the development of a comprehensive framework to evaluate the effectiveness of sustainable practices used in new and existing green buildings. Specifically, we characterize the in situ IEQ for a naturally ventilated LEED Certified Gold building through physical measurements and occupant surveys. This paper presents the collected data on temperature, humidity, and occupant comfort surveys in both a small office and a commercial kitchen environment of a naturally ventilated LEED Gold building on UW campus in the year of 2014.

3 METHODOLOGY

3.1 Equipment Selection and Set-Up

After investigating the required measurement equipment, the research team mounted all the handheld devices on a moveable I.V. pole and delivered the three measurement stations to the office and the kitchen. The research team consulted multiple references (ASHRAE, USGBC, & CIBSE 2010, ASHRAE 2009, Haruyama et al. 2010, Simone et al. 2013, Stoops et al. 2012) to evaluate the necessary equipment for accessing the IEQ of the office area and commercial kitchen. Table 1 lists all the purchased equipment related to measurement of air temperature (Ta), globe temperature (TG), and relative humidity (RH) for the study to physically measure the thermal comfort parameters. Mounting heights were also extracted from existing sources (ASHRAE 2013a) and are summarized in Table 2.
Table 1: Partial specifications of instruments used in this study

<table>
<thead>
<tr>
<th>Parameter (Abbreviation)</th>
<th>Unit</th>
<th>Model Name</th>
<th>Sensor Type</th>
<th>Accuracy</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature (Ta)</td>
<td>°C</td>
<td>REED SD-4214 Thermo-anemometer/Data Logger</td>
<td>Telescoping Hot Wire Slim Probe (12-mm Diameter)</td>
<td>±0.4°C</td>
<td>0°C~50°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>±0.9°C from 40°C to 60°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>±0.5°C from 5°C to 40°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>±1.1°C from -20°C to 5°C</td>
</tr>
<tr>
<td>Globe Temperature (TG)</td>
<td>°F</td>
<td>Extech HT30</td>
<td>Black Ball: 1.57 Diameter, 1.37 Height</td>
<td>TG Indoor: ±4°F</td>
<td>TG Outdoor: ±5.5°F</td>
</tr>
<tr>
<td>Relative Humidity (RH)</td>
<td>%</td>
<td>Fluke 975 Airmeter</td>
<td>Built-in</td>
<td>±2% RH (10% RH to 90% RH)</td>
<td>10% to 90% RH, Non-condensing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HOBO U12 Temp/RH/Light/External Data Logger</td>
<td>Built-in</td>
<td>±2.5% RH (10% RH to 90% RH), to a Maximum of ±3.5%</td>
<td>5% to 95% RH</td>
</tr>
</tbody>
</table>

Table 2 Vertical placement information for the instruments

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Height (above Floor)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>0.1, 1.1, and 1.7 m</td>
<td>0.1, 0.6, and 1.1 m</td>
</tr>
<tr>
<td>Air velocity</td>
<td>0.1, 1.1, and 1.7 m</td>
<td>0.1, 0.6, and 1.1 m</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>1.1 m</td>
<td>1.1 m</td>
</tr>
</tbody>
</table>

3.2 Testing Location Selection

Three locations were used for data gathering. The selection of each location was based on how well it represented the surrounding area. Through consulting the kitchen and office staff, the research team decided that these locations were ideal in terms of keeping the impact of the data measurements on normal business operations to a minimum level. Within the kitchen environment there were two data-gathering
locations. The first location was near the restaurant’s cooking equipment. The second location was identified near the dishwashing machine. In the office, the unit was located in the general occupant seating/desk area.

3.3 Survey preparation

The International Organization for Standardization and ASHRAE have established indoor thermal environment standards. The Center for the Built Environment (CBE) of the University of California, Berkeley provided an occupant IEQ survey for researching building performance (Center for the Built Environment n.d.). The survey covers thermal comfort, indoor air quality, lighting/daylighting, and acoustics and served the purpose of this study. The CBE also has large databases of accumulated survey results. Therefore, the research team chose to use the CBE survey for occupants in the office inside the HUB.

The kitchen area is a different indoor environment from the office areas. The main activity in the HUB kitchen is cooking, which generates heat and effluents that must be captured and exhausted in order to control and guarantee thermal comfort and good air quality for the employees (ASHRAE 2009). Relatively little research has been conducted regarding thermal comfort in commercial kitchens. Therefore, a standardized survey for commercial kitchen employees could not be found. Haruyama (Haruyama et al. 2010) used questionnaire surveys to evaluate subjective thermal strain in different kitchen working environments in Japan. In the United States, ASHRAE-supported research (Simone et al. 2013, Stoops et al. 2012) investigated the thermal comfort in commercial kitchens of different types and locations in different climatic zones. A modified version of Stoops et al’s “Thermal Comfort in Commercial Kitchens Survey” was used in this research to collect subjective measurements. The modified survey contained 36 questions covering background information, personal comfort, personal control, work conditions, environmental sensitivity, and clothing.

Both the office and kitchen surveys were pre-tested with the HUB associate director. Based on the feedback, kitchen survey questions about building features including window blinds, roller shades, exterior shades, and security systems were deleted since they were not available or accessible to most kitchen staff. Questions in the office survey about exterior shades and the security system were also deleted given their limited installation.

4 PRELIMINARY RESULTS AND DISCUSSION

The preliminary results are provided for the thermal comfort measurement in the office and the kitchen. The results of the thermal comfort measurements include the indoor operative temperature, measured data as plotted in the graphic comfort zone, and the vertical temperature difference measured at 0.1, 1.1, and 1.7 m. The results for the office area were assessed separately for occupied hours for both summer months and autumn months. Summer months were from June through August. Autumn months were from October through November. Survey results were used to assess whether these objective data aligned with the occupants’ subjective assessment of the thermal comfort.

4.1 Measured Thermal Comfort Data

4.1.1 Office Area

Figures 1 and 2 contain representative time series plots comparing the daily average five-minute mean indoor operative temperature readings for the working hours for the summer and autumn, respectively. The indoor operative temperature (ASHRAE 2009) represents the temperature of a uniform environment that includes the effects of relative humidity. The globe temperature measurement is used as equivalent to the indoor operative temperature. Excursions of peak values above and below the 80 percent ASHRAE acceptability limits as defined in ASHRAE 55-2013 Section 5.4 occur occasionally, especially early in the morning during the summer months due to the free-cooling strategy, night ventilation. The 80 percent limits are a function of the outdoor temperature and vary as the weather changes. The statistical variance in the record is much smaller for the autumn readings.
Figure 1: Representative time series data for globe temperature TG (°C) in the office during working hours in the summer.

Figure 2: Representative time series data for globe temperature TG (°C) in the office during working hours in the autumn.

Figures 3 and 4 contain the measured data as plotted in the graphic comfort zone method for identifying the acceptable range of dry-bulb temperature and humidity as defined in Section 5.3 of ASHRAE Standard 55-2013 (ASHRAE 2013). For summer, the 0.5 clothing insulation zone is shown in Figure 3. Both the 0.5 clothing zone and the 1.0 clothing zone are shown in Figure 4 for autumn to reflect the clothing choices made by the office workers. The data often extended beyond the suggested comfort zones during the summer months. The plots illustrate the variability in the ranges of thermal comfort in the summer, with a wider, more acceptable range in the autumn.
Figure 3: Graphic Comfort Zone for working hours (8 am to 8 pm) in the office during the summer. The “boxed” area with dash line shows the 0.5 clothing zone.

Figure 4: Graphic Comfort Zone for working hours (8 am to 8 pm) in the office during the autumn. The two “boxed” areas represent the 0.5 (dash line) and 1.0 (solid line) clothing zone.

The vertical temperature difference in the office was also investigated but did not exceed the recommended ASHRAE limit of 3°C during the study. The ASHRAE limit of 3°C was occasionally violated during summer (1.81 percent of the time during summer months and 0.36 percent of the time during summer and autumn months). Most of the violations happened between 5 p.m. and 6 p.m.

4.1.2 Kitchen Area

Indoor temperatures at various vertical locations in the kitchen cooking area were notably different. ASHRAE Standard 55 recommends that the vertical air temperature difference between 0.1 and 1.7 m should not exceed 3°C. Figure 5 shows the five-minute average air temperature on a weekday at three heights as well as the spatial average. During the peak service hours, which are from 11:00 am to 1:30 pm, the spatial average ranged between 26 and 28 °C while the temperature at 1.7 m was above 27°C. The vertical air temperature difference was above the ASHRAE recommended limit 17 percent of the time for a particular day.
Figure 5: Five-minute average indoor air temperature in the cooking area on Wednesday July 2, 2014.

Figure 6 shows the five-minute average air temperature near the dish-washing machine on a weekday. Similar to the cooking area, the spatial average temperature ranged between 26 and 28°F during peak service hours. The vertical air temperature difference was also above the suggested standard limits 38 percent of time for that particular day.

In the cooking area, the difference in the vertical temperature gradually increased from 10 a.m. and peaked around 12:30, followed by a gradual decrease. The dishwashing area showed recurrent peaks and valleys, most likely due to the fact that heat was generated when the dishwashing equipment was in operation intermittently to clean the cooking utensils, dishes, cutlery, and other items. In the dishwashing area, the vertical temperature difference peaked around 14:30. This lag of about two hours was observed as the kitchen cooking activities peaked and started to decrease at about 12:30.

Figure 6: Representative five-minute average indoor air temperature near the dishwashing area on Thursday July 24th, 2014.

Figures 7 and 8 contain the measured data as plotted in the graphic comfort zone method for identifying the acceptable range of dry-bulb temperature and humidity as defined in Section 5.3 of ASHRAE Standard 55-2013 (ASHRAE 2013). For both the cooking and dish washing area, the “0.5 and 1.0 clothing insulation zone” is shown in Figures 7 and 8. The data repeatedly extended beyond the suggested comfort zones in both kitchen areas.
Figure 7: Graphic Comfort Zone for cooking area (6 am to 9 pm) in both summer and autumn. The solid “boxed” area shows the 1.0 clothing zone. The dashed “boxed” area shows the 0.5 clothing zone.

Figure 8: Graphic Comfort Zone for dishwashing area in both summer and autumn. The solid “boxed” area shows the 1.0 clothing zone. The dashed “boxed” area shows the 0.5 clothing zone.

### 4.2 Survey Results Regarding Occupants’ Thermal Comfort

#### 4.2.1 Office Area

The survey used seven-point ordered scale questions to evaluate the occupants’ satisfaction with the thermal comfort parameters. These seven-point order scales ranged from very dissatisfied (0) to very satisfied (7), with neutral being the midpoint (3). The initial invitation to participate in the survey was emailed to only those six office employees that were stationed in the space where the continuous measurements of the IEQ were being collected. However, recognizing that the building (HUB) serves 54 other permanent employees throughout the various office spaces, an identical survey was made available online to capture the responses from a greater number of occupants of the building. A total of 41 responses were collected out of 60 employees, which resulted in a 68.3 percent response rate. This also exceeded the ASHRAE Standard 55 (ASHRAE 2013) requirement for having at least 35 percent of occupants respond to the post-occupancy survey for evaluating the IEQ in a subjective manner.
Determining thermal comfort included asking questions about the indoor temperature in the workspace. On average, the respondents indicated feeling slightly above the neutral level at 3.5. However, about 40 percent of respondents were slightly to very dissatisfied (range from 0 to 2) with the indoor temperature. Of those people that were dissatisfied, 75 percent of them actually had a portable fan in their workspace, and 37 percent had access to window blinds or shades and/or operable windows. In conclusion, 94 percent of the occupants that expressed discomfort had means to individually control their environment with personally adjustable or controllable systems in place. None of the occupants indicated discomfort from the cooler morning temperatures.

4.2.2 Kitchen Area

The kitchen survey asked employees questions about air movement and discomfort. The employees of the kitchen area consist of regular staff and temporary student employees. Fifteen regular staff members worked in the kitchen at the time of assessment. The manager distributed 15 paper copies of surveys to the regular staff, and all 15 copies were answered and returned.

Over half of the employees (60 percent) did not feel adequate air movement normally during work. Those employees complained about excessive heat from ovens or woks, and suggested increasing air flow and installing air conditioning or fans. Seventy-three percent of the employees stated that they did not feel comfortable most of the time. Most of them felt warm at the front and back of their bodies. Regarding different environmental conditions in the kitchen that could cause discomfort, “too high temperature” and “sweating” bothered most of the employees. Complaints of other conditions such as “draft” or “smoky kitchen” were relatively low.

5 CONCLUSION

Occupants of the offices were mainly satisfied with the thermal comfort of the building. Nevertheless, slightly lower and higher room temperatures were observed during early mornings and late afternoons in the summer. The free-cooling strategy, night ventilation, was successful in reducing the indoor operable temperature to a comfortable level in the morning. Without a mechanical air-conditioning system in the office spaces, the rise in outdoor temperature during the summer afternoons, in combination with the higher occupancy rate, increased the temperature to exceed the 80 percent ASHRAE acceptability limits as defined in ASHRAE 55-2013 Section 5.4. The survey showed that occupants were not bothered by the lower temperature in the morning but were disturbed by the higher temperature in the afternoons. Interestingly, 94 percent of those that were dissatisfied with the temperature had means to control their environment with personally adjustable or controllable systems such as windows and fans.

Objective measurement of the two kitchen areas, cooking and dishwashing, showed frequent exceedance of 80 percent ASHRAE acceptability limits as defined in ASHRAE 55-2013 Section 5.4. Complaints did exist among most of the kitchen employees about the indoor operable temperature. Specifically, these included low air movement causing discomfort with high temperature and sweating. An overwhelming number of respondents, almost three-fourths, indicated that most of the time they felt uncomfortable working in the kitchen. They suggested adding additional mechanical cooling systems.

The results presented here are preliminary and data collection continues through 2015.

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References


ENHANCING THE CONSTRUCTION SAFETY TRAINING BY USING VIRTUAL ENVIRONMENT: V-SAFE

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Abstract: Construction is one of the most high-risk industries in the world. The safety records of the construction sector report that, construction workers are approximately over three times more likely to be exposed to serious accidents comparing to other industries. In addition to these injuries and fatalities, work-related accidents also cause financial damage, conflictual cases and pecuniary penalties for the construction companies. Therefore, the significance of the safety management process has been increasing in the construction industry. However, since the majority of the construction activities are complex and require collaboration between the workers, the provision of the safety has become one of the challenging tasks. So, the behavior-based skills of the workers play a crucial role in the safety management. Traditional safety training methods have been merely focusing on information-based techniques such as lectures, videos, written materials, etc. On the other hand, previous research has indicated that adequate safety training should also involve behavioral modeling and hands-on training, together with traditional learning methods. Due to the nature of the construction projects, hands-on training in the construction field is not practicable. In this sense, using virtual environments is an effective method that enables a safe environment for the users without being exposed to adverse effects of the failed tasks. Thus, virtual environments allow visual simulation that is helpful for the improvement of the trainees’ behavior-based skills. Therefore, virtual environments provide an important opportunity to advance the level of safety training. The main aim of the study is to describe the developed virtual safety training environment called V-SAFE (Virtual Safety Analysis For Engineering applications), which involves methods to simulate, and visualize construction operation scenarios. V-SAFE is based on the Unreal game engine for the visualization of the environment, and USARSim is used for the high-fidelity simulation of the robot behavior and environment mapping. V-SAFE is projected to establish a base to identify construction-specific safety risks and to improve the behavior-based skills of the construction project participants. In brief, V-SAFE has high potential to improve the risk recognition capability, and situational awareness of the construction managers, workers, safety managers, field engineers. So, V-SAFE could be beneficial for the construction organizations aim to advance the effectiveness of the safety training.

1 INTRODUCTION

The number of fatal accidents in the construction industry indicates the risky environment of the construction projects. During a 10 year period between 2004 and 2013, 558 fatal accidents were recorded in Canadian construction industry which was accounted for the highest number of fatal occupational
accidents of any industry sector (Workplace Safety and Insurance Board, 2013). Quite similarly in the
United States, around 800 occupational fatal accidents occurred in the construction industry that
correspond to 11.8 per 100,000 full-time equivalent workers in 2013 (U.S. Bureau of Labor, 2014).
Moreover, the fatality rates did not differ in the European Union (EU) countries. Approximately 3,800 fatal
injuries occurred in 27 European countries in 2012 (Eurostat, 2013). Shortly, statistical results
demonstrate that construction workers are exposed to excessive on-site hazards that could result in injury
or even death. Therefore, we can conclude that occupational accidents in the construction industry are
still a major worldwide problem.

The occupational accident records clearly indicate inadequacies in the construction safety management
process (Waehrer et al., 2007). Coleman (1991) highlights that about 90% of the fatal construction
hazards could be avoided and 70% of these construction site accidents originate from the inadequate
safety management action. Similarly, Carter and Smith (2006) also show that hazard identification level in
the construction projects are not satisfactory, and 33% of the risks could not be precisely identified by the
workers. As a result of the insufficient hazard identification level in the construction field, accidents
inevitably occur on the construction site. One of the main reasons of the unforeseen hazards could be the
lack of adequate safety training for the workers in the construction industry (Helen and Rowlinson, 2005).
Several studies thus far have highlighted that efficient safety training could improve the hazard
identification and with this way the accidents could be prevented before they occur.

Moreover, previous studies (Hung et al., 2013; Aranda, 2000) have shown that, traditional training
methods might be able to improve the hazard identification level only to some extent that is not sufficient.
For instance, Hung et al. (2013) found that fall-protection training could be able to improve the
identification of some risk sources leading to the falls. Similarly, Aranda (2000) utilized the navigable
movies to set-up training program for the improvement of the hazard identification. However, all of these
training methods merely focus on the information transfer by using the materials such as lectures, 2D
drawings, photos, etc. Yet, previous research has indicated that adequate safety training should also
involve behavioral modeling and hands-on training, together with traditional learning methods (Burke et
al., 2006), but, the application of the highly engaging training in the construction field is not practical, it is
costly and even risky. Considering the need for an alternative safety training method, this paper
introduces a novel method using virtual reality that involves both behavioral modeling and hands-on
training in a risk-free environment.

2 LITERATURE REVIEW

The provision of the adequate safety training is one of the challenging tasks in the construction industry.
Therefore, in order to provide an effective safety training, identifying the critical issues for the
improvement of the safety training is important. Frese and Zapf (1994) state that, proactive training
methods are more efficient, comparing to passive techniques. In other words, Frese and Zapf (1994)
argue that conveying the safety information by practice plays a crucial part in the effectiveness of the
training. Similarly, Burke et al. (2006) extended the measurement of safety efficiency approach by
categorizing the training methods. Accordingly, Burke and colleagues identify three main safety training
methods; least engaging, moderately engaging and highly engaging (Burke et al., 2006). The least
engaging training methods are the information delivery systems such as videos, written information,
lectures, etc. The major limitation of the least engaging methods could be considered as only focusing on
the information delivery, rather than practical training. On the other hand, moderately engaging methods
also consist of quantitative feedback-based training methods such as questionnaires, interviews, etc.
Comparing with the least engaging methods, moderately engaging training methods also provide
feedback to the users. Finally, according to Burke et al. (2006) the most engaging active training methods
should cover the integration of the knowledge transfer and behavioral modeling. So, a precise safety
training should involve relevant information transfer, hands-on training, behavioral modeling, and
feedback mechanism (Burke et al., 2006). However, due to the nature of the construction projects, hands-
on training in the construction field is not practicable; it even increases the risk of accident.

In this sense, using virtual reality based training tools could be a suitable method for the trainees since
virtual training provides a safe work space for the users without being exposed to negative effects of the
failed tasks. Consistently, Sokolowski and Banks (2009) also state that the use of virtual simulation is useful when it is not possible to interrelate with the real system. So, the virtual system could be helpful to the users to apply the training recursively. Thus, they could learn from their mistakes and correct them. As a result, users could enhance their safety knowledge by modifying their safety attitudes and improving their cognitive abilities.

Similarly, virtual reality-based training systems have been used in several fields. Preliminary work on surgeon simulation was undertaken by Satava and Fried (2002) to describe the effects of using the virtual reality to advance the surgical simulation performance by the improvement of the relevant psychomotor skills. On their comparative experiment, results show that the use of the virtual training significantly improved the operation performance of the surgeons. Consistently, Lin et al. (2007) assessed the cognition capabilities of the drivers by quantifying the responses. The study shows that adequate virtual training could significantly improve the drivers' cognitive responses.

Similarly, virtual environments have been used in various fields in the construction industry as well, such as information management, geotechnical engineering, scheduling, structural design, etc. For instance, Arduino et al. (1997) developed an innovative virtual reality-based training platform for the trainees by using a geotechnical triaxial device. Study results show that virtual reality based training was helpful for the users to understand the soil behavior. In addition, a comparative study of Comu et al. (2011) measures the impact of the facilitation in a global project while the participants are geographically distant. Accordingly, results provide an insight into the role of the facilitation in the virtual project networks. Similarly, Wen et al. (2009) used the virtual reality for the training of the rigging operators. Results show that the trainees' operating skills were positively affected by the use of the virtual training.

The studies presented in different fields of the construction area point out that virtual reality has a great potential to improve the training level. Recent and growing body of literature has investigated the use of the virtual safety training tools in the construction industry. In a comparative analysis, Albert et al. (2014) aimed to improve the hazard recognition skills of the workers by using the virtual reality based safety training tool. As a result, a human-computer interactive augmented virtuality training platform was developed and cognitive mnemonics based on energy sources such as mechanical, electrical, etc. were presented. The results show that identifying hazards according to the energy-based cognitive mnemonics significantly improves the hazard identification level by the support of the systematic categorization. Similarly, a recent study by Guo et al. (2012) integrated serious gaming technologies into the construction safety management process to improve the training performance. The study reveals that the safety performance of the plant operatives and tower crane workers were significantly improved. Quite similarly, Le et al. (2014) developed a safety training tool for the safety education purposes. The system provides a role-playing platform for allowing the students for dialogic and experiential learning. Moreover, Park and Kim (2013) created a framework for the visualization of the novel safety management process by integrating building information modeling, location tracking, and augmented reality. Study results show that safety management visualization systems improve the hazard identification and the real-time communication between construction management team and workers. Taken together, these results indicate that the virtual safety training tools and visualization system improve the construction safety management by enhancing the effectiveness of the field safety risk identification, providing a better understanding for the workers about risk recognition, improving the real-time communication between construction manager and workers.

In the lights of these several studies (Albert et al., 2014; Guo et al., 2012; Le et al., 2014, Park and Kim, 2013) which contribute to the body of literature of construction safety management, we also aim to make a meaningful contribution. In this study, we analyzed the features, characteristics, and potential contributions of a virtual platform called V-SAFE (Virtual Safety Analysis For Engineering applications). In addition, the paper also discusses how the V-SAFE could be able to address the inadequacies in the construction safety training in a systematic manner by offering an enhanced and highly engaging training method. Hence, the study provides insights in a way that how virtual safety training could be applied in construction-specific training program. In addition, the study highlights that features of the virtual tools play an important role in the construction safety training.
3 RESEARCH METHODOLOGY

3.1 Overview of the Virtual Safety Analysis For Engineering applications (V-SAFE) Development

The main objective of this study is to develop a virtual reality based safety training tool for the construction industry. The tool simulates hypothetical construction activities in a three-dimensional (3D) virtual media. The main properties of the tool such as surrounding environment, reality integration, and collision detection, help to improve the hazard identification level of the users, and also advance their behavior-based skills. In other words, by using the V-SAFE, the trainees are exposed to real construction risks in a virtual simulation environment. Accordingly, users learn about the hazards they may face in their workplace and experience the potential consequences of their own mistakes or their colleagues' mistakes, in a safe virtual environment. In addition, this software also aims to enhance the performance of the operators since it provides repeatable training practice. In the virtual environment, workers are subjected to varied alternative incidents in putting up a brick wall. In this task, we defined two different roles as the crane operator and site workers that are assigned on-site duties. The task-based simulation consists of the major factors leading to hazards in the field, and trainees are asked to finish their task with appropriate safety behavior. Thus, the system aims to not only improving the hazard identification level of the workers, but also, enhancing the collaboration between different participants in the field.

V-SAFE is based on the utilization of the "Unreal Engine" by virtue of the "Unreal Software Development Kit". Unreal Engine (UE) is a cross-platform game engine written in C++ first released in 1998 by Epic Games, which is a popular game engine. The usage of the Unreal Game Engine is not limited to the games. NASA, U.S. Department of Transportation and Warner Bros are listed among the licensees of UE3 (Slashdot, 2006; Epic Games, 2011). Consequently, UE3 is also used in training, transportation and movie storyboard simulations.

Another component of the V-SAFE is USARSim (Unified System for Automation and Robot Simulation). USARSim is a robot simulation environment built using UE3. USAR enables combining the use of engineering and scientific application in the adequate virtual environment (Balakirsky et al., 2006). Recently, researchers have shown an increased interest in the use of USARSim, due to its broad range of expertise such as advanced locomotion systems, sensor fusion, cooperative multi-agent planning, human-robot interfaces and more. USARSim, an open-source project is funded by National Science Foundation, supervised by National Institute of Standards and Technology and used in rescue virtual robot competition league of RoboCup (Balakirsky et al., 2006). USARSim is designed to simulate disaster scenarios in which virtual robots perform rescue missions (Balakirsky et al., 2006). For this purpose, many robots and sensors are implemented in UE3. In the V-SAFE, USARSim is used to control autonomous agents in the simulation environments and observe the environment using sensors.

The general structure of the V-SAFE involves four major stages. In the first phase, users create their accounts and avatars. Hence, they could share their personal information through the media with the other users. Secondly, users select their simulation preferences using the Lobby Web Server interface via their web browsers. Thirdly, when all users are ready, the web browser starts the USARSim and Unreal Simulator with the given parameters. Finally, during the simulation, the USARSim, and Unreal Simulator communicate with the simulation coordinator running on the V-SAFE server. Simulation Coordinator tracks the state of the simulation on all users' accounts and synchronizes the simulation events when necessary. The structure of the V-SAFE training system that involves the data tracking and visualization is shown in Fig. 1.
As we mentioned, the V-SAFE is powered by Unreal Game Engine and Unreal Software Development Kit. So, all the components, functions, and digital tools were all developed through the Unreal Development Kit and USARSIm editors and the kits in the game engine. First of all, terrain editor function primarily aims the integration of the virtual terrain to the virtual scene (Mooney, 2012). The general virtual terrains are supported by the dynamic multiple layers of the deformable blended materials. Thus, virtual terrains such as grass, concrete, etc. could have been integrated into the virtual environment. Secondly, object modeling is also another important feature of the environment. In our study, we defined static and dynamic 3D objects related to the construction tasks such as the crane, building, electrical equipment, scaffold, machinery, etc. In the modeling process, object editor provided to input the geometric properties of the materials inside the virtual environment, accordingly the quality of the simulation is significantly enhanced. The third important feature of the engine is the collision detection system. This feature allows the users to move around and inspect the elements of the virtual environment. So, collision detection development advances the realistic effects of the virtual media (Mooney, 2012). By using these functions, all the simulation related elements were embedded into the virtual environment.

3.2 V-SAFE Training Procedure

The training procedure of the V-SAFE was based on three steps. In the first step, we identified all the possible hazards that could have occurred during the building up a brick wall task based on previous construction projects. In addition, we also considered the number of the identified hazards; precursors lead to these hazards, and their potential impacts. In other words, we defined which accidents are more likely to occur, how these hazards could be prevented and what are the possible effects of these hazards. By this systematic analysis of the hazards, we identified the most critical hazards for the simulated construction activities. In the second part, we defined these hazards into the virtual environment of the V-SAFE together with their probability of occurrence. During the identification of these hazards, we assigned three principal reasons of the hazard occurrence as material-based, safety knowledge-based and behavior-based. Thirdly, we associated these hazards with the objects and activities in the virtual environment. After the completion of three stages, we developed the main scenario. Thus, we finalized the V-SAFE virtual environment for the user interaction.

After the completion of the V-SAFE virtual environment, we conducted an alpha test in order to validate the functionality of the V-SAFE. The Alpha test was aimed to gather information about the strengths and limitations of the V-SAFE and to evaluate the fundamental functions of the virtual tool. So, the preliminary analysis of the V-SAFE could be conducted, and the tool could be upgraded considering the feedback provided by the trainees. During the preliminary analysis, firstly the trainees were assigned two different
roles that are the crane operator and the site worker. For instance, when building up a brick wall, the crane operator moves the necessary materials and equipment to the designated work area on the second floor. In the virtual environment, even though users attempt to fulfill their assigned duties individually, at the same time they closely collaborate in the environment. According to their behavior in the virtual environment, trainees could be possibly become subjected to different types of exposures such as falls, struck by the objects, electric shock, etc. Consequently, during the alpha testing, participants were asked to monitor and use the V-SAFE environment and models to evaluate the system competence for the user interaction.

During the interaction, trainees use the standard computer hardware such as keyboard, mouse and monitor. The viewpoint is based on the first person view of the avatar, and the users could move their avatar by using the keyboard and mouse (Fig. 2.).

Mouse provides the orientation of the character in z-axis while the keyboard provides the movement in x and y axes. During the virtual tour, the users could walk on the virtual terrain and interact with the static and dynamic 3D objects and other users by their avatars (Fig. 3.). So, the users can interactively take place within the simulation, and they can repeat the virtual training till the desired performance level is achieved.

4 DISCUSSION

In this research, we aimed to develop a highly engaging safety training tool, the V-SAFE, which involves necessary information transfer, hands-on training, behavioral modeling, and feedback mechanism. As mentioned in the literature, there are potential benefits of using the virtual reality based construction
safety training tools. In traditional hazard identification, the identification process is satisfied with the examination of the 2D materials such as drawings, structural and architectural designs, photographs and videos. However, this approach does not improve the spatial awareness and decision-making capabilities of the trainees. As a result, the cognition and vision of the users are extremely limited, and several potential hazard sources could be easily neglected, due to the lack of the third dimension consideration. However, the virtual environment could improve the spatial awareness by establishing a base for manipulating with the objects and navigating in the virtual environment. Thus, the hazards could be identified more effectively since 3D environment supports the correct safety information processing and enables collaboration among the users.

All previous studies (Albert et al., 2014; Le et al., 2014; Park and Kim, 2013) show that virtual construction safety training methods improve the hazard identification level, even though the methods used vary significantly. For example, Park and Kim (2013) aimed to integrate a question and answer procedure into the relevant hazard sources. Thus, the related safety questions about the risk sources could be directed to the trainees while the users encounter with the hazard source in the virtual environment. In that case, the virtual environment could be considered as a moderately engaging training method according the definition by Burke et al. (2006), since this technique focused only on the transfer and evaluation of the safety information. On the other hand, this method did not address behavioral modeling and safety attitudes of the users. Similarly, Le et al. (2014) developed a safety training tool based on the inspection of the virtual media. During the investigation of the different construction tasks, users can monitor potential hazards in the custom scenarios. However, this method still fails to evaluate the users’ safety behavior. In the same vein, Albert et al. (2014) developed a human-computer interactive augmented virtuality and cognitive mnemonics based on construction hazards and on-site energy sources. With this approach, the safety memories of the users were significantly improved, yet the study was not aimed to improve the behavioral safety approach. So, the common characteristic of all of these existing approaches could be considered as the usage of virtual training tools as the enhancement of the traditional methods while they are still at the moderately engaging level.

With the V-SAFE, we aimed to fill this gap in the literature by developing a tool that provides highly engaging safety training unique to the construction industry. First of all, we formed up an experiential learning method, for not only improving the hazard identification level, but also improving the users’ behavior-based safety skills at the same time. The term experiential learning refers to the process of learning directly from the experience (Gentry, 1990). However, processing the safety information through experience on the construction sites is not practical. In this sense, the V-SAFE tool provides a safe platform for hands-on training. With this way, users could accumulate their safety knowledge and improve their behavior. During the alpha test, each trainee was given a different role in the simulation. For instance, one of the users was responsible for the crane operation, which requires both the use of safety information and correct decision-making process. As a result of this interaction between the users and the surrounding virtual media, trainees oriented to improve their safety behavior and gain practical experience.

Another significant feature of the virtual construction safety training is the provision of the individual and interpersonal learning (Wen et al., 2009). In the learning process, self-learning is an important part of the safety training especially for the workers with insufficient safety knowledge. In the construction projects, falls are among the most common causes of occupational accidents. For instance, during the virtual training, the inadequate behavior of a user such as not wearing a full-body harness could lead to the falls. By realizing the consequence of such an action in the virtual environment, users could modify their safety behavior in the real workplace. As a result, trainees could learn about the construction hazards in the virtual environment and do not repeat the same hazardous actions on job-site. Just like self-learning, interpersonal learning is also another major part of the virtual safety training (Wen et al., 2009). The V-SAFE establishes a platform for the trainees that interact with other users and with this way learn from each other. For instance, when a user violates a safety rule in the virtual environment, other users could warn him to modify his action. Similarly, trainees can also observe the safety violations and take lessons from others’ mistakes. Therefore, utilizing the V-SAFE has a great potential to fulfill two primary learning models by providing collaborative tasks and multiuser environment.
One of the most important features of the simulated environments is providing the sense of reality (Park and Kim, 2013; Albert et al., 2014; Cheng and Teizer, 2013). In other words, the users interact with the surrounding environment and other participants as if it is in a real workplace. In the virtual environments, the sense of reality is also supported by spatial awareness of the users. Accordingly, by interacting with the 3D environment, the users can improve their hazard identification understanding. In order to provide a better hazard identification process, the sense of reality and the visualization quality of the virtual tool are extremely significant. In this sense, visual features, object modeling, etc. of the virtual environment should be realistic and visually effective. In the V-SAFE tool, UE3 supports several image quality functions such as rendering, auto adjusting, etc., which provides high-quality images and object modeling. As a result, users could be able to monitor the virtual environment and the objects in the high quality and full HD resolution. Briefly, more effective visualization by the V-SAFE has a high potential to improve the sense of reality and spatial awareness of the users.

This study demonstrates the features and potential benefits of the V-SAFE training tool based on the alpha test results. The results of the alpha test show that the main functions of the tool such as collision detection, terrain generation, static and dynamic models run without having a major problem. Moreover, we noticed that the multiuser environment of the V-SAFE successfully enabled both the user-to-user and the user-to-virtual object interaction. On the other hand, there are several limitations in this study. First of all, because the V-SAFE is at the alpha testing stage, the number of the scenarios, objects and assigned roles to the trainees were considerably limited. As mentioned, we defined only two major roles that are the crane operator and site workers. Also a single construction scenario, building up a brick wall on the second floor, was implemented. At this stage of our research, we only focused on developing the V-SAFE and identifying the work logic, methods and training procedure. In the following versions of the tool, we plan to simulate more construction process tasks among more roles. Consequently, we will conduct a pilot test of an upgraded version of the V-SAFE. Hence, we will be able to evaluate the training effectiveness of the V-SAFE more accurately.

5 CONCLUSION

The safety management of construction projects is extremely challenging due to projects’ dynamic and complex nature. Providing adequate training could be considered as an important element of the safety management process. Traditional safety training methods have been merely focused on information transfer techniques. The recent developed virtual safety training tools convey the safety information through a 3D supported environment that improves the hazard identification level of the users. Yet, the safety behavior of the users has not been taken into account. This study fills an important gap in the literature by recommending a highly engaging training method for the construction projects. In this study, we introduce the V-SAFE that is a virtual reality based safety training tool and also evaluate the potential benefits of using it in order to achieve a better safety performance level. We also showed that this tool can improve the risk recognition capability and the spatial awareness of the users. Consequently, the V-SAFE contributes not only to the literature on construction management but this novel method could be beneficial for the construction organizations that aim to advance the effectiveness of the safety training and hazard identification level.

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SOCIAL CAPITAL IN CONSTRUCTION PROJECTS: AN EXPLORATION

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Abstract: The concept and phenomenon of social capital has been identified as an organizing logic that can add value to project organizations. In this respect, social capital is conceptualized as both personal and impersonal linkages between individuals in project organization, the quality of these linkages, and the shared representations embedded within these linkages. Social capital provides a means of coordination and collaboration among project participants. However, given the novelty of the concept in construction settings and peculiarities of construction projects, key questions arise as to what represents and are the forms of social capital in project settings? We adopt a mixed methods approach to answer these questions. Data from a survey of 376 respondents and a case project converge into forming a coherent conceptualization of social capital in construction projects. The findings confirm the multi-faceted nature of social capital and reveal the mechanisms by which social capital facilitates project organizing. Social capital appears to be more acutely needed in construction projects. While structural capital provides the platform for information and influence transfer, relational capital provides psychological safety upon which cognitive capital is translated into task performance. We conclude by discussing both the theoretical and practical contributions of the study to the relational governance discourse in project management.

1 INTRODUCTION

There is an increased recognition of the importance of social context and relationships among participants in the management of construction projects (e.g. Anvuur et al. 2011; Bresnen 2009; Cheung et al. 2006; Fong and Lung 2007; Smyth and Pryke 2008). In the relational paradigm discourse, the learnt wisdom implies that relational issues are often the causes of breakdown in teams rather than the technical complexity of the project (Fong and Lung 2007). Under this backdrop, because construction projects are organized around a network of firms and individuals that are economically independent but technically interdependent (Rooke et al. 2003), and project participants relationships are embedded in those networks that are intertwined through social interactions, those relationships are important as they affect the level of cooperation among the participants. In this respect, the concept and phenomenon of social capital has been identified as a concept that can add value to the study of network-based organizations such as construction projects as it can be used to facilitate actions (Koh and Rowlinson 2012). However, given construction peculiarities, a key question that remains relatively unexplored is, what represents social capital and what the forms of social capital are in project settings? Adopting Nahapiet and Ghoshal’s (1998) conception of social capital, another key question posed in this paper is, what are the manifestations and effects of structural, cognitive, and relational dimensions of social capital in project settings? We employed a mixed methods approach to answer these research questions.
2 PROJECT SOCIAL CAPITAL

2.1 Relevance of Social Capital in Construction Projects

For the purpose of our study, project social capital is defined as the sum of the actual and potential resources embedded within, available through, and derived from the network of relationships possessed by an individual or a cluster of individuals that can be used to achieve the goals of a project (Brookes et al. 2006; Nahapiet and Ghoshal 1998).

A project organization is characterized by factors that are germane to the application of social capital. These factors include interdependence, intensive social interactions, and closure. While providing a condition for project operations, the high level of mutual interdependence also promotes social capital by increasing the opportunity of participants’ interactions (Nahapiet and Ghoshal 1998). In this respect, project organization provides a community, a space to bring together project participants for the performance of tasks in terms of supervision, coordination, and mutual adjustment (Mintzberg 1979). The project operational features also render a need for social capital. Because a project organization is established for a specific purpose to be realized in a definite time, the intensity and dynamics of social interactions in project organization are much higher if compared with those in permanent organizations. As network type of organizations often lack a central authority (Poldony and Page 1998), the coalition formed by project participants requires social mechanisms such as trust and reciprocity to function effectively (Jones et al. 1997; Powell 1991). In terms of closure, although permeable to some extent, a project organization nevertheless has a social boundary that separates members from non-members (cf. Bourdieu 1986). This closure is conducive to the development of norms, identity, or even trust among participants. It is this feature of closure that leads especially to the development of cognitive and relational type of social capital (Coleman 1990; Nahapiet and Ghoshal 1998).

2.2 The Three Dimensions of Social Capital

The three dimensional conception of social capital propounded by Nahapiet and Ghoshal (1998) comprises the structural, cognitive and relational aspects. The structural dimension refers to the impersonal configuration of linkages between persons or social units. The main facets under this dimension are network ties among project participants and the existence of approvable organization that is created for one purpose but can nevertheless be used for other purposes (Coleman 1988; Nahapiet and Ghoshal 1998). The cognitive dimension refers to those aspects that provide shared representations, interpretation, and system of meaning among group members (Nahapiet and Ghoshal 1998). It reflects the condition whereby project team members share a common understanding (Bolino et al. 2002) and the extent to which they have developed a shared cognitive scheme among themselves (Maurer and Ebers 2006). The relational dimension is characterized by the personal relationships actors develop among themselves through the history of interaction (no less in the construction project settings) (Granovetter 1992). Relational dimension involves emotional closeness and reciprocal services among actors (Granovetter 1973). This dimension concerns interpersonal connections that are affective in nature (Krackhardt 1992). It focuses on the quality of the relationships in terms of trust, intimacy, obligations, expectations, etc. (Bolino et al. 2002). The importance of relational dimension lies (with the cognitive dimension) in its ability to facilitate control on project participants.

3 METHODS

The research questions of the present study concerns the exploration of social capital in construction project settings. There is a need to employ both quantitative and qualitative approaches – triangulation (Jick 1979). With the use of the two approaches, we seek to complement the results obtained from one method with those from the other and, in some instances, expand the breadth and range of our inquiry on the phenomenon of social capital in projects (Greene et al. 1989). Questionnaire survey and case study were chosen as the research methods for the study. We employed mixed methods sampling which incorporated both probability (survey) and purposive (case study) samplings (Teddlie and Yu 2007). For the questionnaire survey, responses were solicited from industry practitioners who were either working on on-going construction projects or participated in recently completed projects. We targeted project
managers, site agents, architects, engineers, quantity surveyors, and supervisors/foremen in various capacities as respondents. Their names and contact details were randomly drawn from the membership of professional institutions, trade associations, and governmental departments. In all, 2,186 practitioners were identified and invited to participate in the survey. We received a total of 376 valid responses (17.2% response rate). Of the respondents, 90.2% are male. On the age bracket, 86.3% of the respondents are between 31-60-year old within which 41.7% of them are between 41-50 years old. More than 90% of them have at least 5 years of project experience. Slightly over half of the respondents (50.8%) worked on building projects. The remaining worked on civil engineering (47.6%) and process plant projects. We operationalized the structural dimension with network ties (NW) and informal grouping (IF), the cognitive dimension with shared understandings (SU), and the relational dimension with trust (TR) among project participants (see Fig. 1 for the scales). For the case study, we selected a building construction project known as Project Eastern for the study. Based on our preliminary observations, this project’s procurement system, partnering arrangement, and organizational structure provide relevant settings for us to both investigate and illustrate the phenomenon of social capital. Table 1 provides further descriptions of the case project together with the informants selected for the case study.

<table>
<thead>
<tr>
<th>Project Descriptions</th>
<th>Core Project Team Members Interviewed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client: Government department</td>
<td>Client organization:</td>
</tr>
<tr>
<td>Contract sum: HK$434 million (US$1:HK$7.8)</td>
<td>Senior Architect (SA) 1</td>
</tr>
<tr>
<td>Contract period: 36 months</td>
<td>Project Architect (PA) 1</td>
</tr>
<tr>
<td>Contract type: Traditional design-bid-build, with six work packages under modified guaranteed maximum price (MGMP) arrangements with some contractor’s design elements</td>
<td>Structural Engineer (SE) 1</td>
</tr>
<tr>
<td>Project features: The Phase 4 (of six phases) of public rental housing project involving the construction of three 41-storey blocks of about 2,300 domestic flat units, with auxiliary civil and structural works</td>
<td>Building Services Engineer (BSE) 1</td>
</tr>
<tr>
<td>Publicly high visibility project with novel MGMP procurement arrangement</td>
<td>Resident Engineer (RE) 1</td>
</tr>
<tr>
<td>Full compliance of the Independent Checking Unit (ICU) with the contractor’s designs</td>
<td>Project Clerk-of-Work (PCOW) 1</td>
</tr>
<tr>
<td>Numerous new initiatives that render the project a “research project” – new designs, administrative procedures, etc.</td>
<td>Contractor organization:</td>
</tr>
<tr>
<td>Project management teams: Two primary teams: the client (as both designer and project manager), and the contractor</td>
<td>Senior Project Manager (SPM) 1</td>
</tr>
<tr>
<td>Data collection period: April 2007-May 2008</td>
<td>Site Agent (SAgt) 1</td>
</tr>
<tr>
<td></td>
<td>Quality Control Manager (QCM) 1</td>
</tr>
<tr>
<td></td>
<td>Senior Project Quantity Surveyor (SPQS) 1</td>
</tr>
<tr>
<td></td>
<td>Senior Building Services Engineer (SBSE) 1</td>
</tr>
<tr>
<td></td>
<td>Project Supervisor 1</td>
</tr>
<tr>
<td></td>
<td>Health, Safety and Environmental Officer (HSEO) 1</td>
</tr>
<tr>
<td></td>
<td>Total 13</td>
</tr>
</tbody>
</table>

4 QUANTITATIVE DATA ANALYSES

We used confirmatory factor analysis (CFA) to examine the dimensional structure of social capital (SC) and to test the convergent and discriminant validity through a measurement model using the proposed constructs of NW, IF, SU and TR. Preliminary model exploration suggests that IF is represented with only one item. The final measurement model indicated that all items have loading in excess of the minimum 0.5 (Hair et al. 2006: 777) at p<0.001. The model has also yielded adequate goodness of fit (chi-square = 274.14, degree-of-freedom = 163, p-value = 0.00, TLI = 0.96, CFI = 0.97, RMSEA = 0.04). Table 2 shows the validity measures, descriptive statistics, and the reliability measures. From Table 2, while most of the variance extracted (VE) for constructs are greater than the required 0.5, the VE for IF is lower at 0.30. Although the value is less than 0.5, but because informal grouping is an important facet of the structural
dimension of social capital, we decided to keep the construct in the model (cf. Hair et al. 2006). For discriminant validity, the VE for each construct is greater than the squared correlation between the focal construct and other construct in comparison. These results imply that, with the exception of IF, the requirements for both convergent and discriminant validity of the constructs are generally met.

<table>
<thead>
<tr>
<th>Construct</th>
<th>Number of items</th>
<th>Means</th>
<th>Cronbach’s alpha</th>
<th>Squared correlation (VEs on diagonal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network ties, NW</td>
<td>2</td>
<td>17.04</td>
<td>0.71</td>
<td>0.55</td>
</tr>
<tr>
<td>Informal grouping, IF</td>
<td>1</td>
<td>2.84</td>
<td>n.a.</td>
<td>0.12</td>
</tr>
<tr>
<td>Shared understanding, SU</td>
<td>9</td>
<td>4.21</td>
<td>0.91</td>
<td>0.02</td>
</tr>
<tr>
<td>Trust, TR</td>
<td>8</td>
<td>4.01</td>
<td>0.86</td>
<td>0.04</td>
</tr>
</tbody>
</table>

We construct the higher level SC model from the measurement model by introducing the higher lever SC construct that link lower constructs of NW, IF, SU, and TR. The final SC model is shown in Fig. 1.

![SC Model Diagram](image)

The scales used (SPE in bracket):

- **Network ties, NW** (Hatata 2006)
  - H1: Number of persons provide help at work (0.56)
  - H2: Number of persons provide social support at work (0.99)

- **Informal grouping, IF** (Nahapet and Ghoshal 1998)
  - H3: Usefulness of informal grouping (0.49)

- **Shared understanding, SU** (Pinto et al. 1993; Sarker et al. 1998; Tsai and Ghoshal 1998)
  - C1: Shared vision (0.65)
  - C2: Collective goals (0.70)
  - C3: Collective rules (0.70)
  - C4: Shared understanding of project requirements (0.76)
  - C5: Shared culture (0.83)
  - C6: Shared understanding of others’ requirements (0.73)
  - C7: Common understanding emerged (0.71)
  - C8: Shared technical knowledge (0.66)
  - C9: Common thinking emerged (0.82)

- **Trust, TR** (Chen and Huang 2007; Cummings and Bromilow 1996; Nyhan and Marlowe 1997)
  - E9: Meet obligations (0.74)
  - E7: Confident of abilities to perform (0.74)
  - E13: Well thought out decision (0.74)
  - E16: Members are reliable (0.86)
  - E6: Fair treatment (0.61)
  - E8: Tell truth in negotiations (0.70)
  - E12: Not misleading (0.65)
  - E15: Negotiate expectations fairly (0.74)

Figure 1: Second-order social capital (SC) model with standardized parameters estimates (SPE)

In the SC model shown in Fig. 1, although all the estimates are statistically significant, the two constructs that represent structural dimension yielded estimates that are lower than 0.5 – 0.22 for the path SC-NW, and 0.49 for SC-H3. While the slightly lower 0.49 path H3 is acceptable, the 0.22 NW path is less desirable. However, Hair et al.’s (2006: 798) have cautioned, because NW (and IF) represents the mainstay of structural dimension of SC, and that it demonstrates adequate internal consistency and convergent validity (0.71 and 0.55, respectively, see Table 2), NW and IF are retained in the model.

5 QUALITATIVE DATA ANALYSES

We used interview data as the main source of information complemented other data types. We used broad-base questioning topic guide to solicit project informants’ views on the manifestation and formation of social capital, and its impacts on team interactions. We performed thematic analysis for the data.
collected. In Project Eastern, the client team assumed dual role of project manager and designer. They were responsible for design-related issues - design management and getting approval - and contract administration. With the novel modified guaranteed maximum price (MGMP) system which incorporated the contractor’s design, there was a need for full compliance of Independent Checking Unit’s (ICU) requirements. Contractor’s designs must be approved by the more stringent ICU prior to site works. The contractor’s design had to be submitted through the client’s structural engineering division. Handling the ICU submissions and approvals had become significant affairs. To manage design-related issues, the project architect (PA) had convened frequent design meetings dubbed “working sessions.”

5.1 Manifestation of Structural Dimension and Position

Structural dimension serves both explicit and implicit functions. The positions of participants and bridging are the explicit function. The internal network interweaved both the client and contractor project personnel into the core team for the project. Multi-connections were present forming a closed network that facilitated information transfer both laterally and vertically across hierarchies. Bridging involved connecting the actor’s team to other networks that were related to the activities of the focal team. In the project the SAgt had attempted to match and link his own contractor's key staffs to those from the client organization. This network was established with reference to the communication matrix set up during partnering sessions. Both the client’s and contractor’s key staff were encouraged to communicate directly among themselves with reference to their positions and areas of responsibilities in the matrix thereby enabling faster, timely, and more accurate communication through the re-configured network.

Implicit functions are associated with the indirect effects that can be derived from an actors’ position in the network. In Project Eastern, the project clerk-of-work (PCOW) had demonstrated leadership to his frontline junior COWs. The latter were initially insistent on the contractor to deliver highest quality standard of works resulting in slow work progress. Sensing the issue and in the bid to improve progress, the PCOW attempted to convince his subordinates to adopt a more practical stance. With his “imposed” leadership and the contractor’s improved work quality, progress slowly picked up. Here, leadership leverage to improve outcome was effected through and contingent upon personnel occupying strategic positions in the projects. Another implicit function is that of legitimacy. In the project, when some of the contractor’s designs of the MGMP packages were disapproved by the ICU, the client team led by the PA helped the contractor to convince the ICU of the adequacy of the designs.

An intriguing effect of structural dimension is the existence and effects of informal grouping and ties. In Project Eastern, the emergent grouping comprised the client and contractor teams, and the subcontractors. As numerous discussions were needed for the design, frequent and intensive design meetings – “working sessions” - were organized among a wide range of participants occupying different hierarchical levels in the project. This resulted in speedier issues resolution as the arrangement “helps to reduce unnecessary corresponding work” (PA). The intensity of the interactions of all parties also helped foster group cohesion and trust building. The PA proclaimed: “We sit down together once a week or twice a month to resolve design issues, and by doing that, actually we build up trust very efficiently.”

5.2 Manifestation of Cognitive Dimension and Shared Understanding

The first kind of shared understanding is the common goals for all parties. Generally, for Project Eastern the common goals for the core teams were timely completion and meeting project budget. Because of the need to achieve common goals, coupled with the need to face the uncertainty and increased workloads for all parties inherent in the string of new initiatives, a sense of solidarity within the core team emerged (more on solidarity later). The PCOW expressed it this way: “The shared goal is just the same... Actually we are the same, we are on the same boat.” This atmosphere instilled a sense of team cohesion and willingness to share responsibilities among team members in the project. Relatedly, the understanding and appreciation of each other’s constraints among the participants are other kinds of shared understanding. This phenomenon is illustrated by the late issuance of structural drawings from the client’s organization resulting from the sudden surge in the number of projects and a shortage of design personnel at the beginning stage of the project. The late issuance affected the contractor’s work planning. The client’s structural design team admitted their inability to produce the drawings on time. They hence
entertained the contractor’s requests for design-related information on urgent basis to mitigate further delay in the contractor’s program. By appreciating and accommodating other’s difficulties, the core team became more cooperative. These shared understandings of technical and contractual requirements among the parties minimized the number of disputes while improving operational efficiency of the project.

5.3 Manifestation of Relational Dimension and Trust

The forms of relational social capital include team spirit, solidarity, commitment, and trust among the core team members. Collegial team spirit was highly evident in Project Eastern. In the project, one form of project governance was the business-as-usual approach. The traditional contract-based interactions among members characterized this approach. However, alongside this mechanistic arrangement was a more humanistic approach. This phenomenon evolved from the initial socialization period of the core team members. After experiencing intensive interactions for some time, a less contractual approach emerged. The client SA recalled: “For a certain period of time, they [referring to the core team] still get some kind of human relationships, and this is important and, under normal situations, we welcome this sort of arrangement because you are not only client-contractor relationships.” It is this emergent relationship that laid the foundation for further collaboration among parties in the project. In addition, solidarity resulted from the need to deal with uncertainty and the increased workloads in relation to the novel procurement system and the string of new initiatives. A catalyst for the formation of a common rapport was the various episodes of contractor’s submissions of design packages to the ICU which had become common target for both teams. Both sides recognized the need to work together for timely ICU’s approval. Within the atmosphere of solidarity both sides showed increased commitment.

The level of trust – a sense of generalized trust - among Project Eastern core team members appeared to be high. The team worked on “a trust system” (PA). This sentiment was echoed by the contractor’s SPM. The manifestation of the trust system in the project lied in large part on the prevalence of the informal arrangement in project organizing. Often, based on the trust among the team members, design amendments that had been agreed upon in design meetings would be acted upon without the need to wait for written (formal) instruction. On the part of the contractor, in the context of ICU’s submission and approval, the impression was that the client team was always willing to assist in their submission. The next type is contractual trust. As contract administrator, contractual trust was more emphasized by the client’s team. In discharging their contractual obligations the client and contractor reciprocated to each other informal agreements to foster contractual trust. This reciprocity facilitated quicker processes as site works were conducted in parallel with the issuance of formal instructions.

5.4 Manifestation of Personal Dimension

The personal dimension is an emergent theme from the analyses. The project informants converged on their views on the importance of individual’s personality and positive characters in project organizing. Willingness to be consultative is one manifestation of personality as evident from the project. The PCOW adopted a more collaborative approach when dealing with the contractor instead of the traditional “command and control” approach. When a problem was encountered, the PCOW discussed and worked with contractor team on the possible solutions instead of issuing a site direction. This approach helped in bringing the two sides closer. The contractor’s QCM affirmed that this approach “helped build the relationship among the two teams.” The second manifestation of positive personality is the project participants’ willingness to exercise flexibility. The manifestation of this intention was most evident in the dealing of the new initiatives. The PA acknowledged the existence of some “tough grey areas” with the trials of those initiatives. Notwithstanding the need to comply with contract and specification, the client’s team was willing to be flexible to “allow some room for them to “maneuver” (PA).

6 DISCUSSIONS

6.1 Structural Dimension

In the quantitative approach of the study, structural dimension was conceptualized as getting one’s works done with the help of network members and getting social support. Although the quantitative evidence
shows support to these two measures, their formations are not strong. It appears project participants generally do not consider obtaining work-related help and social support as constituting social capital. These phenomena suggest that project participants rely on the project organizational control and role-based coordination for task performance, and the reliance on social support is trivial. The qualitative aspect points to the phenomena of bridging and bonding. In the project, bridging had been effectuated among the contractor’s team through the SAgt. And, bonding social capital was highly evident in the project in that the project core team had demonstrated a spirit of camaraderie. This team cohesion improved the team resilience and ability to absorb the shocks related to the uncertainty and complexity brought about by the new initiatives in the project. Due to the high emotional content and psychological closeness in the relationships (Walker et al. 1997), high bonding team confers flexibility and member supportiveness in the management of group affairs. In a highly dynamic environment as in the project, flexibility is highly instrumental in coping with the flow of opportunities that are typically more complex, ambiguous, and less predictable (Davis et al. 2009; Eisenhardt and Martin 2000).

However, the structural features observed in the project had facilitated project organizing. In the project “working sessions” the core team members were also the central figures in their respective extended individual networks (e.g. SAgt with his subcontractor teams). These core team members not only occupied positions of high centrality in the project organization’s technical advice network, they also occupied central positions in the project formal structure performing the technical coordinating functions. The consistency among the personnel’s roles, responsibilities, behaviors and their formal and prescribed roles had led to structural stability and, to some extent, predictability of the project organizational affairs.

6.2 Cognitive Dimension

The quantitative analyses indicate that shared understanding of project requirement, other’s requirements, technical knowledge, shared culture, common thinking, and collective goals represent the cognitive dimension. These items are similar with those derived from the qualitative analyses. Shared understanding of project and technical requirements provide the basic knowledge domain of works and project organizing among participants. Because these aspects mainly concern the physical construction and contractual provisions of the project, they facilitate the discussion and exploration of alternatives and trouble-shooting. Shared understanding on other’s difficulties and constraints help improves relationships among parties. As participants developed fine-grained knowledge of each other’s processes and operational needs, resources, and abilities, such knowledge improves the appreciation of other’s behaviors and needs (Ritter and Gemunden 2003) that results in adaptation of parties’ work processes.

Shared culture and common thinking convey a sense of identity for the members of a collectivity, enhance the social system stability, and serve as a sense-making device that guide and shape members’ behaviors (Smircich 1983). Within the core teams of the case project, the network of cognition that is characterized and represented by the various type of shared understanding intertwined with the structural features of the project organization. To the extent that network members’ expectations affect their perceptions, the reciprocity and transitivity (Kilduff and Brass 2010) of the cognitive perceptions percolated throughout the core team networks. That is, network ties provide informational indications of the general approach of handling the group affairs (cf. Borgatti and Halgin 2011).

6.3 Relational Dimension

The quantitative data reveals that trust is characterized as parties meeting their obligations, the confidence and obligations to perform, the ability of members to make well thought out decisions, the reliability of members, and the expectations that members negotiate project affairs in a fair manner. The qualitative analyses reveal a more varied and dynamic nature of relational dimension. In the project, the time of interactions was short but crucial, and the interactions were intensive, the teams relied on the development of swift trust of the competent and contractual nature in project organizing. Swift trust entails the reliance of judgment on the other project participant’s professionalism, and it depends on doing rather than relating (Meyerson et al. 1996). In the project, trust was formed through the trustee’s performance of specific tasks to the expected standard. Project informants also stressed the importance of reciprocity in the course of relationships development. In the developmental view, the use of contractual trust was
relatively more prevalent than trust with relational content in the beginning. However, over time, with both competent and contractual trusts slowly institutionalized, coupled with performance and reciprocity, a trust with relational content started to emerge. This observation is in line with the view that control mechanisms embodied in contract and its administration can actually serve as a springboard for the inducement of trust (Rousseau et al. 1998). If trust is taken in a wide sense that includes trust that is based on the contract, then trust and contract go together (Woolthuis et al. 2005).

Team spirit and solidarity are other aspects of relational dimension. These also facilitates the recognition that task completion leads to collective good rather than self-interest (Smith 2009). More importantly, it enables a broader set of values to be instilled among group members. This higher level values enable the group to shift size and focus rather easily. As such, solidarity tends to confer the flexibility in both structural form and cognitive framework of reference of the group thereby adaptation among group members. This increased capacity had enabled speedier decision making among the group members.

6.4 Personal Dimension

In project organization, participants constantly operate in the environments that are fluid, fast pace, emergent, and ever changing where each is vying for favorable position. Consequently, involvement in project can be stressful (Bryman et al. 1987). In this environment, it is essential to maintain relationships that are characterized by vitality, mutuality, and positive regards. This can only be achieved by project participants having positive attitudes and personality as observed in the project. The working relationships that stem from individual characteristics which in turn extend to multi-party interactions, together with their cognitive and relational embeddedness, lead to high quality connections among them. In this respect, personal dimension is an important addition of individual attributes in the discourse of social capital in project settings (cf. Kilduff and Brass 2010) and this is a key finding of our study.

Table 3 presents the integrative results of the two approaches. The analyses facilitate the convergence and corroboration of results on social capital in project settings. The analyses confirm and extend the dimensionality, provides the processual aspects and dynamic scheme of social capital. In this respect, the mixed methods approach provide greater confidence in improving our understanding of the phenomenon of social capital. While contributing to the understanding of relational governance in project management in general, our study and research approach also contributes to team effectiveness in temporary (project) settings in that our study has provided a more nuanced and detailed understanding of the combined effects of team processes, motivational, and cognitive effects (Mathieu et al. 2008) on team working. Further, our key finding of the new personal dimension has added to the recent recognition of individual attributes in the network discourse. Because actor’s properties matter for a group to extract network values, our identification of this new dimension has contributed to the social capital literature (c.f. Kilduff and Brass 2010).

Table 3: Corroboration of results ("Quan" and "Qual": quantitative and qualitative approach, respectively)

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Quan</th>
<th>Qual</th>
<th>Integrative results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-dimensionality</td>
<td>Confirmed</td>
<td>Confirmed</td>
<td>Methods mutually supportive</td>
</tr>
<tr>
<td>Additional dimension</td>
<td>None</td>
<td>Yes</td>
<td>Additional Personal Dimension identified in Qual</td>
</tr>
<tr>
<td>Contextual factors</td>
<td>Yes but not significant</td>
<td>Yes</td>
<td>Factors (e.g. high visibility) provide boundary conditions on the emergence and application of capital</td>
</tr>
<tr>
<td>Processes</td>
<td>None</td>
<td>Yes</td>
<td>Processes and mechanisms identified in Qual</td>
</tr>
</tbody>
</table>

7 CONCLUSION

In this study, we set out to explore the manifestations and effects of social capital in construction project organizations by employing a mixed methods approach. Both research approaches show the dimensional correlation nature of social capital and the identification of a new dimension. In project settings, the simultaneous congregation of the members with both strong and weak ties, positive personalities, the creation of common understanding among members, and the closely knitted relations that emerge in the course of interactions all interact in flux to sustain the social capital in project teams. Through facilitating information, communication, and transfer of influence, the structural dimension provides a forum through
which project members can evaluate the trustworthiness, reputations, quality, and affiliation of other members. While this dimension provides a platform for interactions, relational dimension provides a normative structure that helps generate a common set of convention, climate, rules and routines (Granovetter 1992) in project organizations. Relational dimension provides underlying psychological security among members through trust, commitment, and reciprocity. These two dimensions, in turn, constitute a means by which cognitive dimension is translated into members' task performance by facilitating the alignment of disparate project parties. Viewed this way, social capital, as a means of relational governance, is more pertinent to project operation if compared with other more permanent organization. For these reasons, it is important for project organizers to promote socialization among project participants and devise mutually supporting network structures that allow consistent application of roles, responsibilities, and authorities of those participants.

References


BEST VALUE PROCUREMENT FOR HIGHWAY DESIGN-BID-BUILD PROJECTS

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Abstract: Best value procurement is the process in which factors additional to price are considered in the selection of a contractor. Time, operation and maintenance, technical and managerial merit, and past performance are the other key factors considered along with price in best value projects. Compared to the low-bid procurement, best value procurement offers several advantages, including opportunities to improve project quality, promote innovation, and enhance project performance. Best value procurement, while commonplace in highway design-build (D-B) projects, is limited in use for design-bid-build (D-B-B) projects. This paper explores the procedure and existing practices of D-B-B best value contracts for highway projects. Data was collected from a survey questionnaire, structured interviews, and case studies. The survey questionnaire was nationwide distributed to 52 state Departments of Transportation (DOTs) to identify the practices of using best value procurement in transportation projects. The seven structured interviews and four case studies were conducted in detail to investigate the opportunities and challenges of evaluation criteria, selection methodologies, and evaluation committee structure in D-B-B best value projects. The results indicate that evaluation criteria and selection methods are established on a project-by-project basis. The owner agency should develop selection criteria and establish evaluation committees that are most beneficial to a given project. This paper provides some guidance for state DOTs to use best value procurement for their D-B-B projects.

1 INTRODUCTION

State departments of transportation (DOTs) have historically used a low bid approach to procure construction services. Under the low bid approach, price is a sole competitive factor. Non-price factors such as qualifications, experience, technical approaches, and innovative solutions are not considered. Typically, DOT awards the contract based on the lowest responsive bid. The best-performing contractors who will deliver high quality projects are less likely to be awarded the contracts in low bid contracting (Elyamany and Abdelrahman 2010). Researchers have identified several benefits of using low bid procurement including potential for monetary savings (Palaneeswaran et al. 2003), easy and simple implementation, reduced protests and disputes (Gransberg and Senadheera 1999), a long-standing legal precedence, and enhanced competition (Scott et al. 2006). While the low bid approach offers several advantages and is inherently transparent, it does not always offer the best performance during and after
construction. To improve project quality and performance, a number of DOTs are increasingly using best value procurement to deliver their transportation projects.

A review of literature indicated that a number of studies have investigated best value procurement for highway projects. However, most of them have focused on highway design-build (D-B) projects. Limited studies, if any, have explored the use of best value procurement for traditional design-bid-build (D-B-B) projects. Building upon the relevant literature, the objective of this study is to examine how to employ best value procurement in the D-B-B delivery method for highway projects.

2 BACKGROUND

Best value is defined broadly in the literature. Even in the highway industry, the best value definition may vary by state. This study uses the best value definition based on the National Cooperative Highway Research Program (NCHRP) Report 561 as follows: best-value procurement is “a procurement process where price and other key factors are considered in the evaluation and selection process to minimize impacts and enhance the long-term performance and value of construction” (Scott et al. 2006). The report also indicated that best value procurement allows both objective and subjective elements to be considered in the selection process. The objective elements may include contractor experience, timeliness and accuracy of submittals, record of safety, or compliance with material and workmanship requirements. The subjective elements may include effective management, proactive measures to mitigate risk, training programs, customer satisfaction, and client relation.

Best value procurement is one of many procurement options. It is not ideal for every project, but it can provide benefits on appropriate projects. Project goals and project characteristics can determine if the use of best value will be advantageous. Goals that align well with best value procurement include shortening of the project duration, creating opportunities for innovation, and selecting the most qualified team. Appropriate project characteristics include opportunities for innovation, the amount of design required to develop a competitive industry proposal, agency experience with the process, and market capability. For example, researchers show that the best value method more often delivers projects that meet owner expectations (El Wardani et al. 2006). Projects delivered using best value usually stay close to the original budget and schedule (Molenaar and Johnson 2003). Best value procurement is useful on those projects with unique objectives or challenges that may be difficult to meet using traditional low-bid procurement (MnDOT 2013).

State DOTs are increasingly using best value procurement for delivering their transportation projects. The 1996 version of the Federal Acquisitions Regulations (FAR) stated that best-value procurement should be selected when the project needs innovation and new technology or when a specific type of experience is required to obtain the desired outcome (FAR 1996). Considerations for best value procurements can include price, schedule, technical and managerial merit, financial health and past performance (Scott et al. 2006). Because the system provides a balance between price and qualitative considerations, it can optimize the benefits of fixed-price sealed bidding and sole source selection. The inclusion of key factors in evaluation criteria that match the specific needs of a particular project can raise the likelihood of meeting project performance goals (Abdelrahman et al. 2008). In fact, public clients use best value procurement when they aim to achieve the maximum outcome for their projects as opposed to the lowest price (Zhang 2006).

As mentioned above, although various studies have focused on the use of best value procurement on D-B highway projects, a little research explores how best value procurement can be used for highway D-B-B projects. This paper attempts to fill this knowledge gap by conducting four case studies with state DOTs.
that have experience using best value procurement on their D-B-B projects. The following sections present briefly how these four case studies were selected.

3 RESEARCH METHODOLOGY

The research methods employed in this study include three main steps: (1) a national survey, (2) structured interviews, and (3) case studies. The objective of step 1 is to preliminarily determine and identify the current state of practice on using best value with D-B-B projects. Based on the results of Step 1, the authors conducted interviews with seven state DOTs who have the most experience with best value procurement. Finally, step 3 involved conducting four in depth case studies to explore how best value procurement can be applied to these four D-B-B projects.

3.1 Survey

Because of the lack of information about the best value D-B-B contracts, the authors developed a nationwide survey to preliminary collect data. The survey consisted of 18 questions related to the topic such as: project delivery methods using the best value, experience of the agency, evaluation criteria, selection methods, evaluation committee, debriefing, legal, and protest information. The survey was sent to all 50 DOTs across the United States including the District of Columbia, and Puerto Rico. After two follow-up requests, the authors received responses from 46 state DOTs. It is noted that the survey questionnaire asked the participants to describe not only their state of practice related to the best value D-B-B approach, but their perception regarding the use of best value procurement for D-B projects. The survey results indicated that 19 state DOTs are using or considering the use of best value procurement in their D-B-B projects. Based on these responses, the authors searched for relevant information on these state’s D-B-B best value projects in their websites. Much information from state DOT websites could not be found about the use of best value procurement with design bid build apart from the agencies like New York, Michigan, Minnesota, and Oregon.

3.2 Interviews

The responses from the survey were analyzed to determine which state DOTs have the most experience on best value projects. As a result, seven state DOTs were selected for interviews to further investigate the use of best value procurement with the D-B-B delivery method. The interview questions were divided into four sections, including 1) proposal evaluation criteria, 2) selection methodologies, 3) evaluation committee, and 4) debriefing procedures. The authors invited the DOT officials to participate in an interview by phone and email. The interview questions were sent in advance to the officials who had agreed to provide information on their best value projects. After the interviews, the author sent a request for potential case studies on best value D-B-B projects. In addition, the interviewees were requested to provide the documents most relevant to their best value procedures.

3.3 Case studies

Due to the lack of data collected in the survey, and interviews about the use of best value procurement on design bid build delivery method, the case study is a main research tool for this study. In this step, the authors analyzed documents collected from the survey and potential case studies provided by state DOTs in the interview process. As a result, four case studies were selected to conduct a detailed analysis. These four case studies were selected because of the completeness of the documented best value process. In each case study, the authors followed a rigorous case study protocol that included the following four primary criteria: (1) evaluation criteria; (2) selection methodology; (3) evaluation committee; and (4) debriefings. The following sections present the results of these four case projects.
## 4 RESULTS AND ANALYSIS

Table 1 summarizes the key findings from evaluation criteria, best value award algorithm, and evaluation committee of the four case projects.

<table>
<thead>
<tr>
<th>No</th>
<th>State DOT</th>
<th>Project Name</th>
<th>Evaluation Criteria</th>
<th>Best value Algorithm</th>
<th>Evaluation Committee</th>
</tr>
</thead>
</table>
| 1  | Michigan DOT| M-39 Southfield Freeway, Michigan      | 1. Air Quality (40 points)  
2. Noise restriction (40 points)  
3. Managing utilities to homes (40 points)  
4. Construction traffic and mobility (40 points)  
5. Avoiding damage to adjacent property from vibration (40 points)  
6. Local Contractor and Workforce Participation Concerns (150 points)  
7. Safety and Mobility (100 points)  
8. Schedule concerns (50 points) | Contract awarded to proposer with lowest composite score.  
Composite score = Bid price/technical score | Detroit Transportation service center (TSC) Manager  
TSC development manager  
TSC delivery engineer  
Metro region Engineer  
Metro region planning specialist  
Director of MDOT office of small business development  
Contract services division administrator |
| 2  | New York DOT| Patroon Island Rehabilitation Project, New York | 1. Responsiveness to RFQ  
2. Legal  
3. Financial  
4. Experience  
5. Past Performance | Project is awarded to lowest cost responsible bid | A technical selection committee comprised of officials from NYSDOT. |
| 3  | Oregon DOT  | Dennis L. Edwards Tunnel, Washington County | 1. Construction and general tunnel experience (40 points)  
2. Specific tunnel experience (24 points)  
3. Traffic control and safety plan (16 points) | Price: 50%  
Technical qualifications: 40%  
Technical Approach: 10%  
Proposal with highest score is awarded the project | Experts from ODOT bridge engineering section, region 1 technical center, project Manager, and representative from FHWA |
| 4  | Oregon DOT  | I-84: Sandy River-Jordan Road, Bundle 210 project, Multnomah County | 1. Qualifications and Experience (18 points)  
2. Project Understanding and approach (21 points)  
3. Key personnel (21 points)  
4. In water work approach (16 points)  
5. Steel Box girder approach (8 points)  
6. Diversity (16 points) | Price: 70%  
Technical and qualification factor: 30%  
Proposal with highest score is awarded the project | Individuals from ODOT, non-scoring members from outside ODOT |
One can observe from Table 1 that the price component is an important factor in selecting the contractor for the D-B-B best value projects. For example, in the case study with NYDOT, it was observed that the contractor was selected based on the lowest responsible bid. The case studies with Oregon DOT revealed that the price factor accounted for 50% and 70% associated with Dennis Edwards Tunnel and I-84 Sandy River Jordan Road projects, respectively. However, the technical factors considered in the evaluation process were varied depending on the project type and characteristics. For example, Oregon DOT asked the proposers about their specific tunnel experience with regards to the Dennis L. Edwards tunnel project. Michigan DOT specified a list of detailed technical criteria such as air quality, noise restriction, safety and mobility on their M-39 Southfield project. New York DOT used standard evaluation criteria that are similar to D-B best value projects on their best value D-B-B Patroon Island Rehabilitation Project. These evaluation criteria include responsiveness to request for qualifications (RFQ), legal, financial requirements, experience, and past performance. The following sections discuss each case study in detail.

4.1 Michigan DOT case study: M-39 South Field Freeway Project

M-39 Southfield freeway project involved the reconstruction of roadway from McNichols to M-10, roadway rehabilitation of 28 bridges, freeway lighting and signing, sanitary sewer and screen wall replacement. Michigan DOT (MDOT) does not have a standard procedure for their best value projects. The selection process and evaluation criteria were determined depending on the type and location of the project. The eight evaluation criteria for this project include: 1) air quality, 2) noise restriction, 3) managing utilities to homes, 4) construction traffic, 5) avoiding damage to adjacent property due to vibration, 6) local contractor and workforce participation concerns, 7) safety and mobility, and 8) schedule concern. The maximum point available for each factor is shown in Table 1. The maximum points available for the technical proposal are 500. The composite score of the proposals is calculated by dividing the bid price of the proposal by technical score. The proposal with the lowest composite score was awarded the contract.

The technical evaluation committee was comprised of the Detroit transportation service center (TSC) manager, development manager, delivery engineer, region engineer, region planning specialist, and director of MDOT office of small business development. The committee started with a baseline score and added points for innovative ideas. The final technical score of the proposals was the consensus rating of all the committee members. Price proposals were opened by the committee after evaluating the technical proposals. Finally, the project manager conducted debriefings to unsuccessful proposers after their request. Detailed comments about the strengths and weakness of the proposals were discussed in that meeting.

4.2 New York DOT case study: Patroon Island Rehabilitation Project

The Patroon Island bridge project involved the construction of ramps connecting the I-90 interchange with I-787, repairing the bridge decks and bearings, and painting the bridges. The project manager worked with the chief engineer to determine the evaluation criteria for the project. The evaluation factors for this project are responsiveness to RFQ, legal and financial information, experience, and past performance of the proposers. These evaluation criteria for D-B-B projects are similar to that of D-B projects. The proposals were evaluated against these factors by the evaluation committee on the pass or fail basis. After evaluating technical criteria, the evaluation committee evaluated the cost proposals. The proposer with the lowest cost bid was awarded the contract.

The evaluation committee, which included officials from the New York DOT, was responsible for the evaluation of the proposals and the selection of the best value contractor. The evaluation committee was prevented from seeing the cost proposals to avoid any potential bias during the evaluation process. The
agency conducted debriefing to the unsuccessful proposers. A debriefing was conducted by a procurement official who is familiar with the selection and contract award process. Strengths and weaknesses of their proposals were explained to the proposers.

4.3 Oregon DOT case studies

Oregon DOT has employed best value procurement for several D-B-B projects. To identify the differences of using the best value approach with different type of projects, the authors conducted two case studies in Oregon DOT.

4.3.1 Dennis L. Edwards Tunnel Project

This project involved removing and replacing the existing lining, improving the wall drainage, and improving the lighting system of the tunnel along with the installation of a bike warning system. Oregon DOT (ODOT) used price plus technical qualifications plus technical approach best value process to select the contractor. The price factor accounted for 50% of the weight in evaluation process while the technical qualification and approach accounted for 40% and 10%, respectively.

The three evaluation criteria for this project included (1) construction and general tunnel experience, (2) specific tunnel experience, and (3) traffic control and safety plan. The evaluation committee was comprised of two technical experts (one from ODOT bridge engineering section and the other from regional technical center), the project manager, a representative from the Federal Highway Administration (FHWA), and the engineering consultants who acted as facilitators and observers during evaluation process. The proposals were evaluated and scored separately by the members and the average of all the scores was the final technical score of the proposers. The project was awarded to the proposer whose combined score is the highest among all the proposers.

4.3.2 I-84 Sandy River – Jordan Road, Bundle 210 project

This project was a typical highway project that involved replacing and repairing the bridge. Different from the Dennis L. Edwards Tunnel project mentioned above, the price factor accounted for 70% of the weight in the selection process and the technical qualifications and approach factors accounted for 30%. The main reason for this is that this project was a typical highway project while the tunnel project was more complex. As a result, the technical factors of the tunnel project accounted for more weight in the evaluation process. In the tunnel project, the agency used a specific tunnel experience factor to select the proposer who have more experience and offers the best value for the particular type of work involved. On the other hand, for the I-84 Sandy River project, which is a typical highway project, the agency preferred setting more weight on the price factor for their D-B-B projects. In addition, the evaluation committee of this project was simpler than that of the tunnel project. Technical experts, a member from FHWA, and a consultant were not required for this project. Only officials from ODOT and a non-scoring member from outside ODOT were included in the evaluation committee.

5 DISCUSSIONS

The case studies presented above illustrate the use of best value procurement in D-B-B projects. It is observed that Michigan and Oregon DOTs develop the evaluation criteria depending on the nature of the project. New York DOT has employed a similar best value D-B project procedure for their best value D-B-B projects. In general, price accounts for the greatest weight in the best value evaluation process for D-B-B projects. Specifically, New York awards the project to the lowest bidder from the list of prequalified bidders while Michigan and Oregon assign more weight to the price while calculating the best value
scores. Michigan selects the best value contract based on the least composite score, which is calculated by dividing the price over the technical score. Oregon selects the best value contractor for their D-B-B projects based on the highest score that is combined between price and technical factors. Recently, Minnesota DOT has published a manual for the best value procurement on D-B-B projects. This manual introduces a streamlined approach to best value procurement that can be applied to a variety of projects. The approach, which is intended for projects that requires advance design, suggests that the agency should develop pass-fail criteria to reflect the benefits of the project and select the low bid from the proposals meeting the criteria (MnDOT 2013).

Based on the four case studies, one can observe that the evaluation committees are often comprised of officials from state DOTs. In some cases officials from outside the agency (i.e., consultants, a representative from FHWA, or a non-scoring member) may also be included in the evaluation committee. Typically, after awarding the best value contract, state DOTs conduct debriefing sessions for the unsuccessful proposers. In these meetings, a member in the evaluation committee often explains the strengths and weaknesses of their proposals.

6 CONCLUSIONS

Transportation agencies are increasingly using best value selection procedures to deliver transportation projects. While low bid procurement processes are simple and transparent, they do not allow agencies to evaluate additional factors that may add value to the agencies and stakeholders. Best value procurement is often used for D-B highway projects. This paper shows that best value approach can be applied to the traditional D-B-B projects. The case studies presented in this paper explained about the methods adopted by the state highway agencies the selection process of a best value contractor. The findings from this paper suggest that the use of best value for D-B-B projects in several state DOTs brings significant benefits to their agencies. Non-complex projects, in particular, have the potential for using streamlined best value processes. The evaluation criteria and award algorithms need not be as complex as those found on large D-B projects. In addition, the owner agency should develop the evaluation criteria and establish the selection committee based on a project-by-project basis.

Although the findings from this paper encourage the use of effective best value procurement on D-B-B delivery, the paper has several limitations. First, due to the lack of best value D-B-B project data, it is challenging to compare the project performance between best value and low bid procurement on D-B-B projects. Second, the sample size for this research is small. This study has not focused on some important factors like industry outreach, stipends, and training to evaluation committee which plays an important role in the selection of the best value contractor. A more substantial study with consideration of other factors and a large sample size should be performed to identify the best practices of using best value procurement on D-B-B delivery method. In addition, future research could determine how to streamline best value procurement, allocate the risks equitably for the agency and contractors, and quantify the project performance between D-B-B low bid and best value projects.

References

USING SIMULATIONS TO BETTER TRAIN FUTURE AND EXISTING
CONSTRUCTION MANAGEMENT PERSONNEL

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Abstract: In the construction industry, there is a continued need for training current employees as well as
future employees. Such training opportunities that exist include safety, technical, and project
management. Historically training has included lectures from subject matter experts by those considered
to be experts in a particular subject or field. However, this has required removing personnel from projects
to allow time for training or by requiring employees to invest time outside the normal working hours for
training. With the advent of the internet, on-site lectures have been replaced with webinars and/or telecast
to allow personnel to remain in one location and receiving training; however, many educators cite that
student engagement is often limited and learning is not as in-depth when compared to in-person training
sessions. One new training technology that is developing is the use of virtual simulations that are
designed to allow for specialized training while engaging them in the educational process. One such
simulation, the COnstruction INdustry Simulation (COINS), has been developed to train students in the
management of a construction company managing multiple projects simultaneously and is
slowly moving to advance company trainee. COINS engages
students in the decision making of heavy civil construction and commercial building sector. This
simulation has been used in the classroom and now is just available to construction firms to use with
personnel. This paper describes the development and use of COINS simulation designed and developed
to educate future and existing construction management personnel. It is currently used at a number of
different universities including the Czech Technical University in Prague.

1 INTRODUCTION

If one were to survey construction educators and construction trainers, we would fine a small number
using large scale complex simulations. Most university faculty opt for traditional lectures using
powerpoints and a number use case studies, and a few use management games. The question is why
don't we use simulations? The definition of a simulation is the imitation of the operation of a real-world
process or system over time. This definition begs the question even more, why don't we use simulations?
Fear of technology, availability, overly complexity, etc. One such simulation, the COOnstruction INdustry Simulation – COINS (Korman, Johnston, Duckworth), has been developed to train
students in the management of a construction company managing multiple projects simultaneously and is
slowly moving to advance company trainee. COINS engages students in the decision making of heavy
civil construction and commercial building sector. This simulation has been used in the classroom and
now is just available to construction firms to use with their personnel.
2 LITERATURE REVIEW

While multidisciplinary project-based learning has been advocated in engineering for a number of years, the initiation of the Accreditation Board for Engineering and Technology, Engineering Criteria 2000 (ABET 2000), and its call for a required multidisciplinary experience stimulated increased interest in developing courses in this area. Still more recently, an increased number of papers advocating multidisciplinary project-based curricula have appeared at conferences and in journals. It has become clear that project-based learning is addressing a need in the preparation of engineers that was not previously satisfied by standard curricula (Mergendoller, Strobel).

Dialogue with the construction management Industry Advisory Board (IAB) revealed the following important issues and obstacles our students experience upon entering industry. First, students often have not encountered large-scale team design projects and, therefore, have to learn how to work in such an environment. Thus, on the job, they must gain experience in the process, develop a technical specialization to support their project role, and build their ability to collaborate on and contribute to multidisciplinary projects. Secondly, we discovered that our students were not prepared to apply design and construction engineering fundamentals to real world complex projects, specifically utilizing project controls to monitor and evaluate an active project.

In addition to the educational deficiencies noted in our curriculum, CCE curricula generally do not present an integrated approach to engineering education that includes practical applications of theoretical knowledge incorporating constructability issues. Students often master the course and laboratory work associated with courses in the curriculum, but they do not gain a comprehensive engineering experience that requires them to synthesize what they have learned in their curriculum and extend their knowledge through independent learning that reaches outside their field of study, specifically in the topics of constructability. This is further observed at community colleges where students do not have the opportunity of being immersed in a large-scale engineering academic environment of a four-year institution and frequently lose interest in pursuing further education or an engineering career (Terenzini, Cabrera).

This educational gap is systematic among engineering universities. Design engineers frequently receive limited feedback regarding the constructability of their design once a project has entered the construction phase and how construction engineers receive limited feedback regarding the progress of their project. This stems from the educational gap that exists between design and construction engineering curricula, which fail to address constructability issues and lack educational tools and methods for students to test and validate project control theory (Kilgore, Atman, Yasuhara, Barker, Morozov).

Traditionally, students have not acquired these skills at CPSLO. In fact, our experience and research indicates that while many universities and community colleges offer lower division courses that teach students about project control theory, they are not able to provide an educational experience where students can practice these skills. Therefore, in an effort to produce a project-based learning experience, the CPSLO faculty have been developing COINS—Construction Industry Simulation—to reinforce several key learning objectives and to provide a valuable experience for students to work on projects that require the application and synthesis of project controls and monitoring knowledge. Through the use of COINS, students will be placed in a virtual environment to replicate, as nearly as possible, the working environment they will encounter after graduation. Students will be exposed to exercises that are significantly different from typical homework assignments in conventional courses. COINS requires students to work collaboratively and use effective communication skills. Based on our review of the literature, we expect that COINS will engage students unlike any other teaching intervention as there are currently no Project Based Learning (PBL) solutions using simulations to enable students to conceptualize the demands of scheduling multiple projects with multiple resources. Other engineering simulations, such as Messner's Virtual Construction Simulator, simulate building a specific project, focusing on very specific job areas (Nikolic). COINS, on the other hand, is conceptual in nature, actively involving students in the scheduling of multiple projects and allocating multiple resources concurrently while enabling them to see the relevance in the real world of what they are learning. Finally, we anticipate that COINS will become a model for other civil and construction engineering programs who
wish to enhance their compliance with the ABET 2000 requirements and foster the success of a greater number of students Vogel, Bowers, Bradshaw).

3 CONSTRUCTION INDUSTRY SIMULATION (COINS)

Construction Industry Simulation (COINS) is a computer simulation built to simulate the business environment for a construction company. The players, participants, play the role of contractors, competing in a market with variable demand for construction work. The simulation immerses trainees into the day-to-day operations of a construction company, requiring them to manage specific aspects of the company with the goal of procuring and managing construction work in terms of its planning, scheduling, and resource allocation. Student trainees have a choice between commercial construction company, a heavy construction company, or a company that does both. Players are required to set up a complete business strategy including the following tasks:

- examine available information
- determine the best portfolio of jobs to bid on
- create strategies to improve bonding limits
- set strategies to create negotiated work
- develop bid prices for desired jobs
- monitor their financial position as work progresses
- monitor and create strategies to improve company’s appraisal metrics
- choose and modify their construction methods to meet due dates and reduce costs
- interpret their competitors’ strategies
- respond to changing conditions and situations proposed to the company and driven by the decisions and actions of the company

3.1 Projects and Activities

Each period the simulation generates a list of projects available for the teams to estimate, schedule and propose on. The types of projects include the following: highways, bridges, site development, mass excavation, and underground utilities on the heavy civil side, and multi-family housing, educational facilities, hospitals and medical office buildings, commercial office buildings, and industrial manufacturing facilities on the commercial side.

All projects have nine (9) activities that the teams need to schedule, generate and cost estimate. The activities that must be scheduled and estimated include the following: clear and grub, rough grading, excavation, underground piping, concrete forming and placing, backfill and compaction, placement of aggregate base, asphalt-concrete paving, and finish grading. On the commercial side, the activities include the following: excavation, foundation, basement, framing, closure, roofing, siding, finishing, mechanical, electrical, and plumbing.

In addition the simulation creates an Estimated Time and Cost Report for each job. Using this information, each company must decide which jobs to bid on, the bid price, and which of the five methods to use for each of the activities.

Every activity has five (5) different construction methods that vary in time and cost. The Estimated Time and Cost Report gives labor and material costs and the amount of time required for every activity using each of the five methods. Heavy construction bids are generally unit price bids while commercial bids are lump sum.

3.2 Use of the COINS Simulations

COINS has been used in several courses including: Professional Practice, Construction Estimating, Construction Accounting, Management of the Construction Firm, and Business Practices
During the 2005/2006 academic year, the simulation was used for regional competition between multiple universities in the Associated Schools of Construction Regional 6 and 7 Student Competition.

Most recently, in November 2009, universities from the Czech Technical University (CTU) - Prague, Czech Republic, Auburn University - Alabama, California State University, Fresno - California, Illinois State University - Illinois, Boise State University - Idaho, Western Carolina University - North Carolina, and Washington State University – Washington, participated in an international competition. Competition Results were evaluated in five categories: Highest Retained Earning - received the highest profit, Highest Appraisal Metrics - the best valuation metrics and third, Most Awarded Projects - the company with the most awarded projects.

4 GAME PLAY SIMULATION

During the simulation, student trainees experience three distinct phases playing through the simulation. These are:

4.1 Phase I – Project Planning and Design

Students begin the simulation in Phase 1 by being presented with a list of potential projects to review. Considering market conditions, student teams proceed by selecting a project to plan and then designing a project control system for the project. This is accomplished by selecting methods for each project activity and balancing the schedule and cost considerations. In Phase 1, students compete against their peers as well as the simulation's virtual companies for award of the project. Award of projects is based on the team's accuracy and proximity to the simulation's internal estimate. Teams that are not initially awarded a project for their efforts must continue with the simulation, refining their plans, until their plans are awarded a project. Thus, the COINS simulation enables student trainees to learn from their mistakes.

4.2 Phase 2 – Construction Engineering

When a student team is awarded a project, they enter Phase 2. In Phase 2 student teams must manage their project by monitoring and controlling the project activities, analyzing the schedule and costs in reference to the methods to the activities they selected for each activity. Throughout the duration of their project, students are presented with real-life scenarios which they must respond to, thus measuring, testing, and validating the design of the project control system. Therefore, students are able to utilize their knowledge and hone their skills at controlling the process through modifying their project control system. The simulation provides feedback to the students which they then can use to continuously improve their model throughout the duration of the simulation.

4.3 Phase 3 – Project Closeout

Phase 3 begins after students have completed each activity for their virtual project. They have the opportunity to evaluate their performance using several predefined metrics, including Schedule Variance, Cost Variance, Cost Performance Index, and Schedule Performance Index.

5 STUDENT TRAINEE LEARNING PROCESS

As mention above, one of the first activities for the student trainees is to determine what positions will make up their main office overhead. This is reevaluated each period, and hire/fire activity is performed by the team. A report is given to the company telling them how they are handling their personnel and it's requirements. Work scheduling is very important in the selection of the methods so projects can be completed by the contractual deadlines, and the costs reduced as much as possible. Each bid price submitted should cover all the firm's direct and indirect job expenses, its main office overhead costs, and the desired profit. At the end of each period the simulation will determine which company is awarded each available project. The lowest bid will not necessarily win since the computer takes into account several other factors:
• Is the firm’s cash-on-hand adequate to provide enough liquidity with regard to the bid price?
• Is the bid price below a minimum amount, computed by the program? If so, then the bid will be
disregarded as irresponsible and be rejected.
• Is the bid price higher than the unknown contractors, the presence of this simulated company assures
a competitive, uncertain environment with realistic bid prices.
• Is the firm within its bond limits?

At the end of each period, teams receive a progress report for the previous two month period, giving a
statement of the firm’s work progress on each of its jobs during that time. It shows the amount of work
completed as well as the expenses incurred for each activity in every one of the company’s projects. The
amount of work completed during a period depends not only on the methods selected for the various
activities, but also on uncertainty factors during that time such as the weather conditions, labor
availability, and the fluctuating cost of materials.

An end-of-period financial report is also provided to the participants showing the expenses incurred
during that period. It lists amounts spent on direct construction services, bidding costs, delay fines, taxes
incurred, and interest on borrowed money. It also shows payments to the contractor by the owner
according to the payment requests and gives total cash-on-hand at the end of the period. Each firm may
at any time apply for a loan to improve its financial situation. Loans granted are amortized over a one year
time period. Changes in company ratios are also logged along with changes to the company’s appraisal
metrics:

• Is the firm within its bond limits?
• Financial Liquidity
• Financial Success
• Responsibility
• Pace
• Ethics
• Name Recognition

At the end of a period, the firms can examine their Progress Reports and decide on the effectiveness of
the methods chosen for the various work activities. If they wish, they may change them and specify
different methods for the following periods. The choice of methods allows companies to utilize slower but
cheaper methods if they fear budget overruns, or faster but more expensive methods if meeting
contractual deadlines is the main concern. In addition, overtime may be used to speed up certain
activities, greatly increasing the labor costs. Firm must be concerned with the amount of liquidated
damages on each project as they vary from project to project.

At the conclusion of the simulation, the program provides each participating company with a final report,
forecasting the expected results of any on-going projects or their position at that point in time. It also
shows the final total worth of the firm. Teams should consider maximization of profit as one of their main
objective, and one of the primary criteria used to evaluate each firm’s performance. As the simulation
progresses, evaluations of company ratio, and appraisal metrics can be used to determine successful
completion of the simulation.

6 LEARNING OBJECTIVES

The phases described in the previous sections were designed with specific learning objectives to ensure
that identified curriculum deficiencies were addressed, integrating knowledge from project planning,
project procurement, schedule control, and cost control bodies of knowledge. Tables 1, 2, and 3 provide
a list of the learning objectives and mechanism COINS uses to assess student learning.
Table 1: Planning and Design Learning Objectives.

<table>
<thead>
<tr>
<th>Learning Objective</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use labor-equipment crew rates and productivity information to select methods for</td>
<td>Students submit their reasoning and logic for selecting methods for each activity. COINS provides feedback on cost and schedule completion dates.</td>
</tr>
<tr>
<td>construction activities.</td>
<td></td>
</tr>
<tr>
<td>Develop a project schedule considering interdependent activity relationships and</td>
<td>Students submit their project schedule. COINS provides feedback on predecessor and successor activities.</td>
</tr>
<tr>
<td>contract requirements.</td>
<td></td>
</tr>
<tr>
<td>Quantify planning, contingency, and bonding expenses and apply to project cost.</td>
<td>Students submit their project cost estimate, including planning, contingency, and bonding expenses. COINS provides feedback on percentages per project.</td>
</tr>
<tr>
<td>Calculate and apply percentages of main office overhead cost to multiple projects.</td>
<td>Students calculate the overhead cost and submit with project cost estimate. COINS provides feedback on project resources allotted for the project.</td>
</tr>
<tr>
<td>Use information regarding bonding capacity, labor availability, materials availability, liquidated damages, and apply modification factors to develop a construction cost estimate.</td>
<td>Students submit their rational for selecting resources based on bonding capacity, labor availability, material availability, liquidated damages. COINS provides feedback modification factors.</td>
</tr>
<tr>
<td>Apply value engineering fundamentals to decrease schedule requirements and reduce project cost during design</td>
<td>Students submit value engineering consideration to reduce cost and schedule. COINS provides feedback on applicability and feasibility of proposed options.</td>
</tr>
</tbody>
</table>

Table 2: Construction Engineering Learning Objectives.

<table>
<thead>
<tr>
<th>Learning Objective</th>
<th>Assessment</th>
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<tbody>
<tr>
<td>Update schedule for in-progress projects.</td>
<td>Students submit their reasoning and logic for selecting methods for each activity. COINS provides feedback on cost and schedule completion dates.</td>
</tr>
<tr>
<td>Calculate final project cost, considering scenarios involving labor cost increases,</td>
<td>Students submit their project schedule. COINS provides feedback on predecessor and successor activities.</td>
</tr>
<tr>
<td>material price increases, and overtime compensation.</td>
<td></td>
</tr>
</tbody>
</table>
Apply project acceleration techniques (changing methods, utilization of overtime, etc.) to decrease project schedule on projects that are behind schedule.

Students are required to reduce project schedules for in-progress projects in response to market considerations by reducing their total number of work days.

Quantify cost associated with applying project schedule acceleration techniques.

Students submit their project cost estimate, including planning, contingency, and bonding expenses. COINS provides feedback on percentages per project.

Develop progress payment reports based on work completed to date.

Students calculate the overhead cost and submit with project cost estimate. COINS provides feedback on project resources allotted for the project.

Apply value engineering fundamentals to decrease schedule requirements and reduce project cost for project in-progress.

Students submit their rational for selecting resources based on bonding capacity, labor availability, material availability, liquidated damages. COINS provides feedback modification factors.

<table>
<thead>
<tr>
<th>Learning Objective</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculate and use Cost Variance to determine cost differentials for project cost.</td>
<td>Students calculate cost variances (CV) at project completion. COINS performs an independent CV calculation and provides feedback.</td>
</tr>
<tr>
<td>Calculate and use Schedule Variance to determine differentials for project schedules.</td>
<td>Students calculate schedule variances (SV) based at project completion. COINS performs an independent SV calculation and provides feedback</td>
</tr>
<tr>
<td>Calculate and use Cost Performance Index to analyze project performance.</td>
<td>Students calculate cost performance index (CPI). COINS performs an independent CPI calculation and provides feedback.</td>
</tr>
<tr>
<td>Calculate and use Schedule Performance Index to analyze project performance.</td>
<td>Students calculate schedule performance index (SPI). COINS performs an independent SPI calculation and provides feedback.</td>
</tr>
</tbody>
</table>

Table 3: Project Closeout Learning Objectives.

7 ASSESSMENT OF STUDENT TRAINEE LEARNING

The simulation has a built-in grading module that can be used to obtain statistic on the various companies for comparison or to use in the classroom for grading the simulation. Each faculty can have their own method of grading. The following criteria can be used by faculty for assessing participation and student learning:
Is the firm within it bond limits?
Number of jobs bid
Minus the jobs rejected (i.e., not enough bonding capacity, substantially low cost estimate, etc.)
Number of times the number jobs you are the lowest cost
Number of times the company retained earnings
Company’s appraisal metrics

8 DISCUSSION AND RECOMMENDATIONS FOR FUTURE IMPLEMENTATIONS

Many new hires will come from academic areas other than Construction management. A need for these employees to understand an overall picture of the industry is important. Another group of employees are in accounting area and they too can benefit from a “capstone” look at their companies. To assist in the development of COINS, the developers have developed an Industry Advisory Board (IAB) from the construction industry as well as a working group of educators to continue the development and ideas for changes. Because of the idea of module development COINS can turn on and off some of its modules, making it a better fit in different classes. For example, estimating can be turned to an automatic mode which in a construction accounting class helps the student focus on accounting and not on the estimating itself which can be very time consuming and complex. Periods can move much quicker giving the students more accounting to analyze and in a shorter time in which they can see the changes that occur within a company without being bogged down in the estimating/procurement of work. Billing can be turned on to auto mode and additional projects can be added to each team to create additional project or backlog. The game play between commercial and heavy/civil construction is also modulized so a faculty can play only commercial, heavy/civil or both can be played in one game. Future additions are also planned as modules, i.e. personnel additions, case studies, and wide use of equipment management.

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THE FEASIBILITY OF PLUG-LOAD MONITORING AND ENERGY-SAVING INTERVENTIONS IN RESIDENTIAL AND OFFICE BUILDINGS ON THE UNIVERSITY OF WASHINGTON CAMPUS

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Abstract: The University of Washington (UW) is aiming to reduce the overall electricity consumption on campus as part of its Climate Action Plan launched in 2009. To achieve this goal, UW installed 216 smart grid meters and automatic heating, ventilation, and cooling control systems across the entire campus and acquired over 200 sets of plug-load monitoring equipment. The university used the smart grid data and the monitored plug-load data to test how occupants in selected residence halls responded to receiving detailed information about their energy usage patterns, its environmental impacts, and associated costs. The experiment demonstrated that in residence halls, plug-load monitoring did not have any significant impact on the occupants' electricity consumption. Hence, there is still a need to further assess which strategies are effective in achieving long-term electricity reduction goals for the university. The goal of this study was to conduct a comparative analysis by replicating the plug-load analysis conducted in residence halls in a faculty/staff office setting. The study entailed interviewing university administrators that were involved in the residence hall plug-load study. Interviewees were asked questions about the findings, shortcomings, and recommendations for future studies. Also, this study characterized the load profiles of the faculty/staff offices by monitoring the plug-load consumption in four offices for nine weeks and explored plug-load reduction interventions applicable to office settings. The study found that the unreliable network connection caused frequent disruptions in data collection and strong bias in the individual electricity consumption data. The inventory of electronic appliances in the monitored offices revealed a high variability in the number of devices which lead to variations in base consumption and peak plug loads between faculty offices, and lack of occupant engagement was found to be the main challenge in the implementation of plug load monitoring campaigns. The results provide universities around the country with valuable information and insights on how to design and implement an on campus plug-load reduction intervention with quantifiable energy-saving potential.

1 BACKGROUND

Worldwide reductions in greenhouse gas emissions are needed to mitigate the most severe impacts of climate change. Commercial buildings account for roughly 18 percent of the total annual energy use in the United States (US DOE 2014). Therefore, sustainability initiatives at workplaces offer a substantial opportunity to reduce the harmful effects on the environment.

The University of Washington (UW) is aiming to reduce the overall electricity consumption on campus as part of its Climate Action Plan launched in 2009. Currently, miscellaneous electricity loads (e.g., computers and office equipment) from offices account for approximately 12 percent of the total electricity
used in the UW, which means that an average of 36 million kilowatt hours of electricity is used annually on plug loads (University of Washington 2012). According to the results presented in recent literature, a well-designed energy intervention in the UW offices has the potential to save up to $360,000 of UW's annual electricity costs. Furthermore, reducing plug loads would not only help the university to reach its carbon neutrality goal but would also improve the power quality on the local grid and moderate peak electrical demand in the Seattle area.

Traditionally, energy-conservation efforts in office environments have been implemented through technological or operational modifications (Starik & Marcus 2000). However, humans are the main operators of technology, and a failure of the human component can fail the entire energy-efficiency initiative. Thus, instead of focusing solely on technological solutions, recent research has shifted to investigate the effects of occupant behavior on building energy use (Fischer 2008, Azar & Menassa 2010, Masoso & Grobler 2010, Schweiker & Shukuya 2010, Kamilaris et al. 2014). The results of these studies have shown that the energy-saving potential of behavioral change is comparable to, and even higher than, that of technological solutions (Masoso & Grobler 2010, Schweiker & Shukuya 2010). Some estimates even suggest that the occupants control or impact up to 50 percent of a building’s energy use and that changing occupant behavior patterns gives the most effective reductions in energy use (Kamilaris et al. 2014).

Changing occupant behavior in offices and other commercial buildings is not without its challenges. A wide variety of studies have looked into the different types of interventions that could most effectively result in electricity savings. One of the most applied measures of impacting and controlling occupant energy use is giving occupants regular feedback on their energy usage patterns (Jain et al. 2012, Jeong et al. 2014, Gulbinas et al. 2014, Hargreaves et al. 2010, Hargreaves et al. 2013, Pereira et al. 2013, Froehlich et al. 2010, Vine et al. 2013). Because feedback frequency and accessibility have been found to correlate positively with the impact on energy reductions (Abrahamse & Steg 2011), most of the recent research on occupant behavior has used real-time monitoring solutions (Jain et al. 2012, Gulbinas et al. 2014, Jain et al. 2013a, Jain et al. 2013b, Ueno et al. 2006). Various studies have shown that frequent feedback is generally effective and correlates negatively with the energy consumption rate (Faruqui et al. 2010, Siero et al. 1996, Vassileva et al. 2012, Murtagh et al. 2013). However, its effects are often temporary, as the engagement of the participants has been repeatedly observed to reduce over time (Hargreaves et al. 2010, Ueno et al. 2006, Murtagh et al. 2013). Furthermore, not everyone is interested in receiving feedback on their electricity consumption: In their study, Murtagh et al. found out that 41% of the participants did not access their individualized feedback even once. These results indicate that in order to design effective electricity interventions with consumption feedback, the focus should be in long-term participant engagement. When implemented successfully, high-frequency electricity feedback can result in total electricity savings of about 20 percent (Murtagh et al. 2013, Acker et al. 2012, Ecova 2011).

UW has already installed 216 smart grid meters and automatic heating, ventilation, and cooling control systems across the entire campus and acquired over 200 sets of plug-load monitoring equipment. In 2013, the university used the smart grid data and the monitored plug-load data to test how occupants in selected residence halls responded to receiving detailed information about their energy usage patterns, its environmental impacts, and associated costs. The project team examined electricity use in each of the buildings over a ten-week period in order to understand which intervention, a technology intervention or education intervention, would have a greater effect (if any) on floor-wide energy consumption. The experiment demonstrated that in residence halls, neither educational nor technical plug-load reduction interventions had any significant impact on the occupants' electricity consumption: Occupants appeared to have higher energy use throughout the study, and educational intervention failed to produce statistically significant results. The research group listed small sample size, inexpensive energy, subjects who do not pay individual energy bills and technical difficulties as some of the factors that may have contributed to these results. Despite the inconclusive results, the team suggests that University has potential to educate students and successfully reduce energy use though other approaches. However, the use of plug load monitoring systems was not recommended as it was found to be an expensive and ineffective tool for changing energy behavior in the context of the University’s residence halls (Black et al. 2014).
The goal of our study is to conduct a comparative analysis by replicating the plug load monitoring campaign conducted in residence halls in a faculty/staff office setting. In addition to collecting monitoring data, we conducted a survey of the university administrators that were involved in the 2013 residence hall plug-load study to learn more about the challenges and opportunities related to plug load monitoring on campus setting. The study will serve as a preliminary study for a plug load monitoring campaign that will be implemented in one of the office buildings at UW campus later in 2015. We believe that the results will provide universities around the country with valuable information on how to design and implement an on-campus plug-load reduction intervention with quantifiable energy-saving potential.

2 METHODS

2.1 Plug load monitoring

2.1.1 Equipment

Plug load monitoring systems with control capability were installed in four faculty offices. The systems consisted of smart power sockets and strips, a Wi-Fi-connected touchscreen monitor with control capability over smart sockets and strips, and an online user account for data collection. (Figure 1) A total number of 20 appliances were plugged into the smart sockets and strips that were connected to the touchscreen monitors over Wi-Fi. High power appliances, such as refrigerators, fans and microwaves had to be excluded from the study as the monitoring system only supports devices with up to a maximum of 15 amps (EnergyHub Inc. 2011). In addition, University’s IT staff requested that desktop computers were kept on at all times to allow for software and security updates.

![Figure 1. Set-up of the plug load monitoring system](image)

2.1.2 Installation and education

The monitoring systems were set up over a period of one week. Prior to installation, the office occupants conducted an inventory of their electronic appliances together with the research staff and identified the appliances that were to be connected to the monitoring system. In addition, each appliance was given a status on the basis of occupant’s requests: If appliance was given an “always on” status, it would stay on even if the smart strips and sockets were turned off. Other appliances with an “on-off” status would turn off normally when the power to the strips and sockets was cut off.

The installation process consisted of three phases. In first phase, sockets and strips were connected to the touchscreen monitor by using strip- and socket-specific set-up codes. In the second phase, the electronic appliances in each socket and strip were named in order to allow appliance-by-appliance electricity monitoring. In the last phase, the status of each appliance was determined by typing the information in the touchscreen monitor. In order to minimize the disturbance to the occupants, installation work was completed when offices were unoccupied.
All study participants were given guidance on system control through touchscreen monitor. Occupants were also introduced to two short-cut commands for electricity use control. By setting the touchscreen monitor to "home" mode, the occupants were able to turn on all sockets and strips, and the appliances plugged into them. By choosing "away" mode, the occupants were able to turn off all appliances with "on-off" status. Apart from this introduction to the monitoring system control, the occupants were not given any additional information about electricity consumption or potential savings.

2.2 Administrator survey

An administrator survey was conducted by personal interviews and e-mail questionnaires. The three participants were chosen among the university employees who had been involved in the residence hall plug load study in 2013 (Black et al. 2014). A set of 14 questions was created on the basis of the following research topics:

1. The staff resources available for administrating plug load monitoring campaigns and other energy interventions
2. The attitudes of campus engineering and operations staff towards the feasibility and value of energy interventions (plug load monitoring and other methods)
3. The findings and shortcomings of previous studies, and recommendations for future studies

Each question addresses at least one of the research topics under the two study dimensions, human resources and study design, and serves the purpose of finding out the feasibility of a plug load study in the UW campus. The questions were formulated in a way that facilitates the response process: comprehension-related issues were designed out by using unequivocal terms and simple phrase structures, and the retrieval/recall process was made easier by giving respondents background information about the theme of each question and allowing the use of retrieval cues by choosing the conversational interviewing method (Schober & Conrad 1997). As some of the questions asking about respondents personal opinions were classified as potentially sensitive, thought was given for the neutrality of the context in which each question was introduced (Tourangeau & Yan 2007). In order to avoid response order effects and allow for more diverse answers, answer options were not given for any of the survey questions. A diagram of the dimensions and sub-dimensions the questionnaire addressed is presented in Figure 2. The interview questions are presented in Appendix 1.

![Concept specification diagram with research dimensions and subdimensions.](image-url)
3 RESULTS

3.1 Plug load monitoring

3.1.1 Monitoring system installation & operation

Depending on the amount of electronic devices in the office, the installation process took approximately 30 to 45 minutes per office. After installation, the exact locations and identifying information of all smart sockets, strips and touchscreen monitors were collected to a directory, which was kept up to date about the performance of the study equipment through the monitoring period. Apart from couple of malfunctioning smart sockets, the monitoring hardware functioned as expected and did not require maintenance over the 9-week study period. The total time used for hardware installation and operation was approximately 1-1.5 hours per office per 9 weeks.

The initial plan was to connect all monitoring systems to the University’s Wi-Fi but after unsuccessful attempts in all office rooms it became evident that the touchscreen monitors did not communicate with the server: users were unable to access their devices remotely and no electricity consumption data were saved to the system database online. The issue was temporarily resolved by connecting the monitoring systems to a wireless server outside University’s network but occasional network problems continued throughout the monitoring period. The unreliable network connection caused frequent disruptions in data collection and strong bias in the individual electricity consumption data. In addition, network problems caused additional workload to University’s IT specialists whose help was needed whenever the Internet connection went down.

3.1.2 Occupant behavior

The inventory of electronic appliances in the four faculty offices revealed a high variability in the number of appliances. Where some offices only had a computer, monitor and printer in them, others were equipped with microwaves, fans, radios and other miscellaneous electronic devices. (Table 1) Consequently, the average plug load level also varied highly between faculty offices. The rooms with highest amount of appliances had a high baseline plug load (plug load level when appliances are plugged in but not used) and higher plug load peaks (highest plug load level when offices are occupied and appliances are in use) during office occupancy. However, the frequent network problems precluded accurate estimation and comparison between per office plug loads and electricity consumptions.

The plug load data also revealed a high variability in occupant schedules during the 9-week monitoring period. The office was assumed to be occupied whenever the plug load level rose above the observed baseline consumption. The monitoring data showed that none of the four occupants followed a traditional office occupancy schedule. The offices were rarely occupied at the same time or for an equal amount of time per day (Figure 3a-d). Only one of the four occupants used the option to control appliance status through the touchscreen monitor and shut off smart strips and sockets when leaving the office. (Figure 3c) None of the participants set schedules for their plug load system to shut off automatically at a certain time of the day. Overall, the consumption patterns of the occupants stayed unchanged during the monitoring period: the occupants who did not use the system features, such as “away” and “home” modes, in the beginning did not develop interest in using them later in the monitoring period either. Respectively, the occupant who used the modes to control office plug load did so throughout the monitoring period.

3.2 Administrator Survey

The interviewed University administrators had different levels of involvement in the plug load monitoring study implemented in UW residence halls in 2013. While first interviewee was the overall project manager and the second interviewee responsible for student involvement and recruitment throughout the project, the third one was only responsible for planning the distribution of the plug load monitoring systems. However, when asked about issues related to the design of plug load monitoring studies, all three interviewees mentioned the lack of long-term engagement as the main challenge. According to the interviewees, participants are usually engaged and motivated to reduce their electricity consumption in
the beginning of any energy intervention, but the involvement fades as the “individuals lose interest” and
“everyday life gets in the way”. From the future plug load monitoring studies, the interviewees hoped for
more data on occupant behavior and long-term impact measurement both in individual and community
level.

Two of the three interviewees saw more potential in plug load monitoring in office environments than in
residential buildings. One of the respondents supposed that the routines and schedules of an office
environment might facilitate the implementation of a plug load monitoring campaign and lead to more
long-term occupant engagement. Another administrator speculated that the engagement level in an office
environment would be higher as occupants are more exposed to a positive peer pressure than in a
residential setting. Overall, respondents considered plug load monitoring as a key method for changing
occupants’ consumption behavior, “raising awareness and help drive decision making processes”. However, the respondents did not see plug load monitoring as an efficient way to reduce University’s total
electricity consumption as plug load was considered to be “fairly inconsequential in the overall electrical
demand of the University buildings”.

In addition to the problems related to the long-term occupant engagement, respondents mentioned
several miscellaneous factors that challenged the implementation of the residential hall plug load study
and might cause problems in the future studies as well. As possible technical difficulties, respondents brought up problems with Wi-Fi connection and the resulting interruptions in data collection. One of the administrators also anticipated that if a plug load study was implemented in a much larger
scale, the operation and maintenance might become an issue due to university staff’s lack of expertise in
the utilized plug load monitoring technology. Other non-technical challenges were mentioned as well. One
of them was the lack of focus in the study design: according to one of the respondents, the residential hall
experiment did not have a strong objective that would have guided the monitoring process from the
beginning to the end. The studied demographic group was also described as challenging: the occupants
of the monitored residential halls were mainly freshmen who had just moved on campus and were
struggling with their new lifestyle in academic environment. Moreover, they did not generally have high
interest in issues related to electricity consumption, as electricity costs were included in their rent. Respondents estimated that student involvement might have been stronger, if situation would have been
different.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Office 1</th>
<th>Office 2</th>
<th>Office 3</th>
<th>Office 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desktop computer</td>
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<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Monitor 1</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
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<tr>
<td>Monitor 2</td>
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<tr>
<td>Fan</td>
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<tr>
<td>Phone charger</td>
<td>●</td>
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<td>Phone</td>
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<td>Lamp</td>
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<td>Printer</td>
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<td>Refrigerator</td>
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<td>Microwave</td>
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<td>Radio</td>
<td>●</td>
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<tr>
<td>Touchscreen monitor</td>
<td>○</td>
<td>○</td>
<td>●</td>
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</tr>
<tr>
<td>Bass</td>
<td>●</td>
<td></td>
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</tr>
</tbody>
</table>

* ○ In the office ● Monitored
Figure 3a-3d: Office occupancy during a 5-day work week in 18.8.-22.8.2014. The electricity consumption (kWh/min) data shows differences in base loads and plug load peaks between four faculty offices. The typical office occupancy schedule is from ASHRAE 90.1-2004.
4 DISCUSSION AND CONCLUSION

The feasibility of an office plug load monitoring study was evaluated by implementing a 9-week monitoring campaign in four faculty offices at University of Washington campus. The findings of the 9-week mini study were compared with the results of a residence hall plug load study that was conducted at the same campus in 2013. In addition to monitoring plug loads, the researchers collected data by surveying university administrators that were involved in the prior residence hall plug load study. The administrators were asked about the findings, shortcomings, and recommendations for future studies. The study was able to identify possible challenges and barriers the stakeholders face when deploying plug load monitoring campaigns on campus settings. Moreover, it was able to characterize the load profiles of the faculty/staff offices, even though it failed to make accurate quantitative analyses of the participants’ individual electricity usage.

Throughout the 9-week study period, the unreliable network connection caused frequent disruptions in data collection and strong bias in the individual electricity consumption data. The disruptions eventually precluded accurate estimation and comparison between per office plug loads and electricity consumptions. In addition, network problems caused additional workload to University’s IT specialists whose help was needed whenever the Internet connection went down. These findings are in accordance with those of the 2013 residential plug load study, where problems with wireless connections between devices precluded plug load analysis on individual level (Black et al. 2014). Problems with wireless networks have been mentioned by other studies as well: Ghatikar et al. (2013) observed that in addition to being limited by their range, wireless plug load monitoring systems can be prone to high attenuation due to common obstructions in the office environments, such as cubicle separations and concrete walls. As many monitoring systems rely heavily on customers’ wireless networks, such connection problems introduce numerous walk away opportunities and limit wide spread occupant participation (Gilbert et al. 2011). Improvement to the current situation could be received by using more efficient network protocols, i.e. preferring 6lowpan protocol over more limited Zigbee protocol that is currently being used by most wireless monitoring systems (Ellaboudy 2012).

The inventory of electronic appliances in the monitored offices revealed a high variability in the number of devices. Consequently, the base consumption and peak plug loads also varied highly between faculty offices. (Figure 3a-3d) Murtagh et al. observed similar variability in their study with weekly energy use of the monitored workstations ranging from near 0 kWh to 21.4 kWh. Both results indicate that even though the work setting for academic office-based researchers is similar to other office settings, there are fundamental differences in occupant behavior and energy use. For instance, depending on their field of study, researchers may have very different needs for IT and other electronic appliances. Moreover, as was observed during this study, some researchers are physically present at their workstations for most of the time, while others are working remotely or sharing their time between several workstations and offices. (Figure 3a-3d) The observed variability in occupant schedules and hours of attendance differs significantly from the widely used ASHRAE 90.1 occupancy profile and implicates that fixed occupancy profiles are not ideal for modeling electricity use and plug loads in academic offices. (ASHRAE 2004) These findings are in line with other recent studies that have suggested updates to the current ASHRAE recommended practice (Bouffaron 2014, Davis & Nutter 2010).

The lack of occupant engagement was found to be the main challenge in the implementation of plug load monitoring campaigns. Although all participants of the 9-week office study were taught how to control their electricity use through monitoring equipment, only one of the four occupants used the option. The lack of occupant engagement, especially in longer term, was also mentioned as the main challenge by all of the interviewed University administrators. These results are in great agreement with prior findings of several short- and long-term plug load studies (Hargreaves et al. 2010, Ueno et al. 2006, Murtagh et al. 2013, Ecova 2011) and indicate that the design focus of future plug load monitoring campaigns should be on long-term occupant activation and engagement.
Acknowledgements

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References


ROAD MAINTENANCE INFORMATION MANAGEMENT SYSTEM
BASED ON PRODUCT DATA MODEL CONSIDERING DISASTER USE

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Abstract: Maintenance management is an essential operation that should be carried out effectively for maintaining, repairing, and rehabilitating highways and roads. It is necessary to accumulate information produced during the entire life cycle of roads in order to analyze problems and find solutions within a temporal sequence and to maintain them strategically and effectively. In road maintenance site, the administrators and engineers want to refer and utilize the road ledger and its drawings. It is difficult to carry and use the ledgers, because they are paper based documents. The primary objective of this study is to develop the product data models, which systematic information is defined for accumulating, exchanging, and sharing in civil infrastructure. And, this paper proposed a road maintenance information management system to collect, accumulate, share, and utilize the information considering disaster use. It is used in maintenance and disaster site by tablet PC. Road data models are effective for building an environment where the various data generated in a construction enterprise are used in an integrated manner. The constructed road data model has structural and work information. Structural information includes road structures such as bridges, carriageways, sidewalks, and road furniture. Inspections, repair judgments, repair of pavement, and construction of pavement are defined as work information. And, disaster information was added in structural information. The location-based expressions ‘GM_Point’, ‘GM_Surface’, and ‘GM_Polygon’ are defined to connect the road data model to spatial information. The proposed system was evaluated the usability and capability in road maintenance.

1 INTRODUCTION

Roads are networks that connect social infrastructure and accommodate the delivery of emergency services. Because of the importance of roads, they should be safe and kept in good condition. Maintenance management is an essential operation that should be carried out effectively for maintaining, repairing, and rehabilitating roads. It is important that the maintenance process is effective and that the quality of inspection is ensured. Cost-effective and high-quality maintenance depend on reliable inspection and condition assessment information (Osama 2003). Furthermore, reliable maintenance information influences management systems (Thompson et al. 2003). Existing management systems do not use standardized information, and cannot exchange, share, and reuse information. In order to carry out effective road maintenance, it is necessary to construct a system where the latest and highest-quality road information can be used and shared, thereby facilitating road planning, design, construction, inspection, and repair.

The primary objective of this research is to facilitate the sharing of road maintenance information with project participants. A fundamental requirement of such a system is the ability to support the modeling
and management of design and construction information and to enable the exchange of such information among different project disciplines in an effective and efficient manner. A Web GIS-based maintenance information management system is proposed using smart devices such as smartphone and tablet PC, and a prototype system is developed and evaluated for an actual road maintenance project. The system has the function of reference of road ledger using smart devices. The information is standardized by constructing a conceptual data model. Conceptual data models for road maintenance are constructed for use in the proposed system.

2 ROAD DATA MODELS

Road data models are constructed so that information within the information management system can be shared among those involved in the management of roads. A road data model is defined as the product data model of a road structure to which attribute information is added in order to link the model to the spatial data infrastructure.

Product data models of social infrastructure facilities are made by various organizations and research institutions (Stumpf et al., 1996; Karim and Adeli, 1999; Hastings et al., 2003; Chau et al., 2004; El-Diraby et al., 2005; Owolabi et al., 2006; Halfawy and Froese, 2007). However, the attributes defined in these data models, and in the data model schemas, are different from the attributes and schemas for road data models. If the same information is stored in accordance with different data models, this could lead to problems with information compatibility in the future. Data models that have already been constructed by various methods are difficult to standardize into a uniform format. Therefore, according to the objectives of the various social infrastructure facilities, standardizing the functions that must be fulfilled by the data models, and the types and items of information to be maintained, can be considered.

Road data models can be classified into two types: geometry information models and business information models. Geometry information models contain information associated with the constituent parts of roads. Business information models contain information necessary for road management work, as well as the results of information analysis produced as the result of such work. Interoperability and compatibility are important for the exchange and sharing of road information. It is, therefore, useful to define the rules of information exchange and sharing using existing standards and specifications. In constructing the geometry information models, design and dimensional information was extracted from the models. This includes information regarding the composition of the particular structures, information from the design and construction stages, and information that should be stored for future road management work. Information regarding the structure composition includes information for roads, slopes, bridges, tunnels, and ancillary items. Information from the design and construction stage includes design documents, numerical calculations, and as-built drawings. Information that should be stored includes the results of work such as inspection, repair, or strengthening of structures. In constructing the business information models, the information resulting from construction, inspection, detailed inspection, and repair and strengthening was extracted. Information resulting from construction includes initial inspection results. Information resulting from inspection includes determination as well as inspection outlines and inspection results. Information resulting from detailed inspections includes detailed inspection outlines and detailed inspection results. Information resulting from repairs and strengthening includes the outlines of repairs and strengthening, as well as the results of the repairs and strengthening.

Information on the geometric shape and attitude of items such as roads, buildings, and rivers has been generated from a wide variety of construction projects. This information should be shared and utilized by project participants. The road data model is a concept for sharing and utilizing information collected over the life-cycle of a construction project. The road data model is a method for analyzing the situation and solving the problem. Construction stakeholders and computer software can share and utilize the standardized information by using the road data model, as shown in Figure 1. The road data model has information from documents, CAD data, drawings, design calculations, and other sources which can be used by those involved in a construction project.

The road data model is shown in Figure 2 the location-based expressions ‘GM_Point’, ‘GM_Surface’, and ‘GM_Polygon’ are defined to connect the road data model to map information. The information
A management system was developed based on the proposed idea. Road data models are constructed so that information within the information management system can be shared among those involved in the management of roads.

![Figure 1: Interoperability of project information using the road data model](image)

Figure 1: Interoperability of project information using the road data model

![Figure 2: Road data model](image)

Figure 2: Road data model

### 3 SYSTEM DESIGN AND DEVELOPMENT

#### 3.1 Design principles

In maintenance, the management system with high accuracy is necessary, so analyzed information in lifecycle should be accumulated. This system is used in each phase of design, construction, inspection, soundness evaluation, deterioration forecast, and maintenance plan. The database of system has the role to support the each stage of life-cycle. For operating the management system, standardized information should be accumulated and shared based on product data models on considering a long-term service stage of concrete highway bridges. The concept of model oriented management system is shown in Figure 3. It is difficult to define unitary the information used in various existing systems and databases.
because of feasibility and operation. Standardized information can be exchanged and shared by exchanging the maintenance information through the product data models in maintenance management system and databases.

A road maintenance information management system was designed based on following design principles. (1) Uniform management of road maintenance data: Road maintenance information such as inspections, repair decisions, and repair work should be uniformly managed. Data is collected in a database and the system is used to retrieve the information. The system has a map interface, through which road administrators can gain an overall view of road damage and repair locations. (2) In disaster use: The system can be used for confirming the site situation when power blackout and network disconnect are occurred in wide-scale disaster. (3) The system is developed which has the functions of handwriting input, posting photos and reference of road ledger data.

![Figure 3: The concept of model oriented management system](image)

### 3.2 System architecture

A road maintenance information management system was constructed to allow those engaged in road maintenance to collect, store, share, and use information. As shown in Figure 4, the four-dimensional information management system consists of a spatial data infrastructure, a road database, road data models, a model library, a common system interface, system sharing functions, and a road application system. The system is structured so that new information items and system functions can be added in the future using the common system interface and road data models.
The proposed information management system is access through the Internet. The system architecture is shown in Figure 5. The system was consisted of a server with database, PC of road administrator for referring road ledger data, and tablet PC in use of site. The system is used for confirming the site situation when power blackout and network disconnect are occurred in wide-scale disaster.
Figure 5: System architecture

The system was developed on a Linux server using Apache, MySQL for database, HTML for showing road ledger data, XML (Extensible Markup Language) for marker on map, and Java for using API and Programming. Digital earth web API (Application Program Interface) of Geospatial Information Authority of Japan was used for Web GIS. In this study, Arrows Tab F-01D (Fujitsu Co., Ltd.) was used. For off-line use, the system was developed as application of smart devices using Java. It has the road ledger data and drawings in tablet PC.

3.3 System functions

The system has four functions: retrieving road ledger data and drawings, reference, input of inspection results, and submission of photographs.

(1) The function of retrieving road ledger data and drawings is used by location point of GPS and road name. The location of road ledger data and drawings is shown by marker of Web API on the map. The marker information are described by XML which represents longitude and latitude of location of road ledger data. The system screens retrieved by GPS are shown in Figure 6. A road administrator updates and stores road ledger data. A database management system was developed for retrieving and registering the information. A user sends a retrieve request from their web browser to the database server and subsequently receives the retrieved results.

(2) The road administrators can refer the road ledger data and drawings using tablet PC through the Internet. The drawings were exchanged from PDF data to PNG data. The each PNG data is about 400 KB and 1600*1200 pixel data. There are 1500 drawings in the system. Figure 7 shows the screen of reference function. The system can be used in online and offline situation. In large scale disaster, power blackout and network disconnect are occurred, and the system should be used in offline situation. In offline system, the road ledger drawings are retrieved by road name and shown on tablet PC. The example of offline use is shown in Figure 8. And the users can write the notations.
(3) The users can write the inspection results and notation on the road ledger drawing or photograph. The examples of this function are shown in Figure 9.

Figure 6: Retrieved results by GPS

Figure 7: Reference function

(4) The photographs are submitted by inspectors when they patrol the managed road and notice the damage using the system.
4 EVALUATION OF THE PROPOSED SYSTEM

The system was used to evaluate usability, smoothness of information flow, application capability, and usefulness. The demonstration data was about 211 MB of data on 550 pages of road ledger drawings in local government. The system operated normally without error. The results of the evaluation show that users rated the performance of the system as average or good. In terms of application capability, the system could possibly be practical for use in road maintenance. The system can be used to retrieve and use past road maintenance information, which can be difficult to find in offices and computers. However, the system has a few problems limiting its practical use.

The system can be used to refer a site situation by road ledger data and drawings, notations, and photographs. The road administrators can share the information stored in the database with workers carrying out maintenance operations. The data model has an environment for exchanging, sharing, and utilizing road maintenance information in road maintenance operation. The system, because it handles historical information, is applicable to road work management. There are barriers to implement the proposed system in a municipal or state road maintenance department where ontology and vernacular are different from those in the proposed system. Accordingly, the system would need to be modified to account for such difference and differences in departmental culture.
5 CONCLUSIONS

In this paper, a road maintenance information management system for storing, controlling, sharing, and using road ledger data and drawings, notations, and photographs in inspection was proposed, and a prototype system was developed. The system consists of a spatial data infrastructure, a road database, road data models, a common system interface, a system-sharing functions, and an application system. The road data model was constructed based on product data model concept. A prototype system was developed using tablet PC and evaluated in actual use. The system has the functions of retrieving road ledger data and drawings, reference, input of inspection results, and submission of photographs.

The main contribution of this study is a significant effort to extend the applicability of product data model. The system approach is based on a road data model. The system handles inspection and road ledger data, and can be used for maintenance management of road work. It is necessary to update the road data model in order to use these data in the process of maintenance operations. The proposed system has a data model framework that can be applied to road asset management, earthquake disaster reconstruction management, road buried objects management, and other types of structural maintenance.

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References

SCHEDULING REFRESHER-BASED RESCUE AND EVACUATION TRAINING FOR WIND TURBINE TECHNICIANS

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Abstract: The adage “once trained, always trained” is a recognized myth. A look at the refresher skill training of wind technicians show that rescue and evacuation skills deteriorate over a period of time of non-practice. Therefore, the importance of safe and efficient rescue and evacuation of wind turbine technicians working at height cannot be over emphasized. An evaluation of the wind technicians’ skill and knowledge proficiency in the use of rescue and evacuation devices after acquisition indicates that poor retention of technician skill in the safe and procedural execution of a rescue during an emergency is a potential problem that is yet to be addressed. This research quantitatively assesses if wind turbine technicians are capable of retaining knowledge and skills learned over a 24 month period, evaluates pre-acquisition, acquisition and follow-up primary measurements at retention intervals of one and three months and proposes a refresher timeframe and benchmark performance that can maximize the proficiency level of technicians. Due to the infrequent nature of practically carrying out on-the-job rescue and evacuation roles, there is a likelihood of skill and knowledge decay in times of significant emergencies except where there is a support system available to the technicians. Possible solutions to overturn these problems are discussed based on the data obtained during the study. Draft results were used to propose a refresher timeframe and benchmark performance that can maximize the proficiency of technicians to an acceptable level as guidelines for management towards scheduling safe wind turbine rescue and evacuation training.

1 INTRODUCTION & BACKGROUND

Skill decay after periods of non-use or non-practice is well known and has substantial implications when relatively long periods of time separate training from the application of learned skills, (Hall, Stiles and Horwitz 1998). Skill retention is significant because of the time that potentially separates skill acquisition and use of the same skills on the job. Without comprehensive evaluation of performance, accurately identifying and predicting skill decay is not feasible.

Researchers have spent a considerable amount of time identifying the relevant factors that affect skill retention, (Arthur Jr., et al. 1998). This is, for the most part, a practical decision because determining the quantitative relation requires greater expenditure of resources in terms of time, equipment, test subjects, etc. Among the factors that have been examined are: length of retention interval; task characteristics; methods of testing for original learning and retention; conditions of retrieval; use of mnemonics and other task aids; prior experience (Arthur Jr., et al. 1998). There are several job situations that demand the application of skills that have not been used over extended periods of time. Despite the apparent importance of skill retention on performance, however, few empirical studies have tested factors that
mediate skill retention in the wind energy sector. Other factors such as extended practice of skills have been associated with increasing skill retention. While practice has been established as a strong predictor of skilled performance, it has not been established whether reliable contexts, such as those found on the job, are related to retention. The work of Hurlock and Montague (1982) concluded that most skill deterioration is the result of several factors which include level of initial learning, non-utilization periods, skill type, events during skill non-use, and lack of effective feedback.

However, some types of skills tend to be better retained than others e.g. the two kinds of motor skills – continuous and discrete. Continuous motor skills are those involving the repetition of a movement pattern with no distinctive start or end (e.g. riding a bicycle) while procedural task which is the main focus of this study are a series of discrete responses, such as operating a rescue and evacuation device system, moving a gear shift etc. Another significant difference is that continuous motor skills decay slowly over a period of months and years while discrete/procedural skills decay rapidly over a period of days, weeks or months. Unlike continuous motor skills, procedural proficiency cannot be maintained in the absence of practice (Schendel, Shields and Katz 1978). Though these responses are usually self-paced and easy to execute, the main problem for the learner is response selection, i.e., deciding what responses to make and in what sequence to make them. In general, the retention of procedural tasks, the sequencing of tasks, and the ability to perform a task in a required time period deteriorate rather quickly.

Skill retention can be addressed using the concept of comparison of performance before, during and after a period of controlled activity – regarded as the retention interval. Performance measurements can vary from different studies and tasks, but ideally, it is based on combinations of speed, accuracy, and the number of procedural steps the subject can correctly recall. An individual’s post-training score on a performance test, combined with the length of the retention interval, according to (Bodilly, et al. 1986) is considered the best predictor of skill retention. Refresher training is typically used to stabilize the effects of forgetting and maintaining proficiency of skills. The significance to this study is to determine the rate at which skills decay, and schedule refresher training such that proficiency does not decay below an acceptable benchmarked performance. Schendel and Hagman (1980) stated that extra training enhances retention regardless of whether it is provided during the initial training or in a refresher training session at some point during the retention interval. Practical issues of cost and availability of personnel however, require that refresher training be conducted in an efficient manner that will both reduce the probability of further accident happening during rescue procedures and reinstate the performance levels of the technicians.

Strategic components of skills and knowledge should be periodically evaluated and supported to determine whether they meet the ever changing needs of the learners and to ensure effective training. Therefore, training needs analysis (TNA) which is a systematic assessment of training can affect improvement in the knowledge, skills or attitude of individuals or teams in the workplace, (Drummond 2008). It forms the basis for structured training and identifies current work-based ‘training gap’ or problems in performance standards that may be resolved through training. TNA identifies the current standard of performance being achieved, and the required standard of performance with the aim of attaining such standards through the scheduling of refresher trainings. The cost of training technicians to an organization when taken into account can be significant in terms of instructor time, cost of preparation, participant time, materials, training venues and equipment etc. Therefore, the money and time may not yield a satisfactory performance benchmark if the training gap of the technicians have not been clearly identified and defined i.e., training objectives, training plans and training programs which are designed based on identifying their training needs.

There is currently no procedure in place to determine skill deterioration, or refreshing needs of wind turbine technicians that will enable efficient technician refresher training decisions. Therefore, this research aims to propose a timeframe for considering when and how often such rescue skills should be refreshed for a ‘benchmark of good practice’. The industry assumption is that wind technicians maintain their individual skills over time and are ready to use such skills whenever needed in carrying out on-the-job rescue and evacuation roles. If this assumption does not hold, then the employers may wish to initiate an effective refresher training program.
A study conducted by Prophet (1976) concluded that the time needed to refresh is less than the time needed for original training. This finding also supported by Shields, Goldberg and Dressel (1979) found that even with skill decay following a no-practice interval, residual skills still remain. In addition, Rose, et al. (1981) found that tasks that were supported by job aids i.e. written materials that are used in the normal performance of the job were retained longer.

2 STUDY OBJECTIVES

- To quantitatively assess if wind turbine technicians are capable of retaining knowledge and skills learned over a 24 month period.
- To evaluate pre-acquisition, acquisition and follow-up primary measurements at retention intervals of one and three months.
- To propose a refresher timeframe and benchmark performance that can maximize the proficiency level of technicians.

3 METHODS

Figure 1: Method of data gathering using basic map explorer

Figure 1 shows the breakdown of the method employed in this study using a simple map explorer. The research participants were those registered to undergo the basic RenewableUK/Global Wind Organization (RUK/GWO) approved height safety and rescue training (purposive-expert sampling) and the study focused on the final 30 wind technicians. The ‘refresher participants’ connote returning trainees while the ‘fresher participants’ are first time trainees. The training was procedure- and system-based averaging 6-hours per day over two-day sessions with emphasis on emergency rescue, how to approach rescue situations in wind turbine generators (WTG) and competent use of rescue equipment. The research implemented longitudinal design approach for data gathering (de Vaus 2001) in order to track changes over time and establish the sequence in which events took place.

Closed-ended questionnaires were designed based on ‘Job Knowledge inventory Test’ (JKT) (Teachout, et al. 1993). This was used for the entire knowledge assessment from pre-acquisition to retention. Retention measures using JKT was administered online at intervals of one and three months. Skill pre-acquisition and acquisition involved ‘hands-on practice’ using the automatic constant rate descender (CRD) RG9A, (Lawani, Hare and Cameron 2014b). Only refresher participants were assessed during skill pre-acquisition stage because they have used this device in prior training sessions. Data for skill acquisition was collected for all participants while skill retention assessment was administered online using ‘Situational Judgment Test’ (SJT) (Lievens, Peeters and Schollaert 2008), with the aid of cued recognition using pictograms to prompt the participants. The participants were required to evaluate the randomized written performance description and the associated pictograms by correctly sequencing the
procedural execution of the use of RG9A for rescue and evacuation. These retention assessments 
engaged participants in the use of computer-based information displayed using two-dimensional (2D) 
images of the RG9A device. The performances were based on the number of device steps recalled and 
recognised in the correct sequence (skill) and the number of job knowledge information correctly recalled.

4 RESULTS & ANALYSIS

This study having been piloted, reviewed and amended is based on results of 30 research participants 
that fully participated all through the assessment period. This reflected an overall response rate of 36.6% 
out of a total of 82 initial research participants.

4.1 To quantitatively assess if wind turbine technicians are capable of retaining knowledge 
and skills learned over a 24 month period.

The magnitude of procedural skill and knowledge decay are presented in Tables 1 & 2. The refresher 
participants display an average of 14.9% and 21.8% decay in skill performance after one and three 
months respectively while the fresher participants show 19.8% and 29.6% decay in skill performance, 
(see Table 1). The magnitudes of knowledge decay for refresher participants were 10.5% and 9.5% after 
one and three months while the fresher participants were 20.4% and 21.4%, (see Table 2). Result of skill 
(59.8%) and knowledge (30.5%) decay at 24 months reflects the actual mean performance of refresher 
participants before embarking on the height safety and rescue training (see Table 1 & 2). Figure 2 (a) & 
(b) depicts the trend estimating that at 24 months retention, refresher participants will retain averagely 
35% skill and 66% knowledge competency indicated by the dotted red lines. These 24 month estimates 
were accomplished using actual pre-acquisition refresher assessment data to generate the theoretical 
curves describing the path of skill decay.

Table 1: Magnitude of skill retention over one and three month period

<table>
<thead>
<tr>
<th>Time</th>
<th>Refresher Skill performance (%)</th>
<th>Magnitude of decay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Refresher</td>
<td>Fresher</td>
</tr>
<tr>
<td>T₀</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>T₁</td>
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<tr>
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<td>68</td>
<td>57</td>
</tr>
<tr>
<td>*T₂₄M</td>
<td>*35</td>
<td>*</td>
</tr>
</tbody>
</table>

*T = extrapolated time at 24 months

Table 2: Magnitude of knowledge retention over one and three month period

<table>
<thead>
<tr>
<th>Time</th>
<th>Knowledge performance (%)</th>
<th>Magnitude of decay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Refresher</td>
<td>Fresher</td>
</tr>
<tr>
<td>T₀</td>
<td>66</td>
<td>55</td>
</tr>
<tr>
<td>T₁</td>
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<td>T₄</td>
<td>86</td>
<td>77</td>
</tr>
<tr>
<td>*T₂₄M</td>
<td>*66</td>
<td>*</td>
</tr>
</tbody>
</table>

*T = extrapolated time at 24 months
4.2 To evaluate pre-acquisition, acquisition and follow-up primary measurements at retention intervals of one and three months

Visual inspection for trends to determine the relationships for both skill and knowledge retention and any possible interactions was done using actual performance data. It was observed that after initial task proficiency, quantitative relationship between a task’s factors and its associated performance data at a particular time interval could serve as a generalizable model of skill decay. Figure 3 depicts the mean percentage performance for both skill and knowledge assessment from pre-acquisition to retention highlighting performance trends for refresher and fresher participants. Both set of participants experienced rapid increase in performance score from pre-acquisition to acquisition respectively with peak performances at T1 (Figure 3a) and T2 (Figure 3b). The participants experienced significant drop in performance levels for skill and knowledge assessments at one month and gradually dipping toward three month retention. Figure 3a confirm refresher participants outperforming the fresher participants from acquisition to retention periods suggesting the probable influence factor might be due to prior training and experience. Although this study reveals that at acquisition, both refresher and fresher participants can attain almost same level of peak performances (Figure 3b), however, over the retention periods, the probable impact of prior training and experience of the refresher participants seem to enhance their ability to retain knowledge longer than fresher participants. It shows that development is relatively continuous and gradual, and the participants are never at the same level for all skills, (Fischer 1980).

Statistical analysis (knowledge assessment) of tests of normality using Kolmogorov-Smirnov test with conservative alpha level ($\alpha = 0.01$) at T0; T1; T3; T4 ($p > 0.01$) meet the assumption of normality while T2 ($p < 0.01$) did not. Levene’s test for equality of variance ($\alpha = 0.05$) for knowledge test at T0, T1, T2, T3 ($p > 0.05$) show that there is not a statistically significant difference between the group’s variances. Therefore “Equal variances assumed”. T4 with ($p < 0.05$) show variance is significantly different and assumption of equal variance is not met. Independent sample test results ($\alpha = 0.05$) compared the Sig. ($p$) values for refresher and fresher participants: T0; T1; T2; T3; ($p \geq 0.05$) indicating that the refresher participants did not statistically significantly perform more than the fresher participants during the knowledge assessment. T4 ($p \leq 0.05$) conclude that refresher participants performed significantly more than the fresher participants.

Skill tests T0, T1 with Sig ($p < 0.01$) did not meet the assumption of normality while tests at T2; T3 Sig ($p > 0.01$) satisfy the assumption of normality. Levene’s Test for equality of variance ($\alpha = 0.05$) show T0 with ($p < 0.05$) and conclude there is a statistically significant difference between the group’s variances, “Equal variances not assumed”. T1; T2 and T3 had Sig ($p > 0.05$) and conclude that there is not a significant difference between the group’s variances. Therefore, “Equal variances assumed”. Independent sample skill test ($\alpha = 0.05$) for refresher and fresher participants T0 ($p \leq 0.05$) concludes that refresher
participants performed statistically significantly better while performances at T₁; T₂; T₃ (p ≥ 0.05) indicate no statistically significant difference.

![Graph of Mean Skill Performance](image1)

![Graph of Mean Knowledge Performance](image2)

(a) Skill Test Score: 1 = T₀ pre-acquisition @ day 1; 2 = T₁ acquisition @ day 2; 3 = T₂ retention @ 1 month; 4 = T₃ retention @ 3 months

(b) Knowledge Test Score: 1 = T₀ pre-acquisition @ day 1; 2 = T₁ acquisition @ day 2; 3 = T₂ retention @ 1 month; 4 = T₃ retention @ 3 months

Figure 3: Mean performance plots for skill & knowledge from pre-acquisition to 3 months retention

### 4.3 To propose a refresher time-frame and benchmark performance that can maximize the proficiency level of technicians

The education sector has a history of setting 75% as the benchmark for passing score (McKnight 1999). This study adopted Table 3 as guideline for diagnostic assessment of performance benchmark at limit state of 70%. The structure implemented for carrying out these assessments for benchmarking skill and knowledge is shown in Figure 4. Mean skill performance score for refresher participants at one and three months were 74% and 67.5% while the fresher participants performed at 65% and 57.22%, (Figure 5a). The skill performance at one month for refreshers at 74% was above the 70% threshold which this study considers as the limit state performance, while at three months, it falls short (see Table 3). The fresher participants performed below this threshold. Results for knowledge performance (Figure 5b) show that the mean retention score for the refresher participants at one and three month was 84.5% and 85.5% while the fresher participants performed at 77.9% and 77.1% which are above the 70% benchmark considered as the limit state performance. This indicates that the participants are capable of retaining their knowledge up to three months after acquisition.

<table>
<thead>
<tr>
<th>Grade %</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>80-100</td>
<td>Outstanding demonstration of learning outcomes</td>
</tr>
<tr>
<td>70-79</td>
<td>Excellent demonstration of learning outcomes</td>
</tr>
<tr>
<td>60-69</td>
<td>Comprehensive demonstration of learning outcomes</td>
</tr>
<tr>
<td>50-59</td>
<td>Satisfactory demonstration of learning outcomes</td>
</tr>
</tbody>
</table>

Table 3: Proposed diagnostic performance benchmark

![Diagram](image3)

Figure 4: Performance benchmarking structure for skill and knowledge retention
5 DISCUSSIONS

The results of this study build on existing knowledge by extending skill decay theory to field-based application. Further, empirical data has been used to identify the actual magnitude of procedural skill decay. Significantly, the magnitude of procedural skill and knowledge retention declined rapidly after one month and gradually toward three month. This is comparable with the study of Wetzel, Konoske and Montague (1983) which reveal that immediately after training and a four weeks interval, participants had a 21% drop in scores while Austin and Gilbert (1973) observed a 16% loss of basic problem solving skills after 8 weeks. A common construct regarding this is based on the feedback the trainees receive during acquisition (Ramaprasad 1983; Gibbs and Simpson 2004; Sadler 2010). When such feedback contains information about the magnitude and direction of performance errors, it directs the trainees towards ways of correcting the error and improving their performance while the infrequent or the total absence of feedback is associated with skill and knowledge loss, (Hurlock and Montague 1982; Driskell, Willis and Copper 1992). Another factor, whether direct or an intervening variable, is the time interval between training and performance. It is therefore not startling that the longer the time interval between practice and performance, the greater will be the skill decay. This study revealed that rescue skills decay over time where performance decreases rapidly soon after training then occurring at a slower rate, which is similar to results reported in the works of (Arthur Jr., et al. 1998; Wixted and Ebbesen 1991). According to (Driskell, Willis and Copper 1992; Wixted and Ebbesen 1991), this pattern appears to be consistent across a variety of skills and tasks. Previous skill retention research has sought to identify factors that influence the rate of individual skill decay (Rose, et al. 1985; Wisher, et al. 1991). If tasks could be reliably described according to these factors it would then be possible to examine, using actual performance data, how particular combinations of factors influence performance at some time interval (e.g. 24 months) after initial task proficiency had been achieved.

Learning is characterised by an initial steep learning period that asymptotes to maximum proficiency, while forgetting is characterised by an initial steep drop in proficiency, which then levels off, dropping more slowly as time goes on (Stothard and Nicholson 2001). According to Stothard and Nicholson (2001), the major decay in skill occurs in the first few weeks/months after training, with smaller differences over time. Findings from this study which are based on in-situ real life field data validates that the theory of skill decay is correct with proficiency dropping between time zero and three months. This confirms the results of Stothard and Nicholson stating that the drop in proficiency was greater between time zero and three months, than between the sixth and eighth month as suggested by others. ‘Forgetting’ over the three-month period occurred at different rates for refresher and fresher participants. The refresher participants tend to perform better on average than the fresher participants as depicted in the mean plots for both skill and knowledge tests. It should be noted that the degree of successful performance of an individual on any of these tests is largely reliant on the learning experience, or the type of practice and instruction received. Also, this study identified that task steps that are forgotten tend to be those that are not suggested by the previous sequence of steps or by the equipment and Shields, Goldberg and Dressel.
(1979) identified these as amongst factors accountable for differences in retention. The initial level of learning which is obviously related to the amount of initial training is one of the most important factors in determining retention (Hurlock and Montague 1982). An individual's level of initial proficiency has a direct relationship with the level of skill retention, and relation between recall success and skill level (Watson and Fischer 1977). Other contributing factors to procedural skill decay of wind technicians could be associated to their peripatetic nature of work which has limiting factors in this research; practice; aptitude; equipment design and task difficulty. Safe working requires robust procedures and it is suggested that training, practice and experience are major contributing factors influencing procedural skill decay during rescue and evacuation. This study also discovered that technicians mostly forgot task steps at the beginning and end of a task and steps related to safety and this was validated by the work of Osborn, Campbell and Harris (1979). Different literature has shown that skill retention for all tasks deteriorates; and the rate of retention differs by task characteristics. Tasks with performance that deteriorates rapidly tend to be procedural tasks which involve a number of steps, have no performance cues, and have time requirements similar to the use of the RG9A device while tasks with performance that deteriorates more slowly are continuous tasks with cues or an obvious internal logic. Ericsson and Lehmann (1996) pointed out that the attainment of exceptional performance is usually accompanied by sustained, deliberate practice and this is not possible with the technicians as the rescue device is considered as being deployed and not fit for purpose if taken out of the airtight storage bag. A central feature of deliberate practice is in the setting of performance goals and the application of practice strategies to attain these goals. Learners also make use of feedback to adjust the quality of practice and feedback is considered critical to remembering information, and timely and accurate feedback will enhance the ability of a learner to retain a skill.

Scheduling refresher training is costly, entailing time, personnel, and equipment costs which are necessary when training is periodic. For refresher training to be effective, technicians need to experience a range of job situations involving information or skills previously acquired but impaired through non-practice. Job-like problems should be varied and practice in solving them should provide feedback on the quality of performance. People generally need feedback, or “knowledge of results” to correct errors, observe and use cues associated with task performance, and generate effective procedures (Hurlock and Montague 1982). Therefore, implementing the proposed benchmark performance of 70%, it is advisable that refresher participants be scheduled to undertake rescue and evacuation practice drills within three to six months after skill acquisition. For fresher participants, it is recommended that they undertake an early practice drill within one and three months after skill acquisition to restore their proficiency to optimum. Performance benchmarking should be a continuous process of validating technician's performance to determine best practice and to establish process goals for improvement. Determining the limit state performance which is considered as the critical margin of safety performance for wind technicians involved four steps (see Figure 5): the ‘safety assessment’ of key competencies and the ability to perform those competencies within a specific task safely; the ‘accurate planning’ of an achievable path that a technician can follow to maintain or improve identified competencies by mapping strengths and weaknesses; the ‘acquisition’ of skills and knowledge required to maintain or improve identified competencies; and lastly, ‘timely validation’ of performance-based test conducted to determine if a technician retained proficiencies three months after skill acquisition. This structured approach towards benchmarking skill and knowledge can serve as a standardized scenario within which collective or individual performance can be assessed frequently as required to maximize basic skills and knowledge. Therefore, a limit state performance benchmark of 70% indicates that the study participants barely attain this limit after one month of skill retention assessment while their knowledge performance was beyond the outlined benchmark. It should be noted that even one error can be fatal in a rescue e.g. participant could score 80% which is a pass but the 20% wrong can result in fatality.

6 CONCLUSION

The skill and knowledge assessment is a strategy for sustaining technicians’ readiness toward efficiently using the RG9A device in carrying out rescue during periods of emergencies whilst working at height. Dynamic simulation technique is a favoured approach that can be applied to boost the strategy for refresher training rather than static representations (pictographs) used in this research. When employed,
such techniques can provide training of progressively greater complexity and realism. Dynamic simulation will permit technicians to apply real world and real time decisions to specific rescue and evacuation problems and to observe realistic responses to those decisions.

The principal application of this study addresses the facilitation of instructional and practice strategies that can lead to competent application of acquired skills and knowledge in the field. This is beneficial for practicing procedural skills that require timing and precision that can only be acquired through deliberate practice with authentic tasks.

Data on the feasibility of using technician-generated retention estimates to facilitate predictions about the scheduling of refresher training timeframes are suggestive, but not absolute. In general, the literature indicates that, in the absence of practice or other reinforcement, skill retention declines over a period of time. Since relearning or refreshing of skills can take significantly lesser time than original learning; this study has attempted to estimate relearning needs of wind technicians by adopting a benchmark performance and tentative timeframes for scheduling refresher trainings. Given that skill decay will occur even if wind technicians are over-trained, another approach of defining means to optimize the schedule of refresher training is needed so that technicians will receive training when needed to preclude them from falling below a set criterion level of performance. This can be accomplished by instituting the type of assessment used in this research where the technicians are required to carry out a situational judgement test and job knowledge inventory test as a function of estimating their training needs.

This assessment can also be used as ways of examining and predicting skill retention with the ultimate goal of improving the sustainment of performance or readiness. This study therefore recommends two comprehensive approaches to sustaining skill and knowledge of the wind technicians: enhancing initial learning, enhancing the prediction of skill retention for effective scheduling of refresher training thereby reducing the rate of skill decay. This can be achieved through the development of these potentially practical and accurate means of predicting skill decay to aid the scheduling of refresher training.

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LESSONS LEARNED FROM USING BIO- AND ENVIRONMENTAL SENSING IN CONSTRUCTION: A FIELD IMPLEMENTATION

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Abstract: Both physiological status and jobsite environmental stressors influence workforce behavior and performance. Understanding these relationships at the individual worker level is paramount for sustainably managing the construction industry workforce. Astonishing improvements in sensing technology can benefit field research by providing ways to validate occupational performance models based on data that measure workers' physiological variables and environmental stressors. However, only a few studies have taken advantage of these technological improvements to conduct construction field studies. This paper describes a field monitoring study hosted at a mid-rise, mixed-use building construction site in Seattle, WA. This study was valuable in terms of its breadth and period of the observations because it used some of the latest off-shelf wearable biosensors to collect 339 hours of workers' biosignal data from five subjects, during summer and fall, for a total of up to three weeks per subject. This research empirically validated that the heart rate is a good predictor of a worker's physical strain. Descriptive statistics and a time series plot were used to analyze the heart rate pattern as a predictor of worker's physical strain level. Correlation analysis was used to analyze the association between the workers' heart rate and jobsite environmental stressors. Also, analyzing video recordings and questionnaires helped interpreting the analytical results. This paper reports the lessons learned and the challenges of implementing a selected combination of wearable biosensor and environmental sensing technologies. These research findings are preparatory to validating a demand and capability model to be used for predicting construction workers' performance.

1 INTRODUCTION

Identifying the human factors affecting the performance of labor in terms of productivity, quality, and safety is important for sustainably managing workforce in the labor-intensive construction industry. Worker's low performance is critically related to an unhealthy and overloaded physiological status. In 2010, there were 4,690 fatal occupational accidents in the United States with 802 fatalities being in the construction industry (CPWR 2013). In regard to the workforce employed, the construction industry caused more deaths than any other major industry including transportation, agriculture, retail, and manufacturing. Similarly, the rate of days away from work caused by nonfatal injuries and illnesses is 39% higher for the construction industry than the average in all major industries (CPWR 2013). Accounting for 33% of the total 74,950 non-fatal injuries, bodily reaction and exertion was the largest cause of nonfatal injuries and illness in the U.S. construction industry.

Previous studies have identified workers' accumulated fatigue originating from continuous work activity, and bodily overexertion or repetitive motion as some of the causes of safety accidents and work-related
musculoskeletal disorders (Everett 1999; Putz-Anderson et al. 1997). Cardiovascular diseases, high blood pressure, and obesity are also major health-risk factors for construction workers (CPWR 2013). Workers’ overexertion and high fatigue are known to be negatively associated with labor productivity and quality of work (Astrand et al. 2003; Bernold and AbouRizk 2010). Overall, increases in physical strain and stress are expected to decrease work quality and productivity (Bernold and AbouRizk 2010; Ringen et al. 1995), and have a negative influence on safe work behavior due to an increasing of distractions and fatigue among workers (Hallowell 2010). Moreover, bodily exertion causes declines in work efficiency, reduces attentiveness, and increases errors (Abdelhamid and Everett 2002).

This paper summarizes results and reports lessons learned from a recently-completed field monitoring study that relied on a combination of wearable bio- and environmental sensing technologies. The study aimed at assessing opportunities and challenges in the use of biosensors and tracking devices in a construction site to promote the evaluation and validation of occupational performance models. The study relied on mainstream technology to help collect data related to worker physiological status, activity levels, and jobsite stressors. The adopted technology included a weather station with a wireless data logger, off-the-shelf physiological status monitors (PSM) as the option of biosensors, and global positioning systems (GPS) for tracking workers.

2 DATA COLLECTION AND METHODS

2.1 Data Collection Methods

2.1.1 Biosensor

Heart rate (HR) is one of the most important parameters to indirectly measure the physiological demands of workers (Beek and Frings-Dresen 1995; Garet et al. 2005; Takken et al. 2009). Among wearable sensors that measure HR, the Zephyr BioHarness™ 3 was selected for use in our research because it was considered to have high reliability and applicability (Dolezal et al. 2014; Gatti et al. 2011, 2014). Frequent bending and twisting of the waist is often required by construction workers, and for this reason, a sensor mounted on a chest belt, was considered to be more appropriate than a wrist-mounted sensor. Wrist-mounted sensors accurately measure HR of workers when they are resting or performing moderate activities (Terbizan et al. 2002); however, the pulse reading sensors may lose accuracy because of the unexpected fall-out from the wrist during harsh working activities. Also, chest-belt-mounted sensors measure HR similarly to electrocardiogram (ECG) sensors by recording the electrical activity of the muscular tissue of the heart. They are considered to be more reliable than wrist-mounted sensors using photoplethysmogram in physically active states (Schäfer and Vagedes 2013). The selected biosensor provides the functionality to collect HR (bpm), breathing rate (bpm), posture (degrees), activity level (g) and estimated core body temperature (°C).

2.1.2 Environmental Sensor

Outdoor temperature is one of the environmental stressors affecting construction workers’ performance. An increase in air humidity also influences sweat evaporation and can increase the heat stress of workers in hot weather. Wind speed also affects the velocity of sweat evaporation, and this may differ depending on the type of clothes worn by the workers (e.g. long-sleeve vs. short-sleeve shirt). If exposed to ultraviolet (UV) rays from the sun for long periods of time, workers may experience dehydration that is one of the variables associated with a worker’s physical strain level. Therefore, the amount of ultraviolet exposure the workers received was measured through UV sensors on a weather station in our research. A wireless weather station (Vantage Pro2™ Plus, Davis Instruments Corp.) was installed in the midsection of the tower crane. The height of installation of the weather station changed from summer to fall data collections to adapt to the building floor level on which the subjects were performing their tasks.

2.1.3 Other Data

Location Tracking: Location tracking was added with the expectation that it could help in performing work sampling to assess how long workers spent in various work areas versus the time they spent travelling
between working areas. To track the workers’ location, they wore portable global positioning system (GPS) devices throughout the work day. The i-gotU USB GPS Travel & Sports Logger (GT-600) from Mobile Action Technology, Inc. was selected because previous studies found it to be a fairly accurate GPS device for tracking human movement patterns in urban areas (Paz-Soldan et al. 2010; Vazquez-Prokopec et al. 2013).

Perceived Fatigue Level and Workers’ Major Tasks Performed: Surveys were administered at the beginning of each break and at the end of the work day to (1) assess each worker’s subjective fatigue level using the Samn-Perelli Fatigue Checklist (Samn and Perelli 1982), and (2) identify the major tasks each worker had performed between breaks. The Samn-Perelli seven-point fatigue scale (SPS) is a well-established subjective measurement of fatigue. Samn and Perelli (1982) validated the relationship between subjective fatigue levels on a 7-point scale and the performance capabilities of aircraft operators; a higher score indicated the operator felt a higher level of subjective fatigue. The SPS has been used to measure employee fatigue in most transportation industries including aircraft, truck, and rail. Dorrian et al. (2011) used the SPS in rating rail workers’ levels of fatigue to validate a statistical correlation between shift work and fatigue.

Video Recording: Previous studies relied on video recording to capture subjects’ productivity, activity, and behavior. The research participating contractor installed a webcam on an adjacent building, but this camera was only able to capture low-quality videos. Moreover, many critical working areas were located outside of the webcam’s line of sight. After an initial site investigation, the authors deemed it infeasible to install a high resolution site camera in a fixed position, as done in previous laboratory experiments (Cheng et al. 2012, 2013), due to line of sight requirements. Instead, the authors compromised to video recording only small portions of the workday with the plan of using this additional data feed to help interpret the data gather from the wearable devices. Using a digital camcorder (Canon Vixia HF S21), five-minute video observations were recorded three times for each worker: once in the early morning, once in the morning, and once in the afternoon. Video recordings were helpful for interpreting some of the analysis results and identifying the presence of other intervening factors.

2.2 Data Collection

Five healthy workers (age range: 27 to 40 years old; height range: 175 to 190 cm; weight range: 84 to 104 kg) were recruited from the selected construction site, a mid-rise mixed-use building project in Seattle, WA. The field observation was approved by the University of Washington Institutional Review Board (IRB). Table 1 includes additional information on these subjects. To guarantee the subjects’ anonymity, specific information such as height, weight, and race are ruled out in the table. Data were collected on workdays usually spanning from 7:00 a.m. to 3:00 p.m.; however, subjects often worked 10-40 minutes of overtime to complete daily assignments or to recover from delayed tasks. Throughout a typical workday, workers started with a short stretch and flex session at 7:00 a.m., and then returned to the trailer to prepare a pre-task plan. At this time, biosensors and GPS devices were provided to subjects to be worn. Workers had two break sessions, one between 10:00 a.m. and 10:15 a.m., and another between 12:00 p.m. and 12:30 p.m. During these two breaks sessions, and again at the end of the workday, short surveys were conducted to assess the workers’ perceived fatigue levels and identify major tasks performed. Data were collected during two different seasons (i.e., hot and cold weather) to increase the variability of environmental stressors. Ideally, the authors would have preferred to collect data in winter (between January and March) that is well representative of the cold weather data to increase the inter-seasonal variability contrasted with the one collected in summer. However, the authors were forced to compromise due to the schedule of the activities supporting the concrete placement that were being performed by the subjects. Because this task was scheduled for completion at the end of October, the data were collected in the following periods: (1) July 29th to August 8th (hot season in Seattle), and (2) October 14th to October 18th (mildly cold season). As workers performed tasks on the ground level in the summer, a weather station was set up at the lowest possible level of the tower crane. As workers worked on the roof in the fall, the weather station was moved and set up at the roof level of the tower crane. While working at the ground level, subjects often performed their activities under a temporary deck; therefore, the weather station data are not fully representative of the environmental stressors on these subjects.
Grubbs’ tests were used to detect outliers to be removed from our HR and BR datasets as described in a previous paper (Lee and Migliaccio 2014). Weather data were collected every five minutes, whereas HR and BR data were collected every second. Therefore HR and BR data were calculated as mean values over a time period of five minutes (300 seconds) to perform a correlation analysis.

3 RESULTS

3.1 Heart and Breathing Rates as Predictors of a Worker’s Physical Strain

Our data analysis strongly suggests that HR is a more useful parameter in monitoring workers’ physical exertion than BR. For instance, Figure 1 shows HR and BR time series plots for a selected day of the hot season. The plots show clear drops in HR during the break (10:00–10:15 a.m.) and lunch times (12:00–12:30 p.m.), when the workers were resting. The same trend was observed for all five subjects in both seasons, independently from the tasks being performed. On the other hand, the BR data do not provide the same information. This analysis shows how real-time HR data are important to monitor and predict workers’ physical exertion, which is in return associated with workers’ physical strain levels (Bernold and AbouRizk 2010).

<table>
<thead>
<tr>
<th>Subject Codes</th>
<th>BMI</th>
<th>Major Task</th>
<th>Study Participation</th>
<th>Total Hours of Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Summer (Jul. 29 to Aug. 8)</td>
</tr>
<tr>
<td>S.F.1</td>
<td>27.4</td>
<td>Formwork</td>
<td>●</td>
<td>120</td>
</tr>
<tr>
<td>S.F.2</td>
<td>25.8</td>
<td>Formwork</td>
<td>●</td>
<td>85</td>
</tr>
<tr>
<td>F.3</td>
<td>26.9</td>
<td>Formwork</td>
<td>●</td>
<td>27</td>
</tr>
<tr>
<td>S.4</td>
<td>30.4</td>
<td>Concrete Pouring; Cleaning Deck</td>
<td>●</td>
<td>59</td>
</tr>
<tr>
<td>S.5</td>
<td>25.1</td>
<td>Layout; Pour Watch</td>
<td>●</td>
<td>48</td>
</tr>
</tbody>
</table>

|               |     |                                 |                     | Fall (Oct. 14 to Oct. 18)    |

Figure 1: Comparison of HR and BR Time Series Plots for S.F.1 on July 29th
3.2 Jobsite Environments

The field weather conditions during the observations are described in Table 2. As expected, higher ambient temperature levels, higher solar radiation levels, and lower relative humidity levels were measured in the summer season than in the fall. The variability of these factors was lower in the fall season than in the summer season. The daily raw data show that the outdoor temperature continuously increased from the beginning to the end of the workday. Conversely, the humidity level decreased throughout the workday. The rainfall data collection failed due to the existence of a hole in the rain collector, which was blocked by wood dust from the construction site. This event suggested that a debris filter should be installed for rain collection in future developments of the research. The amount of solar radiation was generally higher in the summer than in the fall. We did not find differences in wind speed patterns between summer and fall.

Table 2: Weather Condition on Jobsite

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Summer, Week 1 (Jul. 29-Aug. 2)</th>
<th>Summer, Week 2 (Aug. 5-Aug. 9)</th>
<th>Fall, Week 1 (Oct. 14-Oct. 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Median Min Max SD</td>
<td>Mean Median Min Max SD</td>
<td>Mean Median Min Max SD</td>
</tr>
<tr>
<td>Ambient Temperature (˚F)</td>
<td>61.4 60.9 55.7 70.1 3.5</td>
<td>69.2 69.9 58.8 81.0 5.8</td>
<td>49.9 50.0 42.0 59.4 3.7</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>79.7 81.0 57.0 96.0 9.9</td>
<td>67.2 65.0 37.0 89.0 12.2</td>
<td>89.1 90.0 64.0 98.0 7.4</td>
</tr>
<tr>
<td>Wind Speed (mph)</td>
<td>3.9 4.0 1.0 8.0 1.3</td>
<td>4.3 4.0 0.0 11.0 2.1</td>
<td>3.5 4.0 0.0 9.0 2.1</td>
</tr>
<tr>
<td>Solar Radiation (W/m²)</td>
<td>344.5 238.0 30.0 923.0 288.3</td>
<td>516.6 643.5 49.0 865.0 312.2</td>
<td>158.4 101.0 0.0 583.0 150.0</td>
</tr>
</tbody>
</table>

3.3 Heart Rate versus Climatic Conditions at the Season Level

Jobsite environmental stressors are expected to affect HR, and so we analyzed our data to this end. To compare the two seasons, we focused our analyses on the subjects who had participated in both summer and fall data collection efforts: S.F.1 and S.F.2. For our analysis, five minute subject-level data were segmented into three sessions per workday depending on the break schedule (i.e., early morning, later morning, afternoon). Moreover, we only included in the analyses those data points corresponding to sessions for which we had data for both the subjects. Finally, we excluded data from August 5th-7th from the data analysis because an unusually heavy workload was performed on these days by subject S.F.2. Therefore, sessions from the following dates were included in the dataset: July 29th-31st, August 1st-2nd, and October 14th-18th. Finally, our dataset included a total of fifteen data points per subject per season (i.e., three sessions multiplied by five days per season). Each data point was represented by a four-dimensional vector that included average, median, minimum and maximum sessional values per subject.

Using this dataset, season-level descriptive statistics were computed (see Table 3). For both the subjects, we found that maximum HR values were higher in fall than in summer. Similarly, we found that average HR values were higher in fall than in summer. To analyze whether this higher average HR in the fall over the summer was statistically significant, a one-sided two-sample t-test was performed. For this analysis, the week 1 summer data were compared with the week 1 data collected in the fall. For the subject S.F.1, the average HR was 115 bpm in the fall season and 109 bpm in the summer season. With 95% confidence, the null hypothesis that the average HR between the two seasons would be the same was rejected ($p=0.047$, $\alpha=0.05$ level). In the case of subject S.F.2, the average HR was 107 bpm in the fall season and 101 bpm in the summer season. With 90% confidence, the null hypothesis was rejected ($p=0.061$, $\alpha=0.1$ level).

This result contrasted literature-based expectations that suggested a positive association between HR and outdoor temperature. An analysis of the amount of clothing used by the workers in the two seasons...
can help explain this result. In fact, our subjects wore longer sleeves and thicker clothes during the fall season, which may have restricted their physical movement (see Figure 2). Consequently, this may have caused an increase in their core/skin temperatures, and limited the mobility of their arms and torsos while working, which would have required more worker movement, and therefore increased overall physical exertion. As a result, workers reached higher level of physical strain. This result suggests a significant role of clothing insulation in physical exertion, which should be evaluated in future studies.

### Table 3: Seasonal Comparison of Heart Rate (bpm) Between Subjects S.F.1 and S.F.2

<table>
<thead>
<tr>
<th>Subject Codes</th>
<th>Summer (Jul. 29 – Aug. 2)</th>
<th>Fall (Oct. 14- Oct.18)</th>
<th>Two-sample t-test Summer vs. Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
<td>Min</td>
</tr>
<tr>
<td>S.F.1</td>
<td>109.3</td>
<td>110.3</td>
<td>57</td>
</tr>
<tr>
<td>S.F.2</td>
<td>101.3</td>
<td>102.4</td>
<td>55</td>
</tr>
</tbody>
</table>

**Figure 2: Summer Season Clothing (left) and Fall Season Clothing (right)**

### 3.4 Heart Rate versus Climatic Conditions at Peak

In addition, we analyzed the dataset for peak climatic conditions on August 6th. This day was selected because the daily deviation of the ambient temperature was high and biosignal data from three subjects (S.F.1, S.F.2, and S.4) were collected fully over the eight work hours. S.5 was also present, but the last 3 hours of data for that subject were lost due to malfunctions in the chest belt unit. Subject F.3 did not participate in the summer study because he enrolled only for the fall dates. A Pearson correlation analysis found no correlation between ambient temperatures and HR for subjects S.F.1 and S.F.2, and a positive weak correlation for S.4 (r=0.24, p<0.05) (see Table 4).

### Table 4: The Pearson Product-Moment Correlation Coefficient between Ambient Temperature (F˚) and Subject’s Heart Rate (bpm) on August 6th

<table>
<thead>
<tr>
<th>Subject Codes</th>
<th>Pearson-r (r)</th>
<th>n</th>
<th>p-value (α=0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.F.1</td>
<td>0.11</td>
<td>91</td>
<td>0.320</td>
</tr>
<tr>
<td>S.F.2</td>
<td>-0.18</td>
<td>91</td>
<td>0.085</td>
</tr>
<tr>
<td>S.4</td>
<td>0.24</td>
<td>91</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Since previous studies have suggested that wet-bulb globe temperature (WBGOT) rather than outdoor ambient temperature should be the index used to evaluate workers’ heat stress levels and can be a more useful parameter for predicting workers’ heat strain (OSHA 1999; Rowlinson and Yunyan 2014), we also performed a correlation analysis between WBGOT and HR (see Table 5). The outdoor WBGOT is estimated
by the weighted sum of the natural wet-bulb temperature ($T_w$), the globe temperature ($T_g$), and the
ambient temperature ($T_a$), as shown in Equation 1.

\[\text{WBGT}= 0.7T_w + 0.2T_g + 0.1T_a\] 

To estimate the $T_w$, the dew point temperature, the ambient temperature and atmospheric pressure data
collected by the weather station were cross-referenced in the American Society of Heating, Refrigerating,
and Air-Conditioning Engineers (ASHRAE) Psychrometric Chart. The $T_g$ calculated by Tonouchi et al.
(2001) was estimated from the wind speed and solar radiation as shown in Equation 2 below:

\[T_g= T_a + 0.007 \times S - 0.208 \times U\]

where $T_g$ is the black globe temperature (°C), $T_a$ is the ambient temperature (°C), $S$ is a solar ration
(W/m²) and $U$ is wind speed (m/s). Since the equation is developed in SI base units, imperial units were
converted to SI units to apply this equation. From these processes, the WBGTs were estimated for every
five minute period from 7:30 a.m. to 3:00 p.m. on August 8th. Since the WBGT calculation model is
empirical, it should be different from the measured WBGT from heat stress monitors incorporating WBGT
sensing technology. With this calculated data set, additional Pearson correlation analysis found no
statistically significant correlation between WBGT and physical strain measured by HR for subjects S.F.1
and S.F.2, and a positive weak correlation for S.4 ($r=0.23$, $p<0.05$), as shown in Table 5, from the
uncontrolled field data.

Table 5: The Pearson Product-Moment Correlation Coefficient between WBGT (F°) and Subject’s Heart
Rate (bpm) on August 6th

<table>
<thead>
<tr>
<th>Subject Codes</th>
<th>Pearson-r (r)</th>
<th>n</th>
<th>p-value ($\alpha=0.05$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.F.1</td>
<td>0.16</td>
<td>91</td>
<td>0.140</td>
</tr>
<tr>
<td>S.F.2</td>
<td>-0.19</td>
<td>91</td>
<td>0.067</td>
</tr>
<tr>
<td>S.4</td>
<td>0.23</td>
<td>91</td>
<td>0.027</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS AND LESSONS LEARNED

The study narrated in this paper used some of the latest off-shelf wearable biosensors to perform an
extensive field observation that produced a raw dataset: 339 hours of workers’ biosignal data from five
subjects, during two seasons (summer and fall), for a total of up to three weeks per subject. The research
empirically validated that HR is a good predictor of a worker’s physical strain. Descriptive statistics and a
time-series plot were used to analyze the HR pattern as a predictor of worker’s physical strain levels.
Correlation analysis was used to analyze the association between the workers’ HR and jobsite
environmental stressors. Whereas no association was observed between the climatic data and HR, the
approach initially selected to evaluate environmental stressors may have been flawed. In fact, at the end
of the study, the site environmental health and safety (EHS) manager, who performed several daily walk-
throughs of the jobsite, informed us that there was a considerable difference in conditions between the
location of the weather station in the tower crane and the microenvironment on the deck or in the
basement where the workers were working. Ideally, the authors would have preferred to collect data in
winter (between January and March) that is well representative of the cold weather data to increase the
inter-seasonal variability contrasted with the one collected in summer. However, recent advances in
sensor networks may provide a solution to this need for a diffused network of environmental sensors that
could be resistant to the harshness of a construction jobsite in the future. The preliminary findings from
this extensive field study with five subjects are not sufficient to generalize the statistical outcome to all
construction workers in Washington State or the United States because the purpose of this study was to
evaluate the use of bio- and environmental sensing technologies for understanding processes affecting
construction workers’ performance and health.
The authors were challenged by various practical issues during this first extensive field study. These issues are shared hereafter for the advantage of other researchers.

**Use of GPS Trackers:** Whereas the adopted GPS units were found reliable in urban environments by previous studies on tracking general human movements, they did not seem as adequate for tracking construction workers. GPS data lacked reliability due to serious signal disconnections. This issue was attributed to the many barriers (e.g., working under the slab formwork, working in the basement, and using a portable toilet) that obstructed clear GPS satellite communications, as well as artificial errors caused by electrical power lines near the site (see Figure 3). Still, we expect that the same devices may provide satisfactory tracking in open-sky conditions.

![Figure 3: Causes of GPS Malfunction](image)

**Confounding Factors:** We observed that some subjects frequently drank energy drinks and smoked during the breaks. These confounding factors may have affected the HR and BR data. Thus, additional survey instruments on the subjects’ dietary and smoking habits should be implemented, and potential compounding variables need to be controlled in the field study.

**Fear of Reporting to Supervisors:** Based on early conversations during the design of the field study, we perceived construction workers being concerned that the study’s results would be reported to their supervisors at the individual level. This created a sense of resistance for the workers to be monitored through wearing sensors. Therefore, we implemented a careful recruitment process in which a consent form was used to instruct workers about the confidentiality of their data and to assure them that the results of the research would not cause them any disadvantages relative to their supervisors. Still, we adopted a top-down recruitment approach wherein project management helped recruit workers. As a result, a member of the field management team was able to “figure out” who the subjects were and manifested an extreme curiosity in knowing his individual workers’ HR trends. Although the researchers strongly protected the confidentiality of the subjects, this behavior resulted in some residual diffidence by the workers that may have caused some of the dropouts. In the future, we will explore alternative approaches to recruitment that are more bottom-up and use unions and apprenticeship programs as recruitment venues. In addition, we will avoid installing instrumentation in the same trailer used by the field management.

**Fear of Underperforming against Peers:** Insincere reporting probably occurred among subjects in the SPS perceived fatigue survey. For example, a worker was caught looking at other subjects’ survey forms, and another worker asked researchers what levels of fatigue other subjects had reported. These behaviors may indicate attempts to report fatigue levels that did not reflect the actual perceived fatigue. Thus, subjects should complete the surveys away from one another.

**Trades to be Observed:** All the subjects worked for the general contractor on site. As a result, the types of tasks assigned to the subjects presented high variability in scope and target outputs. Some of the inconclusive results may be attributed to this issue. In the future, we plan to perform field observation of subjects belonging to specialty trades as the variability in their scope and target output will be reduced.

**Use of Video Recording:** While recording short videos of construction activities that could help capture confounding factors, we observed that subjects often became aware of being recorded and changed their
work behaviors. This was expected and we kept these periods very short. However, positioning several fixed cameras may overcome this issue in the long term.

The cited challenges allowed the authors to outline a roadmap for the successful implementation of bio- and environmental sensors in the construction field. First, it is important to carefully design a study and a managerial strategy to minimize both workers’ resistance to recruitment and insincere reporting of perceived variables. Second, subjects should be recruited from subcontractors involved in the slab framework, roofing, drywall, or masonry trades because these tasks are repetitive and physically intense, require less multitasking, and limit the dimensions of the traveling area, which in return increase the chance of successfully using tracking devices to perform automatic work sampling (Cheng et al. 2013). Third, the use of GPS tracking should be limited to open-sky tasks with minimal barriers presented by built slab framework or roofing. Whereas a need of analyzing indoor activities in established, traditional visual work sampling (Liou and Borcherding 1986) could be applicable to provide an indirect measure of physical exertion and performance. Fourth, cooperation and advice from site superintendents and safety managers is needed to appropriately place environmental sensors for local measurements and cameras that would limit the confounding factor of having a researcher on-site operating these devices.

References


OPTIMIZING EARTHWORK HAULING PLAN WITH MINIMUM COST FLOW NETWORK

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Abstract: Linear programming is commonly used in earthwork hauling plan. However special expertise in forming and solving linear equations, along with considerable efforts in interpreting results, is required to apply these methods in practice. Moreover, previous methods mainly focus on cost estimation and thus largely ignore the constructability issues; this makes earthwork hauling plan impractical for construction planning. We aim to address these problems by introducing an intuitive graph based approach which optimizes the earthwork hauling plan using the minimum cost flow network. We choose the total traveling time as the objective function to be minimized in order to separate the earthwork hauling plan from other factors such as fleet combination. Our method directly connects adjacent sections allowing accessibility between them, instead of connecting the centers of cut and fill cells as potential haul routes as in previous methods. As a result, the proposed method is capable to handle constructability issues caused by "soft blocks" -which cannot be eliminated in establishing the standard flow network as their existence impose constraints on the grading plan. The graphic earth flow network can be used to guide the execution of the earthwork project and generate multiple grading plans, providing more flexibility compared to traditional methods. We present an earthmoving example with a reserved soft area and show that the proposed method is graphically intuitive, easy to establish and able to handle soft blocks.

1 INTRODUCTION

For large infrastructure construction projects such as road construction, it is common that earthwork accounts for about 25% of the total construction cost (Hare 2011). As a result, an optimized earthwork design is essential to enhance the performance of the project. Aiming to reduce the total quantity of earth to be moved, cut-fill balancing algorithms were proposed to equalize the quantity of earth for cut and minimize the quantity of earth handling from borrow pit and to landfill (Goktepe and Lav 2004). The technique has been well-studied and can be easily applied through commercial software such as Auto CAD Civil 3D which facilitates generation of the final topographic surface of the site. The quantity of materials in each cut and fill sections can then be derived from the elevation difference between the original and final as-designed surfaces.

A well designed grading plan can reduce the total amount of earth excavated, however the most significant savings can be achieved by optimizing earthwork operations which involve large numbers of costly heavy equipment such as excavators, loaders, trucks and compactors. According to the research conducted by Hare et al (2011), an approximate optimal earthwork operation plan can result in as much as 48% to 74% cost improvements. The fleet composition and earthwork hauling plan are important factors in earthwork operations hence become the focus of productivity enhancement in earthmoving
projects. Though plenty of research has been done on fleet optimization (Moselhi and Alshibani 2009, Morley et al. 2014), it highly depends on the predefined earthwork hauling plan. Therefore an optimized earthwork hauling plan is critical to further reduce the amount of hauling efforts and facilitate the fleet optimization. Peurifoy and Schexnayder (2002) suggested three most significant factors of an earthwork hauling plan, i.e. the quantity of earth to be moved, the haul distances to move the material and the grade of the road that the material must be hauled over. This research addresses quantity of earth to be moved and hauling path explicitly; the grade of road is represented by travel speed implicitly.

Mass-haul diagram is widely used for making earthwork hauling plan in road construction, but it is limited to linear type of construction. Linear programming (LP) based earthwork hauling plan optimization was first introduced by Stark and Nicholls (1971) and then implemented by Mayer and Stark (1981) using haul distance as the unit cost. Easa (1988 a) proposed building a similar model aiming to optimize road way grades by minimizing the earthwork cost. Given that the unit cost of purchase and excavation of borrow pits is proportional to the quantity of materials required (Easa 1987), Easa (1988 b) modified the model by taking the variability of unit cost for purchase and excavation of borrow pits into consideration. However it is noteworthy that once the final grading design is defined, the purchase and excavation will be fixed and thus will not affect the total direct cost. The commonly applied shortest route cut and fill problem (SRCFP) model in road construction is intended to grade a project site with minimum total distance traveled by earthmoving vehicles (Hare et al. 2011). Because SRCFP considers the variation of return distance due to change in excavation sites, the model is much more realistic but also more complicated. To handle large earthwork projects in road construction, Ji et al. (2010) proposed a one dimensional earthwork section division LP model which minimized the earth handling between sections. Taking the duration into consideration, Jayawardane and Harris (1990) incorporated fleet selection into the linear model. Chu et al. (2012) proposed a time-space network which generated earthwork hauling plan and schedule simultaneously for projects with single type of trucks, the applicability to multiple trucks was undisussed. More recently, Son (2005) introduced a minimal haul distance LP algorithm and proposed a graph based earthwork hauling plan visualization method.

Building the models and solving the complicated equations in previous studies require a large amount of time and expertise, which in turn hampers wide utilization of those techniques in practice (Alshibani 2008). In real world construction projects, establishing these equations in a finite time frame in support of decision making creates additional challenges. Besides, executing a project based on interpretation of numerical results obtained from analytical or simulation algorithms with many “hidden” conditions, assumptions would be more difficult for coordinators on site. These conditions may include “hard blocks” which can be identified without the final hauling plan, and even more complicated “soft blocks” which depend on the final hauling plan. Previous methods like linear programming are able to handle “hard blocks” if well defined, however they usually generate hauling roads with ungraded “soft blocks” due to mutual reliance. To address these problems, this research applies the minimum cost flow network algorithm into earthwork volume balancing. Through a graphic way, the network provides users with an intuitive medium to build the underlying equations. Current linear programming models generally produce a unique grading plan, largely neglecting practical site conditions such as safety of particular haul roads. Such solutions can only serve the need of cost estimation and will likely result in unrealistic grading plans for implementation. Noting this critical issue, this research proposes a neighborhood method based on the classic minimum cost flow network with 4-connected neighborhood, aimed to make the solution ready for execution by integrating constructability issues.

2 PROBLEM DEFINITION AND TRADITIONAL MINIMUM FLOW NETWORK

In graph theory, a flow network is a directed graph \( G(N, A) \) defined by a set \( N \) of \( n \) nodes and a set \( A \) of \( m \) directed arcs. Each arc \((i,j) \in A\) is associated with three properties. The unit cost \( c_{ij} \) indicates the cost of unit of flow on the arc. Capacity limits \( u_{ij} \) and \( l_{ij} \) are used to constrain the maximum and minimum flow on arc \((i,j)\). For each node \( i \in N \), an integer number \( b(i) \) denoting supply/demand is also defined. The nodes can be divided into three different categories based on \( b(i) \). If \( b(i) > 0 \), node \( i \) is a supply node with a supply of \( b(i) \); if \( b(i) < 0 \), node \( i \) is a demand node with a demand of \(-b(i)\); otherwise if \( b(i) = 0 \), the node is a transshipment node. The minimum cost flow aims to find the flow \( x_{ij} \) on each arc \((i,j)\) that
minimizes the total cost subject to the supply and demand constraints formulated as follows (Ravindra et al. 1993):

[1.1] Minimize \( \sum_{(i,j) \in A} c_{ij} x_{ij} \)

subject to

[1.2] \( \sum_{j \in (i,j) \in A} x_{ij} - \sum_{i \in (j,i) \in A} x_{ji} = b(i) \) for all \( i \in N \)

[1.3] \( l_{ij} \leq x_{ij} \leq u_{ij} \) for all \( (i,j) \in A \)

With the original topography and the final layout of the construction site, the site is usually subdivided into small sections as raster format commonly used in a digital earth model (DEM) in order to facilitate cut and fill quantity estimation in commercial software. The DEM is then resampled at a suitable resolution for earthwork volume balancing optimization. Figure 1 gives an example of a balanced grading project with 0 borrow and 0 landfill. In this example the DEM is resampled onto 125m × 125m grids.

![Figure 1: Typical balanced earthwork divided into sections: Positive values in light color indicate cut volumes; negative values in dark color represent fill volumes](image1.png)

![Figure 2: Traditional minimum cost flow network in earthwork hauling plan with cut and fill connected directly. Red indicates cut and blue represents fill. B is borrow pit and L is land fill.](image2.png)
The earthwork hauling plan problem can be depicted as the flow of earth on the construction site from one section to another; thus it can be modeled as a flow network. Each sub-divided section can be regarded as a node in the graph, and the supply/demand \( b(i) \) will be the cut or fill quantity of earth. For extra materials, borrow and land fill sites can be added as either a node or a connected sub-network. In previous research, the equations usually assume that the supply and demand nodes are connected directly as illustrated in Figure 2. Each arc in the figure represents a hauling path which can be built in the field to haul earth.

As the aim of earthwork hauling plan is to minimize the total cost of the project, the definition of unit cost is critical. Considering that various types of costs (such as time, capital, environment etc.) may apply, the unit cost is assigned accordingly. Current algorithms use either the hauling distance or the unit capital cost of material excavation & transportation as unit cost. For rough estimation or linear construction projects, the hauling distance between sections are usually determined as the direct distance between the centers of the two sections. For precise estimation, the hauling distance can be derived with shortest path algorithms (Liu and Lu 2014). The unit capital cost of traveling on the surface relies heavily on the fleet combination, which can be optimized based on the earthwork hauling plan.

The proposed neighborhood method utilizes time as the final criterion based on the observation that no matter how the condition changes, both direct cost and indirect cost are proportional to time. As the amount of earthwork for excavation and dumping will be fixed as per the grading design, the only variable which can be optimized would be hauling. Therefore, only hauling time is considered when define the unit cost.

Previous earthwork hauling plan methods mainly focused on cost estimation and thus barely catered to field construction needs. This often leads to oversimplification or neglecting constructability issues in connection with project execution. However, ignoring certain existing blocks in the field would result in inaccurate estimation of optimal earthwork costs and poor haul road design. These blocks can be divided into hard blocks and soft blocks according to the occurrence condition. The occurrence of hard blocks such as waterways, ponds and rock-bed is independent of the earthwork hauling plan. On the contrary, the existence of soft blocks can affect the final earthwork hauling plan. As hard blocks are known before the establishment of the earthwork hauling plan model, they can be embedded into the flow network with well-defined connections and unit costs. Take river as an example. An extremely high unit cost can be assigned to paths or sections crossing a creek on site. Through this approach the total cost to move the earth across the river will be extremely high and the paths crossing the creek will be automatically discarded through optimization if alternatives are available. On the contrary, the occurrence of soft blocks is unpredictable because they may rely on the earthwork hauling plan which is actually the final output of such optimization analysis. One typical constructability issue in earthwork hauling plan planning is that the sections along the path for particular earthmoving operation should have already been graded into temporary haul road while part of the path lies in soft blocks to be excavated or filled.

Soft blocks may be produced due to mutual reliance when the earthwork plan is not generated properly. To illustrate the mutual reliance, assuming the volumes of C-1, C-2, F-1 and F-2 in the linear earthwork hauling plan (Figure 2) are all the same and regarded as 1 unit. In addition, the unit cost between the sections are defined as \( P1 = 2, P2 =3, P3 = 100, P4 = 1, P5 = 2, P6 = 100, P7 = P8 = P9 = 100 \). The optimal minimum total cost defined in Equation 1.1 for this problem will be 4 units. An earthwork hauling plan with two paths is given as: (A) moving earth from C-2 to F-2 passing F-1 (C-2, F-1, F-2); (B) Moving earth from C1 to F1 passing C2 (C-1, C-2, F-1). In this case, to move the earth excavated in C-2 (operation A), the intermediate sections along the path (C-2, F-1, F-2) will be regarded as soft blocks and should be removed first. Regarded as a soft block, F-1 has to be filled and graded beforehand. However to get F-1 filled, operation B must be completed which requires that C-2, as a soft block, to be excavated and graded first. For earthmoving projects with numerous sections in two dimensions, the mutual reliance will be even more complicated, which is commonplace in solving classic minimum cost flow network problems. Considering the random nature of traditional minimum cost flow algorithms, a conflict-free solution is not guaranteed.
3 NEIGHBORHOOD METHOD MINIMIZING TRAVELING TIME

The proposed neighborhood method is similar to the minimum cost flow network. The major difference between the neighbourhood method and traditional minimum cost flow network is how the flow network is constructed. One of the critical limits of the traditional method is that cut and fill sections are connected directly with predefined hauling route. To improve the accuracy of the cost estimation and make the optimized earthwork hauling plan practical enough to serve the construction needs, the hauling route and cost have to be estimated simultaneously. The neighborhood method establishes the flow network in a way that connects adjacent sections directly with bidirectional arcs instead of connecting cut and fill sections directly with unidirectional arcs.

To get a clear view of the method, Figure 3 shows the flow network for a grided worksite with uniformly distributed unit cost between neighbor cells based on 4-connected neighborhoods. Each section is connected with the sections immediately to its north, south, east and west. Sections 6, 7, 10 and 11 in Figure 3 clearly illustrate a 4-connected neighborhood. Without any other constraints, the connections representing potential transportation directions between neighbor-sections in the example are given as bidirectional arcs with the same unit cost. With combinations of directions and properly defined unit costs, the algorithm enables users to incorporate hard constraints into the system. In some cases, certain areas of the site need to be reserved for particular uses such as snow stockpile or temporary storm water basin after grading. Thus passing through these areas are not permitted. Figure 4 gives an example of this situation. The red area indicates a reserved area which needs to be kept for other uses. To forbid transportation through this area, different unit costs need to be assigned in terms of transportation between reserved and un-reserved areas. If the total amount of earth needs to be moved out of the reserved area is positive (cut), a large unit cost (p3) needs to be assigned to the directions flowing inward from outside (highlighted as red arrows). On the contrary, if extra earth needs to be borrowed from outside, a large unit cost (p2) needs to be assigned to the directions outward (highlighted as blue arrows).

![Figure 3: Neighborhood method: blue indicates cut and orange represents fill](image1)

![Figure 4: Neighborhood method with reservation area: blue indicates cut and orange represents fill](image2)

Compared to hard blocks, soft blocks are associated with the mutual reliance of hauling routes, hence, are much more difficult to deal with. It is observed from previous research that the hauling routes are generated before earthwork hauling plan optimization, while the lack of such consideration during later optimization analysis is exactly the cause of mutual reliance in designing haul roads. Based on this observation, the neighborhood method optimizes the grading plan and hauling road simultaneously, thus avoids soft blocks caused by mutual reliance of the haul roads. In addition, the neighborhood method produces an earth flow network recording the amount of materials passing through each cell, instead of generating the traditional grading plan with source, destination and volume of materials.

Assume the volume of earth in each cut/fill section is 1 unit and the unit cost between neighbor-sections is equal to 1 if not specified. Based on the neighborhood flow network constructed (as shown in Figure 3...
and Figure 4), the earth flows can be generated through the minimum cost flow algorithm (as shown in Figure 5 and Figure 6). The amount of earth transported between sections is 1 unit if not given explicitly in the network. The resulting total cost for earthwork in the reserved area is 15, while the total cost for earthwork with reserved area is 16. For earthwork hauling plan planning with reserved areas, because extra amount of earth needs to be moved out, the unit cost of earth coming into this area is set to 1000 in our case to avoid materials passing through this area. The result given in Figure 6 shows that the proposed method is able to handle the "reserved area" problem as no earth from outside of the reserved area passes through this area. On the contrary, if the area is not reserved, section 2 will be transported passing through this area and then distributed to other sections.

![Figure 5: Flow of earth without reservation area](image1)

![Figure 6: Flow of earth with reservation area](image2)

Because the method only records the quantity of materials passing through the cells, users can distribute the materials passing a certain cell to any other connected cells based on specific requirements in order to obtain the traditional grading plan. The process can also be conducted through automatic algorithms based on the network, which is beyond the scope of this paper. More importantly, redistributing the materials by altering the source and destination will not change the incoming and outgoing amounts of materials, and thus will not increase the total cost because the source and destination do not constrain the cost in this model at all. Due to this advantage, multiple feasible grading plans can be identified to make up a set of optimal grading plans. On the contrary, traditional earthwork hauling plan methods usually produce one single result. The relationship between the solutions of the traditional method and proposed neighborhood method is represented in Figure 7. As the resulting solution set provides managers alternative execution plans, it increases the flexibility and reduces the risk considerably during the execution of the plan especially in earthmoving operations with inaccurate volume estimation due to uncertain field conditions.

![Figure 7: Relationship of solutions from the traditional and neighborhood methods](image3)

Table 1 shows the potential grading plan produced for each flow separately. Soft blocks are the major problem in generating the grading plan. Two rules are used to deal with this problem: 1) "cut from the
boundary”; 2) “fill from the boundary”. The boundary is defined as the interface between a cut area and a fill area with direct or indirect links at a certain stage. At the beginning, the boundary from the cut to the fill will be 3, 5, 6, 7, 10 and 4, 9, 11, 12, 14 respectively. After the cut sections on the boundaries are excavated, the boundary from the cut side will be 6, whilst the boundary from the cut side will be 15, 16. Section 2 will be the boundary eventually after section 6 is done.

Table 1: Grading plan generated from the earth flow network

<table>
<thead>
<tr>
<th>Without reserved area</th>
<th>With reserved area</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

4 EXPERIMENTS AND RESULTS

A case study to apply the neighborhood method was conducted based on a real earth moving project with an area of 1000m × 375m. For optimization purpose, the area is divided into 8 × 3 sections with equal width of 125m in both directions. The layout and volume of the cut and fill cells are illustrated in Figure 1. To improve productivity, two temporary haul roads are designed to increase the speed of the trucks. The objective is to evaluate the design of haul roads and find the optimal grading plan at the same time. The layout of the haul roads is shown in Figure 7. The speed of the trucks on temporary roads is higher than the speed on rough ground, assuming that the average speed of the trucks is 24km/hr on temporary roads and 18km/hr on rough roads.

The flow network of the site is generated with the 4 connected neighborhood without hard blocks. Two minimum cost flow networks corresponding to haul road design scheme A and B are generated through the proposed neighborhood method as illustrated in Figure 8. The final result shows that the optimal average unit cost is 70.72s for the first temporary road design and 61.68 for the second temporary road design. Because the earth is hauled per truck capacity each time rather than per cubic meter, the average unit cost is scalable due to the uncertainty of the capacity of the trucks.

![Layout of road 1](image)

(a) Layout of road 1
Figure 8: Layout of the temporary road design: the integers are the index of the cells

(a) Grading plan based on road 1

(b) Grading plan based on road 2

Figure 9: Grading plan based on given temporary road: the numbers indicate the amount of material

5 CONCLUSION

We propose a 4-neighborhood connection based the minimum cost flow network that takes design constructability and field constraints into consideration to optimize the earthwork hauling plan problem. Due to the utilization of graphs, both the construction of the model and the execution plan are intuitive and simple to use compared with widely used linear programming methods. The method is also proved to
be more practical and realistic because the proposed model not only optimizes the total cost but also provides an efficient way to handle both hard constraints and soft constraints such as reserved areas and mutual reliance of hauling roads which are not solved in previous methods. Moreover, the generated results can be translated into multiple grading plans which can provide alternative plans and support decision making in field execution.

REFERENCES

ERGONOMICS AND PHYSICAL DEMAND ANALYSIS IN A CONSTRUCTION MANUFACTURING FACILITY

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Abstract: Poor workstation design in a manufacturing facility negatively impacts the health and safety of workers, which hampers productivity. A systematic tool, Physical Demand Analysis (PDA), is utilized in a case-study project to quantify and evaluate physical labour and body posture for various production line tasks in a window and door manufacturing company. This paper presents the implementation PDA focusing on the design of the PDA form template, plant observation, and ergonomic risk identification. The data collection methodology and the implementation of time studies for plant observation are described. Four main ergonomic risks are identified: static whole body posture, manual material handling, sensory problem, and awkward body postures. Detailed observation findings, risk assessment method, analysis results and suggested corresponding corrective measures with regard to these four risks are described in this paper.

1 PLANT OBSERVATION AND ERGONOMIC ANALYSIS

A well-designed workstation which takes into consideration ergonomics can ensure the health and safety of workers while improving the productivity of a manufacturing plant's production line (Deros et al. 2011). On the other hand, workstation the design of which fails to consider ergonomics often require awkward body postures for workers, which may contribute to musculoskeletal disorders or injuries. These disorders and conditions, in turn, delay the production line accordingly. Thus these stations need to be redesigned in order to avoid awkward and potentially detrimental postures for workers.

Ergonomic concerns must be considered in the design phase of construction, and this involves negotiation among the ergonomist, engineer, customer, implementer, and management team (Burns and Vicente 1999). The same can be said of manufacturing plant design, whereby worker comfort, wellness, and productivity can be upheld through proper break times and ergonomic measures.

For an existing manufacturing plant that either has not incorporated ergonomic principles in the design phase or needs to be improved or modified to enhance working condition, researchers can address these challenges by conducting observations in the plant and recommending corrective measures accordingly. Physical Demand Analysis (PDA) is a method that enables the health and safety department to comprehend the plant operation in detail for each production line and analyze the potential ergonomic risks for workers station-by-station.
1.1 Physical Demand Analysis

PDA uses a methodical process to collect data pertaining to the physical demands of a given job on specific areas of the human body. The Industrial Accident Prevention Association (2009) defines PDA as “a systematic procedure to quantify and evaluate the physical, cognitive, and environmental demands of the essential and non-essential tasks of a job”. These documents are records, station-by-station, of all the collected physical demand data, which is obtained from plant observations. PDAs can be used as a proactive means of preventing injuries by identifying ergonomic risks, and, in response to an incident, as an aid for rehabilitation. In particular, PDAs can be used for the following purposes (Industrial Accident Prevention Association 2009):

- to assist in identifying tasks for each job, work processes, and equipment that may require further ergonomic assessment and intervention
- to assist in identifying and prioritizing safety risks
- to provide useful documents for recruitment and training workers
- to assist with job assignment and identification of appropriate modified duties for injured workers;
- to devise strategies for modifying tasks in order to prevent injuries on the job
- to provide details on job demands to health care providers and the workers’ compensation boards corresponding to the locations of the company’s manufacturing facilities—the Workers’ Compensation Board (WCB) of Alberta and the Ontario Workplace Safety and Insurance Board (WSIB).

PDAs play a vital role in ensuring the effectiveness and efficiency of return-to-work programs. A PDA is carried out for each job, where each job consists of several tasks that are described in detail in the PDA. A typical PDA usually includes a job overview, work shift schedule, and details pertaining to meals and breaks, job rotation, personal protective equipment, critical tasks, equipment utilized, strength demands (lifting / lowering / carrying / pushing / pulling / grasping), repetitive motion requirements, body posture requirements, sensory demand, environmental conditions, and ergonomic risks. The PDA displays in a form, which has a wide range of uses in the workplace, varying from rehabilitation to injury prevention. Companies are free to select which job receives a PDA form. PDA forms should be kept up to date as a company undergoes innovation and improves its practices.

Performing a PDA can be especially difficult for highly variable, infrequent jobs. For such jobs, direct workplace observation is inconvenient, since these jobs may only be performed for short periods of time and infrequently. One solution is to use video recorders to capture footage of workers performing tasks. The videos are then consolidated and analyzed, giving the rater the ability to perform analysis as if the worker was completing one lengthy task.

1.2 Methods for Data Collection and Time Study

Different methods for collecting time data in a workplace environment can result in drastically different results. Two methods for data collection exist—subjective and objective data collection. Subjective data collection involves the gathering of data by communicating with workers, using questionnaires, and reading logs; objective data collection is carried out either by direct observation or photography / videography. Besides the associated financial burden on the employer, subjective method tends to yield inaccurate risk assessments that exaggerate instances of injury or chronic pain based on anecdotal evidence (Palmer et al. 2000). Descatha et al. (2009) similarly showed that questionnaires tend to identify a higher level of risk than what is actually present as determined through direct observation. Although questionnaires may be a less costly alternative, they fail to encompass all the potential health exposure problems (Descatha et al. 2009). In cases where the employer is interested in minimizing losses due to health and productivity risks at the expense of a lengthier study, an objective method is preferred (Palmer et al. 2000).

A study was performed by McCallig (2010) in a construction company to compare three data collection methods—questionnaire, interview, and direct observation—on estimation of exposure time to hand/arm and whole-body vibration. The study found that the interview and direct observation could provide more reliable results than self-reported questionnaires or surveys (McCallig et al. 2010). Deros et al. (2011)
carried out an observation recording video footage of a motorcycle component manufacturing plant. The video footage was found to allow ample time for observation of posture and movement of the workers. Also, face-to-face interviews were conducted to obtain better understanding of the work being done, problems faced and health concerns. Based on their observation they found that, as a result of poor ergonomic design of workstations, workers are required to frequently bend their spines and twist their necks, which further results in musculoskeletal disorder (Deros et al. 2011). Video-based observation can also be used together with technical measurements to indicate the non-neutral and extreme postures for repetitive motion leading to work-related musculoskeletal disorders (Juul-Kristensen et al. 2001). In the case study presented in this paper, direct observation and video-based observation with the support of interview and manual measurements are the primary methods selected by which to analyze ergonomic risks.

1.3 Objective

This research project has been built upon the hypothesis that the implementation of PDAs in a manufacturing construction plant enables the health and safety department to better assess job requirements, ensure that the workload is within the workers’ capacity, and lower the potential risks of work-related injuries. The paper proposes a methodology to effectively process PDAs in manufacturing facilities and discusses the benefits to industry of implementing PDAs.

2 PDA PROJECT METHODOLOGY

The PDA project includes three steps: PDA form creation, plant observation, and ergonomic risk identification (see Figure 1). A PDA form is selected as the basis of ergonomic risk identification in the manufacturing plant. Developing a new custom form can have certain advantages over using a pre-existing one. A few PDA templates do exist, such as those available from the Industrial Accident Prevention Association, Occupational Health Clinics for Ontario Workers, and the Workplace Safety & Insurance Board. A new PDA template can be achieved when those physical demand factors to which workers are not exposed are omitted. Based on the framework provided by the PDA template, the PDA form specifies which job it pertains to by including job name, department line, and other basic information. A given job may or may not require a PDA, depending on the requirements of the company. Plant observation is required in order to identify tasks, work processes, and equipment that may be required.
In plant observation, required information can be obtained by three approaches: data collection, time study, and photography of tasks. Direct Observation and video recording methods are selected in this methodology due to their high reliability. Interviews are also included as part of the PDA project since communication can assist external observers in better understanding the tasks being analyzed. Other data collection methods include manual measurements (e.g., use of weighting machine). Forms for the “strength demands of job”, “sensory demands”, and “environmental conditions” where frequency data is not required can be completed by this time.

The frequency and body posture requirements can be ascertained through a time study. A 60-minute time study is proposed in this methodology for cases in which most tasks involved can be completed within 30 minutes. In the time study, body postures are recorded in a spreadsheet on one-minute intervals for each job (Figure 2). A combination of direct observation and video recording observation should be used, since video cameras offer the advantage of recording hours of footage for multiple stations simultaneously. This footage is later analyzed by the research team to extract the relevant data. (Video recording, it should be noted, may be unsuitable in cases where the workers are highly mobile since the viewing angle of video cameras is limited. In addition, some stations may be found to have limited working space, resulting in problematic camera positioning. In these cases, manual / direct observation is the recommended method.) The workers should be made aware that they will be observed and informed of the nature of the work prior to observation commencing. Furthermore, in the case of video recording, observers should be cognizant of working hours and scheduled breaks in order to avoid collecting footage during breaks.

![Figure 2: Time Study Sheet](image)

It should be noted that “frequency” in this study is defined as the number of times a motion is repeated over a specified period of time by a worker, which can be estimated using Equation [1].

\[
\text{Percentage of shift} = \frac{\text{number of checkmarks in spreadsheet}}{60} \times 100\% 
\]

Once the percentage has been calculated for each posture, a frequency descriptor is assigned to each percentage range as follows: Never (0%), Rare (1 – 5%), Occasional (6 – 33%), Frequent (34 – 66%), Continuous (67 – 100%).

The last step is collecting photographs for each task to be inserted in the form in order to help visualize the task. Scheduling this process as the last step in the PDA project allows for the workers to become more comfortable with the research and for the observers to familiarize themselves with the production process at the plant. For those workers who decline consent for their face to appear in a photograph, the alternative is to arrange the photograph in such a way that the subject’s back is to the camera. Those who decline this option as well do not appear in any photographs of their respective workstations. In these cases the photographs are taken of the production process, tools, and materials under use but not of the worker/s. Plentiful photographs ensure accurate representation of the tasks performed and of the inherent ergonomic risks.

After the plant observation, researchers can identify ergonomic risks based on the data collected in previous processes and propose corresponding corrective measures. The objective of this process is to identify ergonomic risk factors, ensure that tasks are within the workers’ capacity and limitations, and devise corresponding corrective measures. Based on data collection and time studies, ergonomic risks can be identified. However, risk factors vary in each case study; risk factor assessment is further
discussed in the case study section below. As outputs of the project, the corresponding company is delivered not only a PDA template ready for future use, but a list of current ergonomic risk for each task and corresponding suggested modifications.

3 PDA IMPLEMENTATION

A PDA is implemented as a collaborative project between All Weather Windows (AWW)—a major window and door manufacturer—and the University of Alberta. The manufacturing facility observed in this project is located in Edmonton, Alberta, Canada. PDAs are integral to their operations. PDAs enable workers to perform duties suited to their abilities, while also assisting others to ensure that when injury incidents do occur, the company has a clear picture of worker responsibilities and how to best develop return-to-work strategies. A well-managed return-to-work program allows the company to continue production operations seamlessly while providing meaningful work opportunities for employees rehabilitating following injury. Obtaining PDAs for each job on every production line ensures that the company can work pro-actively to better promote worker wellbeing by lowering the risk of work-related injuries.

With existing PDAs outdated, unnecessarily lengthy and complicated, and not accurately representative of the current state of the plant, the company sought a PDA which reflects recent changes in the plant in terms of tasks and production line allocation, thereby necessitating the PDA revision. The objective of the case study was thus to create a new PDA template suited to completing PDA forms and identifying ergonomic risks for all workstations in the collaborating company’s production facility.

3.1 PDA Template Creation

Based on the existing PDAs and a literature review regarding the content of PDA forms, the researchers develop a new template with detailed task information, basic ergonomic risk identification, strength demands of job, body posture requirements (expressed as frequency per shift), sensory demands, and environmental conditions, as shown in Figure 3. In terms of efficiency and effectiveness, the new PDA template is more practical. It is better organized (contains six tables), shorter (4-5 pages) but more informative compared with the previous PDA, which is lengthy (10-12 pages) and includes redundant content. Thus, the new PDA allows company health care personnel to quickly scan through the form and conveniently identify the primary cause of the worker’s injury.

Figure 3: New PDA template

3.2 Plant Observation

Plant observation involves data collection, time study, and photographing of tasks. The day shift is selected for the plant observation. This shift begins at 7:00 a.m. and ends at 3:30 p.m. with a 30-minute
lunch break and 15-minute coffee breaks in the morning and afternoon. Before any observations are carried out, certain terminologies in the PDA form must be clarified.

A 60-minute time study is implemented. This is considered to be sufficient for most workstations, as most tasks can be completed within 5-25 minutes. Consent of the workers is obtained and efforts are made to minimize any interference with the production line work during observation. The time study observations are followed by short interviews with the workers being observed. Workers are asked to describe which aspects of their work are the most physically taxing and to explain which body parts are strained after a day’s work. Information collected in these interviews is used for ergonomic risk identification.

3.3 Ergonomic Risks Identification

Based on the data collected during plant observation and the summarized documentations, the main ergonomic risks are identified. Four main ergonomic risks are described below. Some of the ergonomic risks can be prevented by taking easily implemented measures, while others may require further machinery development at the workstation.

1. Static Whole Body Posture

Most of the workstations require prolonged standing throughout the workday, which leads to back and foot pain. To counteract this, anti-fatigue matting or shoe insoles can significantly decrease the pressure placed on the spine and feet. Providing footrests for the workers is another effective method to decrease the strain that contributes to back and foot pain.

<table>
<thead>
<tr>
<th>Risk Factors</th>
<th>Risk Findings</th>
<th>Recommendations</th>
<th>Corrective Measures for Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static whole body posture</td>
<td>Prolonged standing</td>
<td>Provide anti-fatigue matting or insoles; Provide footrest for workers to have a rest while standing</td>
<td></td>
</tr>
</tbody>
</table>

2. Heavy Material Handling

Workers are required to lift / push / pull heavy products manually without the aid of wheeled carts. These actions pose ergonomic risk to the back and shoulders. Heavy lifting also occurs in various production lines. The Infrastructure Health & Safety Association (IHSA) has provided a general guide for identifying ergonomics-related hazards (IHSA, 2014). In terms of manual material handling tasks, two worker weight capacity tables are provided by IHSA. If the profiles to be lifted exceed the worker weight capacity as outlined in these tables, the worker will be exposed to a dangerously high risk of injury. These two tables present the lifting/lowering weight limits for males only and for females only or both males and females. Based on this guideline, the ergonomic risks related to material handling can be identified for various tasks.

However, the weight capacity also varies based on four factors: (1) the relative distance the object is to be moved (far/close), (2) the size of the profiles (long/short), (3) the working height (hands end below knuckle height / hands end between knuckle and shoulder height / hands end above shoulder height), and (4) the approximate duration of the move (15 seconds, 1 minute, 2 minutes, 5 minutes, 30 minutes, or 8 hours). The distance to be moved and the working height are obtained from observation, and the description of the profile provides the dimensions and weight. The duration of the move can be estimated based on the shift working hours and the observation results. Shift A is from 7:00 a.m. to 3:30 p.m., and shift B is from 4:30 p.m. to 1:00 a.m., with a 30-minute lunch break and two 15-minute coffee breaks per day. Therefore, the total working hours per shift is 7.5 hours. With the results of the 60-minute time study,
the weight limitations for manual lifting can be calculated using Equation [2]. By comparing the results calculated using this equation against the numbers given in the two IHSA tables (IHSA, 2014), the potential high-risk exposure tasks can be identified.

\[ t_c = T_s \times t \times F \]

Where,

\( T_s \) is the working hours within one shift

\( t \) is the observation time

\( F \) is the frequency (%) of lifting/pushing/pulling within the observation time

<table>
<thead>
<tr>
<th>Risk Factors</th>
<th>Risk Findings</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual material handling</td>
<td>Manual material lifting/pushing/pulling: back/shoulder</td>
<td>To be investigated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Provide lifting machine for heavy doors and windows</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Direct transfer material/items to machine/cart;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Switch task;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Work with others;</td>
</tr>
</tbody>
</table>

The risk and corresponding corrective measures are given in Table 2. The use of a lifting machine to make this task semi-automated should be explored. A direct transfer and feeding machine to transfer the profiles from the cart to the machine or from the machine to the cart would be an even more proactive, albeit more costly, measure. The simplest measure, which the organization can implement immediately, is to stagger the tasks among workers so that particular workers are not disproportionately exposed to ergonomic risks.

3. Sensory risks

The third type of ergonomic risk identified from the observations is sensory risks, including eye fatigue and hand or arm vibrations. As can be seen in the photograph in Table 3, installation requires workers to locate pre-drilled marks in order to install the hardware on the sash. However, this task is difficult for workers, who may have to strain their eyes in order to visually locate the pre-drilled holes. From the researchers’ observation, workers will additionally measure the installation positions manually in order to install the hardware accurately. To overcome these difficulties, an auto-colour marking machine should be used for the predrilled marks, and the accuracy of the markings should be improved so that there is no need to measure manually. The auto-colour marking could be added to the welding machine or designed as an independent machine.

Another sensory problem has to do with hand or arm vibration. An array of tools is utilized in each production line. For many of these tools, such as chop saws, power drills, pneumatic staple guns, and air guns, the worker is exposed to a considerable amount of vibration during operation, with frequent use posing a serious health hazard. Carpal tunnel syndrome is one condition that may result from exposure to this hazard (Health and Safety Executive, 2014). The symptoms may include only moderate pain, white fingers, and sleep disturbance, but in more serious cases it may lead to numbness and loss of strength in the hands, among other symptoms (Health and Safety Executive, 2014). To prevent the onset of Carpal tunnel or other conditions or injuries, two corrective measures are recommended. One is to provide tools and equipment at the workstations, which minimize worker exposure to hazardous vibration. The other is to limit the duration of exposure to this type of hazard for a given work, which can be achieved, (as with risk due to lifting of heavy materials), by staggering the work assignments so that no particular worker is disproportionately assigned to activities which pose this type of ergonomic risk.
Table 3: Risk identification for sensory risks

<table>
<thead>
<tr>
<th>Risk Factors</th>
<th>Risk</th>
<th>Findings</th>
<th>Recommendations</th>
<th>Corrective Measures for Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensory</td>
<td>Eye fatigue: e.g. Figure out the position of installing hardware on sash</td>
<td>To be investigated</td>
<td>Auto-colour marking machine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hand/arm vibration</td>
<td>To be investigated</td>
<td>Provide the proper equipment; Limit the time that workers are exposed to vibration</td>
<td></td>
</tr>
</tbody>
</table>

4. Awkward body postures

Awkward body posture is the main ergonomic risk identified in the manufacturing facility. Postures are categorized into five groups (Table 4): (i) back/neck bent forward or shoulder reaching forward; (ii) reaching above shoulder; (iii) back backward bending; (iv) kneeling, crouching/ squatting; and (v) elbow, wrist flex/extension.

Table 4: Risk identification for awkward body postures

<table>
<thead>
<tr>
<th>Risk Factors</th>
<th>Risk</th>
<th>Findings</th>
<th>Recommendations</th>
<th>Corrective Measures for Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Awkward body</td>
<td>Back/neck bent forward, shoulder reaching forward</td>
<td></td>
<td>Adjust the height of the machine, computer, working stations</td>
<td>Place working table next to hardware or place working station together</td>
</tr>
<tr>
<td>postures</td>
<td>Reaching above shoulder e.g. Profiles transferred from cart to machine table (transfer overhead)</td>
<td></td>
<td>Make sure that the profiles are in proper location, no need to be transferred overhead or rotated</td>
<td>Provide a lifter or lifter for the items</td>
</tr>
<tr>
<td></td>
<td>Back backward bending e.g. Foot pedal too close to machine</td>
<td></td>
<td>To be investigated</td>
<td>Bring the foot pedal away from the machine or place it near the computer</td>
</tr>
<tr>
<td></td>
<td>Kneeling, Crouching/Squatting</td>
<td></td>
<td>To be investigated</td>
<td>Ergo-auto-lift frame</td>
</tr>
<tr>
<td></td>
<td>Elbow, Wrist Flex/Extension</td>
<td></td>
<td>To be investigated</td>
<td>Provide proper tools</td>
</tr>
</tbody>
</table>

1.1. Back/neck bent forward, shoulder reaching forward

Whenever a worker needs to reach an item at the workstation, their back bends forward and shoulders reach forward. The neck is also strained by installations completed on a flat table. Based on the time study, the frequency of each posture can be obtained and further analyzed with regard to ergonomic risk. There are also various measures that can be taken to correct a worker’s posture. First, the height of the machine, computer, or working table can be adjusted to minimize muscle strain. Due to the varying heights of employees, there is no ideal height for these components. Rather, the ideal scenario is for the heights of these working surfaces to be adjustable to the height of the worker. Such a measure is
beneficial in terms of both health/safety and productivity. A second corrective measure is to locate the workstations as close as possible to one another and the profiles for installation as close as possible to the relevant workstation. Third, providing a lifter or tilter for the hardware container at each workstation can ease access to hardware by workers during installations.

1.2. Reaching above shoulder

For instance, large and long window frame profiles are used in three workstations in the organization, which requires workers to reach above the shoulders, rotating and locating the profiles to the cutting machine. As shown in the photograph in Table 4, the profiles are custom designed. However, due to the fact that the profiles are not placed in the proper position, workers must lift the profiles up and transfer them overhead. The profiles are symmetrically cut in pairs and, as a result, workers must rotate the profiles in the same direction before positioning them overhead. Considering the large number of profiles a given worker will handle at the workstation in a given shift, reducing or eliminating the need for manual overhead transfer or rotation can lower ergonomic risk while significantly improving productivity. This can be achieved through improved inventory allocation and management.

1.3. Backward bending of the back

Backward bending of the back occasionally occurs at some workstations, such as the punching and welding station. For instance, when the foot pedal is too close to the punching and welding machine, the worker must step on the foot pedal while bending backward in order to avoid injury through contact with the machine. However, this posture involves ergonomic risk of back pain. The simplest way to address this issue is to locate the foot pedal away from the machine but close to the worker. Alternatively, a hand-operated button could be programmed to control the operation of the welding and punching machine.

1.4. Kneeling, crouching/squatting

There are also situations that require workers to kneel, crouch, or squat to complete a task. For example, product assembly tasks in the display line must be finished on the ground (refer to the first photograph in fifth row of Table 4 for kneeling posture). Frequent kneeling causes pain and strain in the low back and knees and involves a high risk of developing serious muscle and joint problems. Providing a kneeling mat is the simplest measure to protect workers’ knees. On the other hand, for the glazing task (refer to the second photograph in the fifth row of Table 4 for crouch/squat posture), the tops of small windows and the bottoms of large windows are below the height at which glazing can be completed from a standing position, so crouching or squatting is necessary. Accordingly, the organization should invest in an ergo-auto-lift frame, which not only holds the window during glazing, but also raises or lowers the window automatically according to the comfortable working height for the worker. The same measure can be taken for other cases in which workers are assuming a crouching or squatting posture.

1.5. Elbow, wrist flex/extend

A worker occasionally needs to twist their wrist and elbow as part of a task, which may cause pain and strain. Adjusting the height of the workstation components (i.e., tables, computers, and machines) can help to solve this problem. In addition, as indicated in the photographs, using better-designed pliers, which can themselves bend to a certain degree, will minimize the need to twist the wrist.

4 CONCLUSION, CHALLENGES, AND RECOMMENDATIONS

Ergonomic analysis can be achieved after carrying out plant observation and completing the PDA project. As a result of this initiative, health care personnel in the organization’s health and safety department are better informed about the job requirement and better able to determine proactive measures to mitigate potential risks. It also assists with worker recruitment and allocation. After implementing PDA in the manufacturing plant, modifications can be made in the interest of worker safety and production line productivity.
In the case project, as the project progressed some challenges were encountered, such as some workers’ reluctance to cooperate with the research being carried out. Clarifying with the workers the purpose of the PDA, its importance, and the various potential uses of the PDAs served to overcome this challenge. With respect to the time studies in particular, some limitations of video recorders (e.g., battery life, view angle, etc.) were encountered. Manual observations could thus be used to supplement the video recording observation. Meanwhile, for cases in which the operators are highly mobile and the field of view of the video recorders is not sufficient, manual observation is also used. Alternatively, a video recorder with a wider angle of view enables observers to capture multiple workstations at once.

5 FUTURE STUDY

The paper has proposed a methodology to implement PDA in manufacturing facilities. The project involves plant observation, completion of PDA forms, and ergonomics risk identification with corresponding corrective measures. In future studies, different risk assessment methods can be applied based on the same data collected from the observations in order to improve the accuracy of the ergonomic risk assessment. Moreover, it is recommended that the corrective measures be implemented and another PDA be completed comparing the ergonomic risk reduction between two versions of PDAs. It is also recommended that further investments be made in semi-automated machinery to reduce labour-intensive work and mitigate ergonomic risks.

Acknowledgements

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OPTIMIZING ENVIRONMENTAL SUSTAINABILITY AND PUBLIC BENEFITS OF TRANSPORTATION NETWORK PROGRAMS

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Abstract: Transportation is among the highest energy-consuming economy sectors. Therefore, new national priorities and laws passed in the United States in an effort to control the environmental impacts of highway rehabilitation efforts. This created new challenges to planners and decision makers in transportation agencies to optimize, under budget constraints, rehabilitation efforts of aging networks in order to maximize net public benefits while minimizing network energy consumption. This mandates a substantial change in existing ad-hoc and need-based decision-making practices in order to add new criteria to evaluate and measure network energy consumption. Accordingly, this paper presents a new model for planning highway rehabilitation efforts that is capable of identifying near optimal program(s) in terms of maximizing net public benefits while minimizing energy consumption of transportation networks. The new model is designed to: (1) evaluating and measuring the impact of decision making in highway rehabilitation programs on network energy consumption; (2) evaluating the impact of rehabilitation decisions on the cost of travel delays due to highway construction work; (3) estimating the expected savings in road user costs due to the completed rehabilitation efforts; (4) estimating the lifecycle public costs and benefits associated with highway rehabilitation decisions; and (5) optimizing rehabilitation decisions in order to search for and identify the highway construction program(s) that simultaneously maximize public benefits and minimize energy consumption under budget constraints. An application example for a transportation network in South Florida is analyzed to demonstrate the model capabilities and examine the relationship between lifecycle net public benefits and total network energy consumption. The analysis of the application example showed that there is a trade-off between the expected net public benefits and network energy consumption. The new model should prove useful to transportation agencies in identifying rehabilitation program(s) that satisfy public expectations while minimizing energy consumption in transportation networks.

1 INTRODUCTION

Transportation agencies in charge of planning and programming highway repair and rehabilitation efforts face the challenging task of allocating limited funding to an increasing number of competing projects. The American Society of Civil Engineers is forecasting the funding gap is continuing to widen, which will have a direct and significant impact on surface transportation and therefore the United States’ economy (ASCE 2013). Currently, the transportation agencies use ad-hoc and need based approaches to identify and implement their highway repair and rehabilitation programs. For example, rehabilitation programs can be programmed by selecting projects that address roads with the worst pavement conditions and/or highest traffic volume. This approach might not be optimal and leaves ample room for improvement in order to...
include other significant factors to maximize public benefits (Sharaf and Mandeel 1998; Sathaye and Madanat 2011). In addition, the United States government passed a new law, the Moving Ahead for Progress in the 21st Century Act (MAP-21) of 2012, requiring transportation agencies to integrate a number of national goals into highway construction planning efforts (FHWA 2012). Since transportation is among the highest energy-consuming economy sectors with the vast majority of this energy from fossil fuels (EIA 2014), one of the national goals considered in MAP-21 is related to environmental sustainability. This will bring about substantial change to the current ad-hoc and need-based decision making approaches adopted by transportation agencies.

Several research studies focused on planning and optimizing highway rehabilitation efforts. Many of these studies had a single optimization objective focusing on: minimizing construction costs (Chan et al. 1994; Ferreira et al. 2002); and maximizing overall network performance (Wang and Lui 1997). Other research efforts had multi-objective optimization models that focused on: integrating energy consumption, GHG emissions, and construction costs into a single optimization objective (Zhang et al. 2012); minimizing construction costs and maximizing pavement performance (Mathew and Issac 2013); maximizing net benefits while minimizing network service disruption (Orabi and El-Rayes 2011); and minimizing construction costs and GHG emissions (Lidicker et al. 2012). Despite the significant contributions of these research studies, no reported research focused on optimizing highway rehabilitation programs in order to maximize public benefits while minimizing network energy consumption under budget constraints.

In order to address this important research gap, this paper presents the development and implementation of a new model for optimizing highway rehabilitation programs. The model consists of five modules that are capable of (see Figure 1): (1) evaluating and measuring the impact of decision making in highway rehabilitation programs on network energy consumption; (2) evaluating the impact of rehabilitation decisions on the cost of travel delays due to highway construction work; (3) estimating the expected savings in road user costs due to the completed rehabilitation efforts; (4) estimating the lifecycle public costs and benefits associated with highway rehabilitation decisions; and (5) optimizing rehabilitation decisions in order to search for and identify the highway construction program(s) that simultaneously maximize public benefits and minimize energy consumption under budget constraints. The following sections describe these five modules in detail.

Figure 1: Highway rehabilitation programming and optimization model

2 ENERGY CONSUMPTION ESTIMATING MODULE

The main objective of this module is to evaluate and measure the impact of decision making in highway rehabilitation programs on network energy consumption. In order to achieve this objective, energy consumed in transportation networks is categorized into two main types: (1) energy consumed during highway construction operations; and (2) energy consumed during regular operation after the completion of highway rehabilitation works to improve pavement conditions.
First, network energy consumption during highway construction operation is expected to increase, compared to regular operation, due to the reduction in vehicle speed when travelling through construction zones. This reduction in vehicle speed can cause an increase in fuel consumption rate (NCHRP 2012). The change in vehicle speed can also cause the volume of traffic using the road under rehabilitation to change due to some travellers opting to use alternative routes. The total change in fuel consumption during the highway construction operations will also depend on the number of road sections in the network undergoing rehabilitation, road section lengths, and duration of construction operations. In this model, equations 1 and 2 are used to estimate the change in network total fuel consumption due to construction operations, as follows:

\[\text{TFC} = \sum_{r=1}^{R} (V_{W,r} - V_{F,r}) \times L_r \times D_r \times \Delta FR_r\]  

\[\Delta FR_r = FR_{W,r} - FR_{F,r}\]

Where,
- \(TFC\) = change in total network fuel consumption (in gallons) due to construction operations;
- \(R\) = number of road sections in the network;
- \(V_{W,r}\) = traffic volume under work-zone conditions;
- \(V_{F,r}\) = traffic volume under free-flow conditions;
- \(L_r\) = length of road section (r);
- \(D_r\) = construction duration that affects road section (r);
- \(\Delta FR_r\) = change in fuel consumption rate due to construction;
- \(FR_{W,r}\) = fuel consumption rate under work-zone conditions; and
- \(FR_{F,r}\) = fuel consumption rate under free-flow conditions.

Second, the improvement in pavement conditions, as a result of the rehabilitation efforts, will also result in changes to the network energy consumption. In this model, the pavement roughness index (IRI) is used to represent pavement conditions. The IRI of road segments that undergo rehabilitation will decrease after rehabilitation and will therefore cause a significant reduction in energy consumption (Amos 2006) compared to pre-rehabilitation. Equation 3 is used to estimate lifecycle energy consumption in the transportation network over an analysis span of \(Y\) years after rehabilitation. This lifecycle energy consumption takes into consideration the gradual increase over time in IRI and therefore energy consumption. Therefore, network energy consumption is expected to be lowest directly after rehabilitation and gradually increases with time until the network is due for new rehabilitation, as shown in figure 2.

\[\text{TF} = \sum_{y=1}^{Y} \sum_{r=1}^{R} V_r \times L_r \times FR_{N,r}^y \times 365\]

Where,
- \(TF\) = total fuel consumption (in gallons) during operation phase;
- \(Y\) = number of years to new rehabilitation effort;
- \(V_r\) = traffic volume (in terms of AADT) on road section (r);
- \(L_r\) = length of road section (r); and
- \(FR_{N,r}^y\) = fuel consumption rate of road section (r) after year (y) of rehabilitation.

![Figure 2: Impact of rehabilitation efforts on energy consumption](image-url)
3 TRAVEL-DELAY COST ESTIMATING MODULE

The main objective of this module is to estimate the cost of travel delays increased from the expected traffic delay during the construction. Repairing a road can significantly affect traffic conditions on other roads in the highway network. For example, travelers tend to change to a faster route for driving to a destination in order to avoid the disruption that happens in the construction zone. However, this traffic diversion can increase volume in the alternated route and finally exceed the road capability. As a result, all vehicles on the road, including the routine travelers, will be affected from traffic congestion and a lower average travelling speed, which increase travel time. Additionally, travel delays can increase in the construction zone due to speed limit reduction. Therefore, construction is expected to change traffic patterns and increase travel time of all travelers on the highway network.

Equations 4 and 5 represent the estimation of entire travel-delay cost during the construction and change in travel time due to operating speed change, respectively. The cost of travel delays can be estimated from traffic volume, length of road, change in travel time, and unit time value. The last parameter, the predefined value from the user, will convert total travel delays (in hours) to monetary value (in dollars per hour). However, the cost of travel delays in this study was only estimated based on the effect of speed reduction.

\[
4 \quad TTC = UT \times \sum_{r=1}^{R} V_{W,r} \times D_r \times \Delta T_r
\]

\[
5 \quad \Delta T_r = \left( \frac{L_r}{S_{W,r}} \right) - \left( \frac{L_r}{S_{F,r}} \right)
\]

Where,

- \(TTC\) = total cost of travel delay (in dollars) during construction; \(UT\) = unit time value (in dollars per hour);
- \(\Delta T_r\) = change in travel time; \(S_{W,r}\) = average vehicle speed under work-zone conditions; and \(S_{F,r}\) = average vehicle speed under free-flow conditions.

4 ROAD USER COST SAVINGS ESTIMATING MODULE

The main objective of this module is to estimate the expected savings in road user costs from the implementation of rehabilitation programs. This module accounts for the impacts of rehabilitation programs on the road operation phase. Two main components of road user costs are considered, which are: (1) tire depreciation cost, and (2) repair and maintenance costs (as shown in equation 6). However, the cost of fuel consumption is excluded from this module to avoid double counting of the planning objectives in the optimization module. Tire depreciation cost takes into consideration traffic volume, the length of the road section, and variation in tire depreciation rate as shown in equation 7. Tire depreciation rate can be calculated as a result of vehicle speed, vehicle type, and pavement conditions, which is an IRI in this study. The module also takes into account the effect of pavement deterioration over a lifecycle period. As deterioration has impact on pavement conditions, tire depreciation rate tends to increase over time until the next rehabilitation.

Similarly, repair and maintenance costs take into consideration traffic volume, length of road section, and changed rate in repair and maintenance costs as shown in equation 8. This cost rate depends on vehicle type and pavement conditions resulting from deterioration throughout lifecycle. Change in repair and maintenance cost rate can be calculated by comparing the pre-rehabilitation and post-rehabilitation stages.
[6] \( \text{TRS}^{y} = \text{DS}^{y} + \text{MS}^{y} \)

[7] \( \text{DS}^{y} = \sum_{p=1}^{P} V_{p} * L_{p} * (\text{DRI}_{p} - \text{DRN}^{y}_{p}) \)

[8] \( \text{MS}^{y} = \sum_{p=1}^{P} V_{p} * L_{p} * (\text{MRI}_{p} - \text{MRN}^{y}_{p}) \)

Where, 
\( \text{TRS}^{y} \) = total road user savings (in dollars) after year \( y \) of rehabilitation; \( \text{DS}^{y} \) = tire depreciation cost savings after year \( y \) of rehabilitation; \( \text{MS}^{y} \) = repair and maintenance cost savings after year \( y \) of rehabilitation; \( P \) = number of road projects undergoing rehabilitation; \( \text{DRI}_{p} \) = tire depreciation rate of road project \( p \) at pre-rehabilitation conditions; \( \text{DRN}^{y}_{p} \) = tire depreciation rate of road project \( p \) after year \( y \) of rehabilitation; \( \text{MRI}_{p} \) = repair and maintenance rate of road project \( p \) at pre-rehabilitation conditions; and \( \text{MRN}^{y}_{p} \) = repair and maintenance rate of road project \( p \) after year \( y \) of rehabilitation.

5 LIFECYCLE PUBLIC COST AND BENEFIT ESTIMATING MODULE

The main objective of this module is to evaluate the net expected benefits as a result of implementing rehabilitation programs. The calculation employs the concept of lifecycle since the costs and benefits can be found along the lifespan. Figure 3 presents the concept of lifecycle assessment and all related components that are used for calculating the net public benefits in this study, which include (1) cost of travel delays and (2) road user cost savings.

![Figure 3: Expected public benefits of rehabilitation programs](image)

First, the cost of travel delays is the cost incurred from increasing the total time of all travelers on the network. In this study, this cost is assigned by a single value at the beginning of the lifespan (year 0) of the lifespan (see figure 3), as it occurs during the construction stage. The second component is the savings in road user costs, which are the expected cost savings of traveling on the transportation network regarding the improvement of road conditions. It is calculated based on the savings in tire depreciation cost and the vehicle’s repair and maintenance costs in this study. However, the savings are likely to decrease over the time after rehabilitation because the road tends to deteriorate regarding the traffic load and current road conditions. Until the pavement conditions reach an unacceptable threshold, the next rehabilitation is required to keep the road’s better quality.

To evaluate the net public benefits of rehabilitation programs, the concept of net present worth is adopted to calculate the net present value of each component. The discount rate and number of lifecycle year are initially defined by the decision maker. Equation 9 presents how to calculate the net present value of total public benefits for a rehabilitation program.
$$[9] \text{NPV}_B = \sum_{y=1}^{Y} \text{TRS}^y(P/F, \text{ir}, y) + \text{TTC}$$

Where, 
\( \text{NPV}_B \) = net present value of total public benefits; \( \text{ir} \) = discount rate for the public benefit calculation (in percentage); \( \text{TRS}^y \) = total road user savings (in dollars) at year \( y \) after rehabilitation; and \( \text{TTC} \) = total cost of travel delays (in dollars) during construction.

6 MULTI-OBJECTIVE OPTIMIZATION MODULE

The main objective of this module is to optimize highway rehabilitation decisions in order to identify the program(s) that can maximize public benefits while minimizing network energy consumption under budget constraints. To this end, the decision considered in this the module is identifying which projects to select among the competing highway rehabilitation projects. This project selection is constrained by limited rehabilitation funding. In addition, the selection of rehabilitation projects will have a significant impact on the two optimization objectives of: (1) maximizing net public benefits; and (2) minimizing network energy consumption.

The impacts of decision variables on the planning objectives and constraints depend on decision making in project selection. Because of a limitation in financial resources, decision makers are restricted to select only some potential projects from the entire set of rehabilitation projects. In fact, decision making in project selection will have different effects on travelers and the economy since each project has its own characteristic, such as different pavement conditions, traffic volume, and speed limit. For instance, repairing the road with a high traffic volume can save a larger amount of road user costs and energy consumed compared to upgrading a low traffic-volume road. However, a high traffic volume usually requires a high capacity and the road is expected to be a large project. This also requires a higher construction budget. Similarly, improving a high-roughness pavement requires an intensive maintenance and rehabilitation method with a large expenditure. However, it can have a higher saving in road user costs and energy consumption than repairing a low-roughness road.

In this study, an evolutionary algorithm is utilized to solve the optimization problem. NSGA-II, which is the most superior multi-objective genetic algorithm nowadays (Deb et al. 2001), is used to generate the optimal rehabilitation programs to satisfy the planning objectives and constraints. It has proved that NSGA-II is capable of overcoming several challenges in the optimization problem: (1) the multi-objective nature, (2) the nonlinear and non-continuous objective functions, and (3) the large search space. To deal with the constraints, NGPM Version 1.4, which is the recent implementation code of NSGA-II in Matlab, is employed from Song (2011).

The genetic operations of this optimization module are given as shown in Figure 4. The process starts by generating an initial population of random solutions. The population is the set of decision variables that consists of the combination of project selections. In this study, project selection is coded as a binary variable by assigning 1 for selected and 0 for unselected projects, respectively. Then, the fitness functions of each population are evaluated in terms of public benefits and energy consumption. After that, the solutions are sorted based on the fitness values and the best solutions are selected. The genetic operators of crossover and mutation are then performed to generate a new population of better solutions. The steps are continuously repeated for a predefined number of generations or until the error between two successive generations is smaller than a predefined tolerance. The operations then can be stopped and the optimal/near optimal solutions are extracted from the final set of population.
7 APPLICATION EXAMPLE

An application example is analyzed to illustrate the model capabilities in optimizing the highway rehabilitation efforts. The example aims to search for the optimal rehabilitation program(s) that simultaneously maximize total net public benefits and minimize network energy consumption. In this section, the roads in the South Florida’s transportation network are assumed to have rehabilitation needs due to pavement deterioration. The deteriorating roads at ten different locations are hypothetically selected under the limited funding in order to identify the optimal plan(s) that satisfy the planning objectives. Table 1 shows the data for all ten candidate rehabilitation projects. The data include: (1) current pavement conditions in terms of roughness index, (2) traffic volume in terms of annual average daily traffic (AADT), (3) section length, (4) free flow speed, (5) work zone speed, (6) rehabilitation cost, (7) rehabilitation duration, (8) number of lanes in each direction, and (9) total equivalent standard axle load for each project.

In this example, the available funding for the rehabilitation program is assumed to be 35 million dollars. The total benefits are calculated based on a 5% discount rate net present value over a 20-year lifecycle period. All candidate projects are assumed as a rural road with the rehabilitation cost $0.8 per lane-mile (CDTC 2003) for a simple calculation. The rehabilitation durations are estimated by using an average unit time per lane-mile (approximately 5 days per lane-mile) from OECD (2005). The unit cost of travel time ($23 per vehicle-hour) is adopted from Copeland (1998). All rehabilitation costs and the travel-delay costs are adjusted with the customer price index (U.S. Bureau of Labor Statistics 2014) for the analysis.

The result shows the model capabilities of generating a wide set of optimal solutions. These solutions illustrate the trade-off between the two planning objectives: (1) maximizing total net public benefits and (2) minimizing energy consumption. The thirty seven optimal programs were generated as shown in figure 5. The result presents that minimizing energy consumption of rehabilitation efforts can lead to a lowering in public benefits. The trade-off also contains the generated solution of one of the current ad-hoc planning models, which depends on a need-based criteria of pavement conditions, by selecting projects 1,5,6,7,8,9, and 10. This solution provides the highest energy consumption and net public benefits as 144 million gallons and 9.8 billion dollars, respectively (see solution 1). However, the rehabilitation program selected by a high traffic volume, which is another need-based criterion, is not contained in the optimal set. As projects 2,3,4,6,8,9 and 10 were selected, the total energy consumption and public benefits were able to be estimated as 162 million gallons and 6.5 billion dollars, respectively (see solution 2). It is shown that this alternative is dominated by the other optimal solutions. Therefore, selecting projects with a high traffic volume might not be an effective way for highway decision making.
The result can be different from figure 5 if a minimum threshold for available budget is predetermined in the analysis. Under this condition, the optimal solutions will follow the same pattern of trade-off relationship. The number of optimal solutions, however, is smaller for the one with a minimum threshold. As a result, planners and decision makers can adjust their strategies to effectively select the most suitable rehabilitation programs and allocate the remaining funding for other purposes such as transportation safety improvement.

<table>
<thead>
<tr>
<th>Project</th>
<th>IRI (m/k m)</th>
<th>Traffic volume (veh/day)</th>
<th>Length (mile)</th>
<th>Free-flow speed (mph)</th>
<th>Work zone speed (mph)</th>
<th>Construction cost (million dollars)</th>
<th>Construction duration (week)</th>
<th>Number of lane</th>
<th>Total ESAL (million ESAL/lane)</th>
</tr>
</thead>
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<tr>
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<td>4.50</td>
<td>45,500</td>
<td>2.87</td>
<td>40</td>
<td>25</td>
<td>9.17</td>
<td>46</td>
<td>4</td>
<td>0.3546</td>
</tr>
<tr>
<td>2</td>
<td>3.20</td>
<td>55,000</td>
<td>2.11</td>
<td>40</td>
<td>25</td>
<td>5.07</td>
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<td>3</td>
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<td>3</td>
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<td>6.48</td>
<td>33</td>
<td>2</td>
<td>0.5845</td>
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<td>4</td>
<td>3.00</td>
<td>50,500</td>
<td>2.00</td>
<td>45</td>
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The result can be different from figure 5 if a minimum threshold for available budget is predetermined in the analysis. Under this condition, the optimal solutions will follow the same pattern of trade-off relationship. The number of optimal solutions, however, is smaller for the one with a minimum threshold. As a result, planners and decision makers can adjust their strategies to effectively select the most suitable rehabilitation programs and allocate the remaining funding for other purposes such as transportation safety improvement.
The analysis in this example presents the application and capabilities of the developed model in searching for and identifying the optimal rehabilitation programs under the trade-off between total net public benefits and environmental sustainability maximization. This contributes to provide planners and decision makers with a wide range of optimal trade-off solutions, which can be effectively selected to satisfy with transportation agencies’ conditions and requirements.

8 CONCLUSIONS

In this study, a new model to support decision making in highway rehabilitation programming was developed in order to optimize the net public benefits and energy consumption in transportation networks. The model is capable of: (1) evaluating and measuring the impact of decision making in highway rehabilitation programs on network energy consumption; (2) evaluating the impact of rehabilitation decisions on the cost of travel delays due to highway construction work; (3) estimating the expected savings in road user costs due to the completed rehabilitation efforts; (4) estimating the lifecycle public costs and benefits associated with highway rehabilitation decisions; and (5) optimizing rehabilitation decisions in order to search for and identify the highway construction program(s) that simultaneously maximize public benefits and minimize energy consumption under budget constraints. The application example was analyzed to demonstrate the performance and capabilities of the developed model. The optimization result generates the optimal trade-off between total public benefits and energy consumption for highway rehabilitation programs.

The developed model should prove useful to planners and decision makers in promoting the sustainability concept and simultaneously addressing a public perspective in the planning of highway rehabilitation efforts. However, some further improvements can be extended to advance the capabilities of the model. For example, the optimization decision variables can be expanded to include other types of decision. Not only the decision on project selection but it can also be made to prioritize the competent projects and identify the impacts of different rehabilitation methods on the projects. Future works are planned to expand the optimization scope of the developed model to be more practicable to transportation agencies' decision making processes.

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AUTOMATED PRODUCTION PLANNING IN PANELIZED CONSTRUCTION ENABLED BY INTEGRATING DISCRETE-EVENT SIMULATION AND BIM

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Abstract: Panelization, a form of off-site construction with origins in the manufacturing industry, has emerged as a popular, more efficient approach to constructing residential projects. This approach transfers some of the construction activities traditionally carried out on site into factory production tasks, and divides construction management into factory production management and on-site assembly management. This change poses some challenges to construction practitioners with respect to project planning and management, such as how to efficiently create work flow, balance the production line, and satisfy various panel requirements to ensure smooth on-site operations. This paper thus explores an automated approach for construction planning in the production plant with the objective of improving productivity and balancing the production line, which achieves a seamless integration of building information modelling (BIM) and discrete-event simulation (DES). Specifically, a BIM-based special-purpose simulation (SPS) template for the production line is developed in Simphony.NET in order to facilitate more efficient modelling of the production line. The new simulation template provides a BIM-based interface which permits enriched information exchange between the BIM model and the simulation model. A case study of a production line for light gauge steel panels is presented to demonstrate the methodology. The simulation results show that proper production sequencing improves production performance, and that the newly developed simulation template is a useful planning tool for the panelized construction system.

1 INTRODUCTION

The light gauge steel (LGS) panel system provides a cost-effective building solution for mid-rise multifamily residential buildings. In this panelized construction method, most building components, such as the walls and bathrooms, are prefabricated in the factory and then delivered to the site for on-site assembly. Compared with conventional construction systems or methods whereby the majority of construction tasks take place on site, the on-site work involved in LGS construction is limited to the assembly of factory-built building components, such as wall panels and floor joists. This process thus has the potential to minimize the waste involved in the construction process and enhance efficiency. Nevertheless, due to the large number of components (panels) involved, the success of such projects relies on accurate and reasonable scheduling for the production, shipping, and installation of the panels, and delays in panel delivery or overproduction in the factory can result in project delays and increased inventory costs. More importantly, prefabricated panels are unique and vary in product design features (e.g., length, having windows or doors, having various connections). Panel fabrication is recognized as a low-volume and high-variety product mix production process. Consequently, it is a challenge for construction practitioners to formulate
production plans which can balance the production line, and satisfy various panel requirements to ensure smooth on-site operations. Still, in current practice construction plans are typically planned manually based on practitioners’ experience and intuition, a practice which can be subjective, tedious and error-prone.

Building information modelling (BIM) is an information technology that has the ability to change the Architecture, Engineering, and Construction (AEC) industry in terms of boosting productivity and enhancing communication. Since BIM hosts enriched product information, which is required for planning analysis, it is capable of supporting the automatic generation of construction plans. Meanwhile, a simulation-based approach can be utilized to perform operation-level construction planning due to the fact that discrete-event simulation (DES) can mimic the construction operation logic and investigate the allocation of available resources among activities. Nevertheless, simulation-based planning at present only utilizes limited building information (e.g., quantity take-offs) for planning analysis, and it has yet to take full advantage of the rich product information in BIM models in order to automate construction plan generation. It necessitates a large amount of human judgment and intervention for simulation model development and information exchanges between BIM modeling tools and planning tools. In this case, both BIM and DES in current practice have not yet been leveraged to their full capabilities with regard to construction planning. To address these issues, this paper thus explores an automated approach which achieves a seamless integration of BIM and DES for construction planning in the production plant, with the objective of improving productivity and balancing the production line. More specifically, a BIM-based special-purpose simulation (SPS) template for building panel production lines is developed in Simphony.NET, a simulation engine developed at the University of Alberta (AbouRizk and Mohamed 2000). The new simulation template provides a BIM-based interface which permits enriched information exchange between BIM and DES, and customized simulation elements with specific simulation behaviour that are helpful and more efficient in simulation modelling of the panel production facility. A case study of a production line for LGS panels is presented to demonstrate the methodology. Various production scenarios with respect to panel production sequence are evaluated in the simulation model. The results show that proper production sequencing improves production performance, and that the newly developed simulation template is a useful planning tool for panelized construction. Finally, conclusions are summarized and limitations of the present research are identified with respect to future research.

2 LITERATURE REVIEW

BIM is increasingly being embraced within the architecture, engineering, and construction (AEC) industry to support various tasks, including design/drafting, quantity takeoff, cost estimation, and communication among project stakeholders. Efforts have also been made in recent years to formulate construction plans by leveraging the benefits of BIM. For instance, Kim et al. (2013) developed a prototype for the purpose of automating construction scheduling by parsing an Industry Foundation Classes (IFC)-based BIM model. Liu et al. (2014) proposed an approach to generating on-site scheduling under the constraints of structural support and topological relationships among building elements. Later, Liu et al. (2015) further developed a BIM-based integrated approach of detailed construction scheduling under resource constraints, which achieves an in-depth integration of BIM models with work package information, process simulations, and optimization algorithms. Chen et al. (2013) also proposed a CAD-based framework to yield the near-optimum schedule. The 3D CAD model in their framework, however, only provided quantity take-offs for the process simulation model, with a large amount of human effort and simulation knowledge required to develop the simulation model. Moon et al. (2013) developed a BIM-based construction scheduling method with the objective of reducing activity overlaps. Their main focus with respect to BIM was on visualization and did not support construction plan generation.

DES is able to mimic real-world construction systems based on elaborate computer programming and statistical analysis, and could provide construction managers with insight on construction systems by evaluating various construction scenarios. It thus provides a powerful tool to perform comprehensive analysis for the purpose of productivity improvement of repetitive processes (AbouRizk et al. 2010). Halpin (1977) introduced CYCLONE, a simulation environment, which has created the foundation for the advancement of construction simulation. AbouRizk and Hajjar (1998) proposed a framework for the application of simulation in construction, specifically focusing on construction practitioners. They
presented the concept of special-purpose simulation (SPS), which is a computer-based environment specially built for experts in the area, the advantage of this environment being that the user does not need to have prior knowledge of simulation. AbouRizk and Mohamed (2000) introduced Simphony.NET, an integrated environment to model construction activities. This simulation software supports both DES and continuous simulation and can provide different model outputs, such as standard statistical averages, resource utilization, standard deviation, minima and maxima, and charts such as histograms, cumulative density functions (CDFs), and time graphs. There also have been several studies encompassing the use of DES in various fields of construction, such as bridge construction (Alvanchi et al. 2012), tunneling projects (Al-Bataineh et al. 2013; Ruwanpura et al. 2001), simulation-based production line optimization (Altaf et al. 2014), and SPS for industrial fabrication (Sadeghi and Fayek 2008; Song et al. 2006). Based on these studies, simulation modelling provides a promising means enabling engineers to precisely examine different approaches in order to complete the project. Most of the existing research related to BIM and DES-based planning, it should be noted, has focused on building information extraction from the given BIM model or simulation tool/application. However, the development of a BIM-based simulation tool for construction planning which enhances both enriched information exchanges between BIM and DES and simulation network (construction logic) modelling has not yet drawn much attention within the construction industry. This study thus aims to address these limitations in the existing research.

3 FABRICATION PROCESS OF LIGHT GAUGE STEEL WALL PANELS

Presently, in LGS construction practice, some building components, such as structural bearing walls and staircases, are pre-assembled in the factory and installed on site as panels. Washroom modules each consisting of four wall panels, a floor, and a ceiling (which serves as the floor for the level above), are also prefabricated in the factory, with all other components in the washroom, such as the tub, being pre-installed prior to shipment to the site. This research focuses on the wall panel production line in particular. The production line consists of a series of workstations (as shown in Figure 10) where specific operations/processes are carried out to produce the aforementioned building components. The fabrication process begins with steel studs and plates being assembled together into panel frames at the assembly station, regardless of panel category (exterior, interior, or washroom panel). The assembled panels are then moved to the framing station where a pressing process is carried out by a computer numerical control (CNC) machine in order to form the panel into a rigid frame. Subsequently, framed exterior wall panels are transferred to the sheathing station and nailing bridge for placement and nailing of sheathings; interior wall panels, meanwhile, are moved directly to the vertical panel storage area for shipment to the construction site, whereas washroom panels advance to a modular production line where they are assembled into modules. The exterior wall panels, following sheathing and nailing, go through the polysheild station and the polybase and mesh station, sequentially, in order for polysheild, polybase, and mesh to be applied. Finally, exterior wall panels without windows and doors are sent to the vertical panel storage area, while exterior wall panels which are to include windows and/or doors are transferred to the window and door installation station before they are moved to the vertical panel storage area. The prefabricated washroom modules are transferred to the modular storage area for shipment once they are completed.

4 METHODOLOGY

As described by AbouRizk and Hajjar (1998) special-purpose simulation (SPS) is defined as “a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself.” Hence, a BIM-based SPS template is developed in this research and is utilized to more efficiently build the DES model of the production line, thereby assisting production managers in planning and managing factory production. In general, the developed simulation template can reduce the manual data entry required and enhance information exchange (e.g., quantity takeoff and building design features) from the BIM authoring tool to the SPS model, capitalizing on the developed BIM model parser and the new simulation element “Input” in the proposed simulation template (see Figure 1 and Figure 4). The developed BIM model parser can extract
enriched building information from the BIM model and generate simulation entities in an XML file, while the “Input” simulation element can automatically take the enriched and detailed product design information extracted in the form of an XML file as inputs for the simulation model. In addition, other parameters for the production line, such as Capacity of Station (see Figure 6 and Figure 7), are customized as inputs of simulation elements. Icons of the simulation elements match the production line icons with similar functionality for the purpose of facilitating understanding of the simulation models built from this template among construction practitioners. Furthermore, even construction practitioners who do not have a strong familiarity with simulation can develop DES models of production lines in order to mimic the production processes and to perform “What-If” analyses before actual implementation. More detailed explanations with respect to modelling elements are presented in the following sections.

![Figure 1: Overview of proposed methodology](image)

5 SPECIAL-PURPOSE SIMULATION TEMPLATE ELEMENTS

Simphony.Net (AbouRizk and Mohamed 2000) is selected as the simulation platform to build the proposed SPS tool. Six simulation elements—task, input, station, equipment, entity router, and storage—are developed to mimic the factory production processes for panelized building projects.

5.1 Simulation Entity

In the production line, product features (i.e., design parameters) of building components such as length, height, number of studs, number of windows, number of doors, and sheets of sheathing affect the processing time at each station. The functionality of building components such as exterior, interior, structural, non-structural and partition of building components determines the construction processes these components go through. Rich building information, including the aforementioned information, is embedded into building components (parametric objects) as their attributes or parameters in the BIM model (an assembly of pre-defined 3D building objects). Similar to parametric objects in a BIM model, the object-oriented concept can also be adopted to design simulation entities in the new SPS template. (Simulation entities used in most DES engines, including Simphony are capable of representing semi-products or materials traversing the simulation model.)

In order to mimic the fabrication process, simulation entities in the newly developed simulation template are customized to represent building components (parametric objects in the BIM model) that carry detailed design information from the BIM model as attributes, and move through the DES simulation model. These entities will be processed and guided in the simulation model in accordance with detailed design information. For instance, simulation entities will go through different stations based on panel functionality (e.g., exterior or interior). As such, the integration of a BIM product model and a DES model is realized by enriched information entities, which extract rich building product information of building components from BIM and traverse through the simulation model. Figure 2 shows the entity relation diagram of simulation entities representing building components. As depicted in the figure, all the information denoted by solid circles in Figure 2 is extracted from the BIM product model, while the attributes in the dashed-circles are generated by the simulation model. It should be noted that “opening” information and “panel framing” information (in relation to number of windows and number of studs) are listed under the “SubComponents” attribute.
The BIM model in this research is developed in Autodesk Revit. The in-house Revit add-on is developed to parse BIM models, to extract the enriched building information, and to assign it to the simulation entities. Simulation entities with enriched product information are then stored in an XML file, which is the input for the developed simulation model. Figure 3 shows a screenshot of a sample XML file.

```
<BuildingEntity>
  <ElementID>516846</ElementID>
  <ElementType>"Generic 64x64 Corridor Wall"</ElementType>
  <Description>"Walls Generic 64x64 Corridor Wall 516846"</Description>
  <Project>"Project Number Project Name"</Project>
  <Level>"Level 1"</Level>
  <Name="Wall B - 3"</Name>
  <StructureMaterial="Steel, 45-245"</StructureMaterial>
  <Length="22.5625" Width="9.5"</Length>
  <Height="10.569999999999998"</Height>
  <Area="226.60621999999989"</Area>
  <StructuralClipCreate="true"</StructuralClipCreate>
  <touchscreen="false"</touchscreen>
  <Backflow="false"</Backflow>
  <Location X="-491.05382260026226" Y="113.039358942411" Z="-2.5" />
  <Supports> ...
      <Line>556153</Line>
      ...
  </Supports>
  <Connections> ...
      ...
  </Connections>
</BuildingEntity>
```

Figure 3: Sample of simulation entities with building information in XML

### 5.2 Input

The input element reads enriched building information and regenerates simulation entities (building panels) in the simulation model. One property of this element is "BIMXMLAddress", which enables users to specify the address of the XML file generated from Autodesk Revit. Once the simulation is triggered, the input element will read this XML file and release simulation entities into the developed simulation model. Figure 4 shows properties of the input element. As noted in the figure, the input has another property, “SequenceRule”, which allows users to specify the sequence rule of simulation entities being released in order to determine the panel production sequence by writing their own scripts. Simulation entities carrying enriched building element information are transferred out from this element sequentially and traverse through the simulation model to mimic the panel fabrication processes.
5.3 Atomic task

A task element is the most basic simulation element, and it is utilized to simulate an atomic operation or process in construction. It is designed based on the process modelling ontological concept, which refers to the actors involved in the various processes of a project (El-Diraby et al. 2003). As a result, simulation entities representing building products request construction resources to trigger the task/operation, and these entities are held for a specific duration. Upon completion of the operation being simulated, simulation entities are transferred out from this element. The inputs for this element, as shown in Figure 5, include duration and required resources. Notably, a task element can be connected to multiple task elements in order to mimic the operations being executed concurrently (see Figure 10).

5.4 Station

As described above, the production line consists of several work stations where specific fabrication operations or tasks take place. In this context, a station element is developed to represent each work station. A station essentially represents a process which can be divided into more detailed sub-processes or sub-tasks. Consequently, the station element is designed as a “Composite” element, which allows users to place as many task elements as desired inside the station element. To start the operation in a station element, simulation entities (building product elements) need to be granted their requested construction resources (e.g., stationary machines). Once the requested resources are available, and provided the station's capacity is sufficient to accommodate the coming simulation entities, these simulation entities are transferred into the element and kept inside until specific operations/tasks are completed. It is important to note that a work station has capacity limitations and cannot process unlimited simulation entities simultaneously. In addition, various stations have different measurements (e.g., panel length or height) for a given production capacity. In this regard, the station element shown in Figure 6 is customized to provide users an opportunity to define capacity and capacity units in order to mimic the production flow. This element can also collect the statistics data of cycle time, utilization, and waiting time for work stations. These statistics are shown graphically and can be used to assist production managers to manage and to balance the production line, and to improve productivity using lean principles.

5.5 Equipment

In addition to stations, various equipment (e.g., overhead crane) is commonly adopted in the prefabrication production line. Similar with work stations, equipment also has capacity limitations and is utilized to perform defined operations and tasks; however, the capacity works differently for equipment. The work stations process panels or semi-products immediately as long as panels arrive at the station provided that the station has sufficient remaining capacity to perform the operation. When the station reaches its full capacity, panels cannot enter the work station and must wait until some panels are released from the station. In this respect, crane operation differs in that it usually does not carry out its operation (e.g., lifting) until it reaches its full capacity. Furthermore, the operation of the crane is performed on batched semi-products (simulation entities). Once the specific operation is completed, the batched semi-products are un-batched and transferred out to the next operation. Another
interesting scenario is when the crane cannot reach its full capacity even if it takes all semi-products in queue. In this scenario, the crane can start the lifting operation without attaining its full capacity. In order to simulate the crane operation, the equipment element is developed. In addition to capacity and unit properties, the element has another two properties—“HavetoBeFull” and “WaitingTime”. If “HavetoBeFull” is set to true, the equipment cannot start the operation until the full capacity is attained. If “HavetoBeFull” is set to false, “WaitingTime” can be further specified to determine the amount of time the equipment waits for the coming simulation entities before the operation is triggered. Figure 7 presents the inputs of the equipment element.

5.6 Entity router

Due to the fact that panels vary in design features, such as IsExterior and HasWindow, they will go through various work stations. Simulation entities thus need to be routed into the correct stations based on the enriched design information they carry. An entity router element is thus developed to solve the simulation entity routing problem. Figure 8 shows the inputs of this element. In this simulation element, the user can specify the routing rules in “RoutingConditionList”, which is a collection of the next stations or tasks to which the simulation entity should be transferred, along with the condition that should be satisfied in order to send the simulation entity to the station. It should be noted that this element routes simulation entities in accordance with the routing conditions list, rather than connecting them with other simulation elements using directional arrows (as shown in Figure 10). This simplifies the graphical representation of a simulation model for the case in which simulation entities require various unique routes through the production line.

5.7 Storage

The storage element represents the storage area where finished panel products are stored for shipment to site. All simulation entities are finally transferred into the storage element in the simulation model. The main purpose of this element is to collect the statistical data for the total cycle times of the panels. The simulation result recorded into simulation entities as shown in Figure 2 is also written into the XML file by this element.

6 CASE STUDY

The newly developed SPS template was tested in an LGS wall panel production facility for residential buildings. The building shown in Figure 9 is composed of two storeys, each comprising four apartment units, one staircase, and two washrooms. In addition, there are 182 panels, including 60 non-bearing walls and 122 bearing walls. The building rests on 29 concrete footings. The building model is initially built in Autodesk Revit 2014, the building design information is extracted into simulation entities using an in-house Revit add-on, and then the simulation entities with enriched product design information are stored in an XML file. The simulation model can subsequently parse the XML file directly and release all simulation entities into a simulation network via the “Input” simulation element. This template significantly
reduces the effort required compared to preparing the simulation input manually, due to the enhanced information exchange between the BIM model and SPS model. Meanwhile, the simulation template speeds up simulation modelling of the panelized building production line by using customized simulation elements. Figure 10 presents the simulation model of the panel production line described in the previous section. As shown in the figure, the prefabrication process for the Window and Door Station can be further divided into several sub-tasks. In this case, a few task elements are placed inside the Station element in order to simulate the window and door installation process. Also, it should be noted that there are two parallel branches for window and door installation. This exemplifies the fact that some sub-tasks can be executed concurrently, as long as the required labour resources are available. Windows and doors can be installed simultaneously, and their respective processing times are different.

Figure 9: 3D view and framing view of a two-storey panelized residential building

6.1 Processing Time Prediction

As described earlier, the process time is affected by the detailed design information about the panels. In the simulation model, process equations are inputted into the Task element (inside the “Station” element) in order to calculate the process time. For instance, the below equation is used to calculate the process time of the panel assembly operation (Altaf et al. 2014; Shafai 2012).

\[ T_{A} = \sum_{i=1}^{N_{ST}} T_{ST} + T_{BP} \times N_{BP} + T_{TP} \times N_{TP} + T_{W} \times N_{W} + T_{D} \times N_{D} + V \]  

Eq. (1)

Where \( T_{A} \) is the process time of the assembly station; \( T_{BP} \) and \( T_{TP} \) are the times, in seconds (s), needed to place each top and bottom plate, respectively; \( T_{ST} \) is the time needed to place a single stud; \( T_{W} \) is the time needed to assemble studs for each window; \( T_{D} \) is the time needed to assemble studs for each door, \( N_{BP} \), \( N_{TP} \), \( N_{ST} \), \( N_{W} \), and \( N_{D} \) are the numbers of subcomponents in the framing component, and \( V \) denotes variation for the assembly process and is assumed in this research to be a triangular distribution.

6.2 Simulation results

The simulation template and developed simulation model are verified by tracking the chronological list and observing the panel cycle time. Figure 11 presents cycle times of wall panels, denoted as “observation”. As shown in Figure 11.a, there are eight peak values for the cycle time, since the test project has eight similar units and wall panels are produced unit-by-unit. For each unit, wall panels are produced in descending order of panel length. In this sequence, the total production duration is 697.98 minutes. Alternative production sequences, such as level-by-level, are also evaluated in the simulation model, and all the production durations are found to be approximately 700 minutes, with the exception of the scenario in which all panels are produced in ascending order of panel length, in which case the duration is found to be 826.63 minutes. This is due to the fact that in this scenario exterior walls are started later than interior walls because they have a greater average length; however, exterior walls also take more time to produce (as demonstrated in Figure 11.a and Figure 11.b). As a result, the concurrent execution of assembly and framing station of Interior wall panels with sheathing and succeeding workstations of exteriors wall panels leads to reducing overall production duration.
7 CONCLUSIONS AND FUTURE WORK

This research focuses on a BIM-based SPS template for a panel production line. A set of new simulation elements in Simphony.Net 4.0 is developed to speed up simulation modelling of the panel production line. This new simulation template can enhance simulation modelling in two aspects: (1) enhanced information exchange via object-oriented simulation entities, which mitigates the need for massive manual inputting; and (2) customized simulation elements with specific simulation behaviour, which are helpful and more efficient in simulating the production facility and mimicking the prefabrication process. This new simulation template thus enables construction practitioners who do not have a strong familiarity with simulation to develop DES models of production lines in order to perform “What-If” analyses before actual production. The simulation template has been tested using a case study of a production line for LGS panels. Various production sequences have been evaluated in the developed simulation model. The statistical data of cycle time, utilization, and waiting time for work stations are represented graphically and provide construction practitioners insights on production performance. On this basis, construction practitioners can plan and manage the production line using lean principles. The developed tool is demonstrated to be...
helpful for assisting in the planning and management of the production line. In the next stage of research, the template will be further validated and applied to other building panel production lines. Also, data mining technology such as Artificial Neural Network (ANN) will be integrated into the proposed simulation template in order to predict operation process time based on historical data.

Acknowledgements

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References

DEVELOPMENT OF AN OPERATIONAL EXCELLENCE MODEL TO IMPROVE SAFETY FOR CONSTRUCTION ORGANIZATIONS

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Abstract: Construction incidents have numerous root causes, but one of the most frequent is worker behavior. Therefore, construction safety management systems should be designed to maximize the number of safe behaviors by workers, and focus on the execution of construction safety management to achieve excellent safety performance. Operational excellence, a safety concept from the chemical processing industry, is defined as doing the right thing, the right way, every time – even when no one is watching. Good operational excellence results in effective reinforcement of appropriate safety systems, and significantly reduces the rate of unsafe behaviors. Researchers managed to embed the concept of operational excellence into construction safety management. Through an extensive literature review, discussions with industry experts on the topic, and subject matter expert validation, the researchers have developed an operational excellence model designed to evaluate and improve safety performance for construction organizations. This paper describes the model development process and the key elements included in the Operational Excellence Model (OEM). The primary contribution to the overall body of knowledge is developing a practical operational excellence model for practitioners to assess and improve safety performance through behavioral and cultural elements.

1 INTRODUCTION

Despite significant reductions of incidents on construction sites in the past several decades, the injuries and fatality rates for construction workers are still higher than other industry sectors (Bureau of Labor Statistics, 2011). Many safety researchers hold a perception that inherent reasons must exist in the construction industry, which are responsible for the poor safety situation on the jobsite (Davies and Tomasin, 1990). Unsafe behavior during the execution of work is considered as an inherent reason, which causes a majority of construction incidents (Tariq et al, 2000; D.-C. Seo, 2005). Many statistical analyses of incident reports conducted in multiple countries found that almost 90% of the incidents can be attributed to unsafe behaviors or human errors (Salminen and Tallberg, 1996; Williamson and Feyer, 1990; Lutness, 1987; D. Chen and H. Tian, 2012). A conclusion can be made that unsafe behavior is the primary direct cause for the construction incidents. However, other researchers go further to explore the inherent reason behind unsafe behavior. Many unsafe behaviors can be attributed to poor construction safety culture. This idea is widely supported by many researchers (Brown et al., 2000; Oliver et al., 2002; Petersen, 1988; Tomas et al., 1999).
Poor safety culture and unsafe behaviors are both drivers of poor safety performance. Operational excellence involves cultural and behavioral constructs. Operational excellence is a concept proposed by the chemical processing industry, which is based on the philosophy that excellent operation leads to excellent safety performance. Operational excellence is defined as doing the right thing, the right way, every time – even when no one is watching. Good operational excellence results in effective reinforcement of appropriate safety systems, and significantly reduces the rate of unsafe behaviors. To achieve operational excellence, a culture dedicated to excellence must be established. Culture exists as an implicit concept that drives tangible safe behaviors. Safe behaviors generate an authentic and lasting effect on the organization, which in turn sustains and promotes the safety culture.

The primary purpose of this research is to develop a safety model involving both cultural and behavioral elements. Operational excellence is the outcome of the model, which in turn, should improve safety performance. The essence of the model is that culture drives behavior and behavior sustains culture (Maloney, 1989). Through an extensive literature review, discussions with industry experts on the topic, and subject matter expert validation, the researchers have developed an operational excellence model designed to evaluate and improve safety performance for construction organizations. This paper describes the model development process and the key elements included in the Operational Excellence Model (OEM). The primary contribution to the overall body of knowledge is developing a practical operational excellence model for practitioners to assess and improve safety performance through behavioral and cultural elements.

2 OPERATIONAL EXCELLENCE

2.1 Definition of Operational Excellence

Operational excellence is a buzzword that is commonly used across various industries when addressing improvements in production, safety, quality, and cost performance, yet it is often ill defined. The fundamental idea of operational excellence is that perfect operations lead to perfect results.

Operational Performance Systems (OPS), a management consulting company, defines operational excellence as “the performance of tasks according to written expectations, policies and procedures in a safe and professional manner” (Philip, 2013). In other words, operational excellence is about creating a written standard and applying that standard rigorously and consistently across the organization.

Another view is that operational excellence should be separated into organizational level and individual level components. The definition of organizational level operational excellence is “the deeply rooted dedication and commitment by every member of an organization to carrying out each task the right way, each time” (Klein et al., 2011). The definition of the individual level is “commitment to working safely by doing every task, the right way, every time” (Klein et al., 2011). In other words, there is commitment by the members collectively as an organization to do it the right way, every time and individually in their own work practices.

Based on these definitions, the aim of operational excellence is to achieve exceptional performance through the engagement of all members in the organization to do the right thing, the right way, every time – even when no one is watching. Hence, determining the “right thing” and the “right way” is imperative, and those are the elements that are identified and validated in this paper.

2.2 Previous Operational Excellence Research

Prior researchers utilize characteristics to describe and embody the makeup of operational excellence. Dennis Johnson (2005) compiled a set of 10 characteristics to represent operational excellence in the context of the oil industry. Brian D. Rains (2012) identified a set of 11 characteristics. James A. Klein and Bruce K. Vaughn (2008) set up an operational excellence framework consisting of 11 characteristics. Both of these models were developed for the safety improvement of chemical processing industry. Robert J. Walter (2002) proposed a more comprehensive version consisting of 15 characteristics. However, it is also designed for the chemical processing industry and the oil exploration and refining industry.
The extensive literature suggests that a lack of research on operational excellence exists, especially in the context of the construction industry. Due to limited resources, developing OEM will take a great effort to identify, categorize and examine elements associated with the construction industry.

3 METHODOLOGY

The critical elements of OEM are identified through an extensive literature review. Efforts mainly focus on previous research and professional guidance by industry association. To verify these elements, subject matter expert validation is conducted through questionnaire survey and statistical analysis.

3.1 Framework of OEM

As aforementioned, this research aims at developing a model that can be used by practitioners to assess and improve safety performance through behavioral and cultural elements. However, the previous characteristics of operational excellence were compiled by other industries, and therefore have limited applicability to this OEM designed for construction projects. After discussion by the research team, the Critical to Quality (CTQ) tree was chosen as the tool to develop measurable characteristics, which arise from the six sigma methodology (Aristide et al., 2013). CTQ trees are used to decompose broad research objectives into more easily quantified elements.

The OEM must be developed into clear, specific, quantitative requirements, so that it can be used by practitioners as an effective and practical tool. In the context of construction safety, these quantitative requirements are called Critical to Safety characteristics (CTSs). CTSs are the measurable safety characteristics that are considered important to sustain and promote construction safety.

The model was structured as a Critical to Safety Tree. The model has four levels: Safety Driver (SD), Critical to Safety (CTS), Critical to Expectations (CTX, X indicates various expectations), and Specification/Measurement (S/M).

SD indicates the factor that will be used to evaluate the performance of the safety program. CTS indicates elements of the driver, which corresponds to “the right thing” in the definition of operational excellence. CTX indicates behaviors and/or processes used to provide the elements, which corresponds to “the right way” in the definition of operational excellence. S/M indicates a quantitative measurement of the CTX, which corresponds to “every time” in the definition of operational excellence. Generally speaking, the four levels model represents the essence of the operational excellence: focus on doing the right thing, the right way, every time – even when no one is watching. However, the important piece of the “even when no one is watching” is not directly measured. The approach to this issue is to embed safety culture into the whole model. Culture drives behavior and behavior sustains culture. Through the rigid execution of operational excellence, the number of unsafe behaviors will be reduced and the safety culture will be reinforced. Once the safety culture is embedded into every member’s mind, the goal of “even when no one is watching” will be achieved. Consequently, CTS trees based on operational excellence will serve as the framework for the OEM.

3.2 Identifying and Categorizing the Elements of OEM

To identify and categorize the elements on each level, the research team employed three main resources:

- Previous relevant research;
- Documentation from industry associations and government; and
- The expertise of the research team.

A preliminary list of SDs was developed by the use of documentation from past research and publications, which constitutes the first level of OEM. Starting from these SDs, further development of CTSs, CTXs and S/M were conducted, and a complete and detailed list was developed. However, the original version was roughly categorized, which causes the overlapping between different characteristics.
During multiple meetings, research team members rigorously examined and refined the list through brainstorming and nominal group technique. Finally, an improved list of OEM was developed. It has 13 SDs, and each of those SDs represents a major aspect of construction safety (see Table 2 Column 2). From these 13 SDs, 75 CTSs that may have a bearing on operational excellence are identified (see Table 2 Column 2). And then 256 CTXs, and 293 S/Ms were also developed. For CTSs and CTXs, they are listed as a complete phrase or sentence, which ensure consistency of the understanding. S/Ms are ways to quantifiably measure a level of performance.

The thrust of the research team is to conceptually validate the OEM at the SD and CTS level. Therefore, the validation results that follow focus on those two levels. Future research efforts will collect data against the entirety of the model.

3.3 Validating the SDs and CTSs

Subject matter expert validation of the SDs mainly focused on determining the relative degree of significant contribution that each SD makes to operational excellence in construction safety. Researchers also obtained professional views on whether each CTS is suitable to its corresponding SD. Validation was conducted through a questionnaire survey.

For each of the SDs, participants are asked to evaluate their level of agreement with the statement that this SD is significant to operational excellence. Detailed descriptions are attached to each SD to help ensure participants’ understanding of the SD under review. The average value will be computed as the final score for each SD. Respondents are required to rate significance of contribution on a 5-point scale where 1=Disagree, 2=Neither Agree nor Disagree, 3=Slightly Agree, 4=Agree, and 5=Strongly Agree.

In the case of CTSs, participants are asked to evaluate the importance of each CTS to developing and understanding of its SD. The average value will be computed as the final score for each CTS. Respondents were requested to rate importance on a 5-point scale where 1=No importance, 2=Little importance, 3=Some importance, 4=Moderate importance, and 5=Great importance. This Likert scale is skewed intentionally. The researchers had a concern that a traditional Likert scale would not show variability in the responses, since many of the items are based on previous literature and unlikely to have high levels of disagreement.

4 DATA ANALYSIS

Data collection is performed through the use of Select Survey’s server-based software. Most of the participants are experienced practitioners. This online survey system is designed to provide researchers credible data and facilitate research. A total of 92 surveys were initiated, but not all were completed. Each question had a minimum of 60 responses. All responses for each question were included.

4.1 Characteristics of the Organizations

Respondents were asked to provide demographic information on their organizations. Organization characteristics are shown in Table 1. Most companies have participated in national or even international projects and conducted construction-related work. Types of projects they participate in cover almost all construction sectors.
Table 1: Organization Characteristics

<table>
<thead>
<tr>
<th>Work Area</th>
<th>Percentage (%)</th>
<th>Respondent’s Organization</th>
<th>Percentage (%)</th>
<th>Primary Construction Sector(s)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regionally</td>
<td>20.69</td>
<td>Owner</td>
<td>37.39</td>
<td>Industrial</td>
<td>57.03</td>
</tr>
<tr>
<td>Nationally</td>
<td>34.48</td>
<td>Designer</td>
<td>0.87</td>
<td>Commercial</td>
<td>23.44</td>
</tr>
<tr>
<td>Internationally</td>
<td>22.99</td>
<td>Constructor</td>
<td>56.52</td>
<td>Infrastructure/Heavy Civil</td>
<td>8.59</td>
</tr>
<tr>
<td>All</td>
<td>21.84</td>
<td>Other</td>
<td>5.22</td>
<td>Residential</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other</td>
<td>9.38</td>
</tr>
</tbody>
</table>

4.2 Results of the SDs and the CTSs

Two criteria are developed to examine the subjective opinions from experts. The first criterion is a threshold value of 3.50 for all mean values. Three from the 5-point scale means “some importance” or “slightly agree”, a mean value higher than 3.50 indicates that experts agree with the importance of the item to the construction project safety. The second criterion is comparing the percentage of responses higher than 3 with 80%. If the percentage is higher than 80%, it means more than 80% of experts agree that this item is important to the construction project safety. Mean values are given in column 3, and the percentage of response higher than 3 is presented in column 4. The results of the survey can be seen in Tables 2-14 for each safety driver.

Table 2: Survey Results for Recognition and Reward SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Recognition &amp; Reward</td>
<td>4.07</td>
<td>84.13%</td>
</tr>
<tr>
<td>SD 1</td>
<td>Development and review of safety and health policy</td>
<td>4.49</td>
<td>89.09%</td>
</tr>
<tr>
<td>CTS 1.1</td>
<td>Recognize performance of required behaviors</td>
<td>4.63</td>
<td>90.48%</td>
</tr>
<tr>
<td>CTS 1.2</td>
<td>Reward performance of discretionary behaviors</td>
<td>4.27</td>
<td>82.26%</td>
</tr>
<tr>
<td>CTS 1.3</td>
<td>Celebrating group achievement of safety results</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Survey Results for Employee Engagement SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Development and review of safety and health policy</td>
<td>4.67</td>
<td>98.21%</td>
</tr>
<tr>
<td>SD 2</td>
<td>Development and review of safety and health policy</td>
<td>4.49</td>
<td>89.09%</td>
</tr>
<tr>
<td>CTS 2.1</td>
<td>Conducting risk assessments</td>
<td>4.55</td>
<td>96.36%</td>
</tr>
<tr>
<td>CTS 2.2</td>
<td>Organizing for safety and health activities</td>
<td>4.18</td>
<td>83.64%</td>
</tr>
<tr>
<td>CTS 2.3</td>
<td>Implementing the safety plan</td>
<td>4.66</td>
<td>96.23%</td>
</tr>
<tr>
<td>CTS 2.4</td>
<td>Measuring safety and health performance</td>
<td>4.39</td>
<td>89.09%</td>
</tr>
<tr>
<td>CTS 2.5</td>
<td>Investigating incidents, accidents, and near misses</td>
<td>4.65</td>
<td>89.09%</td>
</tr>
<tr>
<td>CTS 2.6</td>
<td>Develop lessons learned from the investigations and review</td>
<td>4.69</td>
<td>94.55%</td>
</tr>
</tbody>
</table>
Table 4: Survey Results for Subcontractor Management SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 3</td>
<td>Subcontractor Management</td>
<td>4.60</td>
<td>100.00%</td>
</tr>
<tr>
<td>CTS 3.1</td>
<td>Prequalification and selection of subcontractors</td>
<td>4.69</td>
<td>96.30%</td>
</tr>
<tr>
<td>CTS 3.2</td>
<td>Require subcontractors to develop a project site-specific safety plan</td>
<td>4.51</td>
<td>90.91%</td>
</tr>
<tr>
<td>CTS 3.3</td>
<td>Prime contractor/subcontractor safety meetings</td>
<td>4.67</td>
<td>96.36%</td>
</tr>
<tr>
<td>CTS 3.4</td>
<td>Subcontractor compliance with requirements</td>
<td>4.55</td>
<td>90.91%</td>
</tr>
<tr>
<td>CTS 3.5</td>
<td>Site safety orientation</td>
<td>4.54</td>
<td>88.89%</td>
</tr>
<tr>
<td>CTS 3.6</td>
<td>Managerial emphasis on the importance of safety</td>
<td>4.73</td>
<td>96.36%</td>
</tr>
</tbody>
</table>

Table 5: Survey Results for Training and Competence SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 4</td>
<td>Training &amp; Competence</td>
<td>4.70</td>
<td>100.00%</td>
</tr>
<tr>
<td>CTS 4.1</td>
<td>Identification of required safety specific competencies</td>
<td>4.67</td>
<td>94.44%</td>
</tr>
<tr>
<td>CTS 4.2</td>
<td>Assessment of competencies held by employees</td>
<td>4.43</td>
<td>90.74%</td>
</tr>
<tr>
<td>CTS 4.3</td>
<td>Gap analysis to determine training needs</td>
<td>4.24</td>
<td>90.74%</td>
</tr>
<tr>
<td>CTS 4.4</td>
<td>Development of training programs to provide required competencies</td>
<td>4.57</td>
<td>96.30%</td>
</tr>
<tr>
<td>CTS 4.5</td>
<td>Conduct training programs</td>
<td>4.60</td>
<td>94.34%</td>
</tr>
<tr>
<td>CTS 4.6</td>
<td>Assess training programs to determine how effectively knowledge and skills have been acquired</td>
<td>4.40</td>
<td>90.74%</td>
</tr>
<tr>
<td>CTS 4.7</td>
<td>Assess safety performance to identify needs for remedial, refresher, and new training programs</td>
<td>4.44</td>
<td>94.44%</td>
</tr>
</tbody>
</table>

Table 6: Survey Results for Risk Awareness, Management, and Tolerance SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 5</td>
<td>Risk Awareness, Management &amp; Tolerance</td>
<td>4.63</td>
<td>98.08%</td>
</tr>
<tr>
<td>CTS 5.1</td>
<td>Considering safety and risk evaluation in all aspects of personnel planning</td>
<td>4.63</td>
<td>94.23%</td>
</tr>
<tr>
<td>CTS 5.2</td>
<td>Evaluating daily construction risk</td>
<td>4.77</td>
<td>96.15%</td>
</tr>
<tr>
<td>CTS 5.3</td>
<td>Considering safety and risk evaluation in the project budget development process</td>
<td>4.33</td>
<td>90.38%</td>
</tr>
<tr>
<td>CTS 5.4</td>
<td>Reviewing safety programs and safety performance periodically by the business (Above project level)</td>
<td>4.42</td>
<td>90.38%</td>
</tr>
<tr>
<td>CTS 5.5</td>
<td>Reducing risk tolerance of workers</td>
<td>4.67</td>
<td>96.15%</td>
</tr>
</tbody>
</table>
### Table 7: Survey Results for Learning Organization SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD 6</td>
<td>Learning Organization</td>
<td>4.35</td>
<td>94.12%</td>
</tr>
<tr>
<td>CTS 6.1</td>
<td>Formal approaches</td>
<td>4.27</td>
<td>90.20%</td>
</tr>
<tr>
<td>CTS 6.2</td>
<td>Informal approaches</td>
<td>4.27</td>
<td>88.24%</td>
</tr>
</tbody>
</table>

### Table 8: Survey Results for Human Performance SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD 7</td>
<td>Human Performance</td>
<td>4.58</td>
<td>94.00%</td>
</tr>
<tr>
<td>CTS 7.1</td>
<td>Reducing errors</td>
<td>4.68</td>
<td>96.00%</td>
</tr>
<tr>
<td>CTS 7.2</td>
<td>Managing defenses or controls:</td>
<td>4.65</td>
<td>98.00%</td>
</tr>
</tbody>
</table>

### Table 9: Survey Results for Transformational Leadership SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD 8</td>
<td>Transformational Leadership</td>
<td>4.45</td>
<td>93.88%</td>
</tr>
<tr>
<td>CTS 8.1</td>
<td>Challenging the process</td>
<td>4.39</td>
<td>92.00%</td>
</tr>
<tr>
<td>CTS 8.2</td>
<td>Inspiring a shared vision</td>
<td>4.60</td>
<td>92.00%</td>
</tr>
<tr>
<td>CTS 8.3</td>
<td>Modeling the way</td>
<td>4.48</td>
<td>91.84%</td>
</tr>
<tr>
<td>CTS 8.4</td>
<td>Enabling others to act</td>
<td>4.64</td>
<td>94.00%</td>
</tr>
<tr>
<td>CTS 8.5</td>
<td>Encouraging the heart</td>
<td>4.50</td>
<td>92.00%</td>
</tr>
</tbody>
</table>

### Table 10: Survey Results for Shared Values, Beliefs, and Assumptions SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD 9</td>
<td>Shared Values, Beliefs, and Assumptions</td>
<td>4.46</td>
<td>95.83%</td>
</tr>
<tr>
<td>CTS 9.1</td>
<td>Routines</td>
<td>4.45</td>
<td>87.76%</td>
</tr>
<tr>
<td>CTS 9.2</td>
<td>Rituals</td>
<td>4.22</td>
<td>81.63%</td>
</tr>
<tr>
<td>CTS 9.3</td>
<td>Stories</td>
<td>4.32</td>
<td>85.71%</td>
</tr>
<tr>
<td>CTS 9.4</td>
<td>Symbols</td>
<td>3.86</td>
<td>69.39%</td>
</tr>
<tr>
<td>CTS 9.5</td>
<td>Power</td>
<td>4.49</td>
<td>83.67%</td>
</tr>
<tr>
<td>CTS 9.6</td>
<td>Safety structures</td>
<td>4.52</td>
<td>89.80%</td>
</tr>
<tr>
<td>CTS 9.7</td>
<td>Safety controls</td>
<td>4.47</td>
<td>91.84%</td>
</tr>
<tr>
<td>CTS 9.8</td>
<td>Underlying assumptions</td>
<td>4.18</td>
<td>81.63%</td>
</tr>
</tbody>
</table>
Table 11: Survey Results for Strategic Safety Communication SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 10</td>
<td>Strategic Safety Communication</td>
<td>4.40</td>
<td>93.75%</td>
</tr>
<tr>
<td>CTS 10.1</td>
<td>Developing project communication program</td>
<td>4.50</td>
<td>91.84%</td>
</tr>
<tr>
<td>CTS 10.2</td>
<td>Providing training in communication skills</td>
<td>4.18</td>
<td>83.33%</td>
</tr>
<tr>
<td>CTS 10.3</td>
<td>Engaging in safety conversations with project personnel</td>
<td>4.74</td>
<td>97.96%</td>
</tr>
<tr>
<td>CTS 10.4</td>
<td>Utilizing posters and newsletters</td>
<td>3.81</td>
<td>61.22%</td>
</tr>
<tr>
<td>CTS 10.5</td>
<td>Employing visual management techniques to communicate safety performance metrics</td>
<td>4.24</td>
<td>81.25%</td>
</tr>
<tr>
<td>CTS 10.6</td>
<td>Evaluating safety information flow</td>
<td>4.06</td>
<td>69.39%</td>
</tr>
<tr>
<td>CTS 10.7</td>
<td>Coaching</td>
<td>4.64</td>
<td>91.84%</td>
</tr>
</tbody>
</table>

Table 12: Survey Results for Just & Fair Practices and Procedures SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 11</td>
<td>Just &amp; Fair Practices and Procedures</td>
<td>4.35</td>
<td>89.80%</td>
</tr>
<tr>
<td>CTS 11.1</td>
<td>Developing Just &amp; Fair policy</td>
<td>4.32</td>
<td>85.71%</td>
</tr>
<tr>
<td>CTS 11.2</td>
<td>Developing an incident reporting system</td>
<td>4.53</td>
<td>89.80%</td>
</tr>
<tr>
<td>CTS 11.3</td>
<td>Implementing policy &amp; reporting system</td>
<td>4.29</td>
<td>87.76%</td>
</tr>
<tr>
<td>CTS 11.4</td>
<td>Recognizing, rewarding, and reinforcing incident reporting</td>
<td>4.28</td>
<td>81.25%</td>
</tr>
<tr>
<td>CTS 11.5</td>
<td>Providing feedback on incident reports</td>
<td>4.34</td>
<td>85.71%</td>
</tr>
<tr>
<td>CTS 11.6</td>
<td>Maintaining incident reporting system</td>
<td>4.38</td>
<td>83.67%</td>
</tr>
<tr>
<td>CTS 11.7</td>
<td>Maintaining policy and system integrity</td>
<td>4.46</td>
<td>89.58%</td>
</tr>
<tr>
<td>CTS 11.8</td>
<td>Employee perception of safety culture</td>
<td>4.63</td>
<td>93.88%</td>
</tr>
</tbody>
</table>

Table 13: Survey Results for Worksite Organization SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD 12</td>
<td>Worksite Organization</td>
<td>4.51</td>
<td>93.88%</td>
</tr>
<tr>
<td>CTS 12.1</td>
<td>Sorting</td>
<td>4.45</td>
<td>89.58%</td>
</tr>
<tr>
<td>CTS 12.2</td>
<td>Straightening/Setting in order</td>
<td>4.43</td>
<td>91.84%</td>
</tr>
<tr>
<td>CTS 12.3</td>
<td>Shining</td>
<td>4.27</td>
<td>81.63%</td>
</tr>
<tr>
<td>CTS 12.4</td>
<td>Standardizing</td>
<td>4.32</td>
<td>91.84%</td>
</tr>
<tr>
<td>CTS 12.5</td>
<td>Sustaining</td>
<td>4.54</td>
<td>91.84%</td>
</tr>
</tbody>
</table>
Table 14: Survey Results for Owner’s Role SD

<table>
<thead>
<tr>
<th>Model Element ID</th>
<th>Safety Drivers and Critical to Safety Elements</th>
<th>Mean</th>
<th>Percentage of response higher than 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Owner’s Role</td>
<td>4.55</td>
<td>95.74%</td>
</tr>
<tr>
<td>2</td>
<td>Establishing and communicating attitudes toward safety</td>
<td>4.65</td>
<td>95.92%</td>
</tr>
<tr>
<td>3</td>
<td>Selection of contractor</td>
<td>4.69</td>
<td>95.92%</td>
</tr>
<tr>
<td>4</td>
<td>Contractual safety management</td>
<td>4.47</td>
<td>93.88%</td>
</tr>
<tr>
<td>5</td>
<td>Owner’s involvement in safety pre-construction</td>
<td>4.49</td>
<td>91.84%</td>
</tr>
<tr>
<td>6</td>
<td>Monitoring contractor safety compliance</td>
<td>4.54</td>
<td>93.75%</td>
</tr>
<tr>
<td>7</td>
<td>Measuring and analyzing safety results</td>
<td>4.45</td>
<td>93.88%</td>
</tr>
<tr>
<td>8</td>
<td>Participation in behavior observation surveys (BOS)</td>
<td>4.17</td>
<td>74.47%</td>
</tr>
<tr>
<td>9</td>
<td>Participation in incident investigations</td>
<td>4.28</td>
<td>81.63%</td>
</tr>
<tr>
<td>10</td>
<td>Providing assistance</td>
<td>4.44</td>
<td>85.71%</td>
</tr>
<tr>
<td>11</td>
<td>Participation in safety training</td>
<td>4.33</td>
<td>87.76%</td>
</tr>
</tbody>
</table>

5 DISCUSSION

Every SD has a mean value higher than 3.50 and a percentage higher 80%. This result means most experts agree that those SDs significantly contribute to the operational excellence in construction project safety. The validation of the SDs lays a solid foundation for the development of CTSs.

Each of the CTSs have a mean value higher than 3.50. Most of CTSs have a percentage higher than 80%, except symbols (69.39%), utilizing posters and newsletters (61.22%), evaluating safety information flow (69.39%), and participation in behavior observation surveys (BOS) (74.47%).

Symbols do not convey detailed information, compared to other CTSs under Shared Values, Beliefs, and Assumptions. This is the reason for its low importance. Utilizing posters and newsletters is not specifically-targeted, and employees lack incentives to check things not exclusively delivered to them. This is why experts assign a lower grade to it. Evaluating safety information flow has a relatively higher mean value of 4.06, but a relatively low percentage of 69.39%. That indicates that there is a diverging opinion among experts. Safety information flow is a foreign concept for construction industry. Experts with a lack of knowledge of this concept would tend to reduce its value. Participation in behavior observation surveys (BOS) also has a relatively higher mean value and a relatively low percentage. The divergence of expert opinions exists. Some experts think BOS is not the owner’s work, others think it is. The disagreement on the owner’s role in safety management leads to the lower percentage.

The CTSs that did not meet the criteria were deleted from the model. Thus, the remaining contents describe a conceptually validated model of operational excellence for construction project safety. Future work will collect data to measure the impact that operational excellence has on construction project safety.

6 CONCLUSION

This study investigated the concept of operational excellence in the context of construction project safety, and developed a practical operational excellence model for practitioners to assess and improve safety performance through behavioral and cultural elements. 13 SDs and 75 CTSs were identified through an extensive and thorough literature review. To validate the applicability of the SDs and the CTSs, a subject
matter expert validation process was conducted through an online survey. Results of the SDs shows that each of the SDs has a mean value higher than 3.5, and more than 80% of experts score them with 4 or 5. This proves that experts significantly agree the contributions made by the SDs. Each of the CTSs have a mean value higher than 3.50. Except for 4 CTSs, the remainders have a percentage greater than 80%. This proves that experts significantly regard the CTSs as important for the development of the SDs. The subject matter expert validation results provide solid evidence for the validity of the OEM.

Acknowledgements

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References


SIMULATED SCHEDULE DELAY MITIGATION VIA FLOAT ALLOCATION

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Abstract: As delays in construction project schedules are widely documented, new approaches to manage this problem are needed. Previous studies have explored float as an inherent ability of schedules to absorb delays. However, all ignore the critical path; some recommendations as to float ownership directly contradict the inherently unfair ‘first come first serve’ principle; and none have derived testable methods to fairly allocate float to multiple participants. This study therefore employs the mathematical analogy of decision-making among a group of unequally sized individuals to explicitly allocate project float a priori to those most vulnerable – the critical path. While intuition might indicate allocation proportional to activity duration, or perhaps equal shares, it is demonstrated that neither is truly fair and a mathematical compromise can be found. The performance of this approach is tested quantitatively by simulating a case example of project schedules with and without such protection. Delays are modeled as probabilistic events that affect activities. It is found that even a relatively small amount of project float allocated along the critical path provides significant delay mitigation.

1 INTRODUCTION

Construction project schedules in many countries unfortunately are frequently inundated with delays (Gündüz et al. 2013). Delays in this research are defined in a strictly temporal view, i.e. negative changes of start and/or finish of activities between the as-planned and as-updated project schedules. What makes delays particularly perilous is the fact that they are not an isolated local phenomenon within schedules, but may initiate a cascading set of ripple effects in later activities that depend on the earlier delayed one. Whatever the diverse causes of such delays are, which may stem from one or several risk factors that are materializing (González et al. 2013), is less relevant to this discussion than the unfortunate outcome, that it becomes likely that the contractually agreed turnover date will be met, i.e. the entire project will be late.

Contractual effects of late completion typically are that the contractor is required to reimburse the owner for consequential cost (liquidated damages) of postponed occupancy of the new facility, which often leads to further side-effects, e.g. protracted court cases over liability that may damage the reputation and lose future clients. The central question remains not one of identifying and treating symptoms, but of curing the cause: What inherent defenses does a project schedule have against incurring delays? Such capabilities could take two forms, either preventive (lowering the probability of a delay occurring) – akin to inoculation; or reactive (gaining better means of alleviating a delay that occurs) – akin to therapeutics in medicine.

To begin answering this question, this research will first review existing theory of project management regarding conceptual limitations of traditional scheduling and opportunities for protecting against delays, then explore potential theory in decision-making from which inspiration for such resilience will be gleaned.
2 LITERATURE REVIEW

2.1 Scheduling Assumptions

Construction schedules are traditionally conceived and handled as networks, which mathematically are acyclic ‘graphs’ (Chen et al. 2001) that consist of nodes (activities) and arcs (links) between them, whose direction is dictated by the passing of time. Exploiting a rather simple and repetitive structure of relations of temporal data among activities led to the so-called critical path method (Kelley and Walker 1959) with which dates are sequentially calculated: Within activities, adding the duration to its start gives its finish \((S + D = F)\). And between activities, all successors must finish as a condition for the successor to start \((max \{F_{\text{pred}}\} = S_{\text{succ}})\). This forward-looking calculation assumes the best case that all activities start as early as possible at their earliest \((E)\) dates. Its inverse, the backward-looking calculation assumes the worst case that they start as late as possible at latest \((L)\) dates, so as to just not yet delay the project finish itself.

Comparing these two scenarios gives information for each activity on how much it can be delayed without impacting (a) any successor (free float, \(FF_{\text{pred}} = min(E_{\text{succ}}) - EF_{\text{pred}}\), or ‘only’ (b) the project finish (total float, \(TF = LF - EF = LS - ES\)). Thus float is defined by an assumed delay. Due to the aforementioned vital importance of the project finish for contractual liability purposes, this research will focus on the total float. Float in the literature has been presented as the opposite of importance of the project finish for contractual liability purposes, this research will focus on the total float.

Hidden assumptions also lie in the inputs to such analysis, notably links and durations. Links (or schedule ‘logic’) are primarily determined based on technical reasons per laws of physics, but may also be modified for administrative reasons or even to artificaly generate opportunities for success or failure (Zack 1992). This research assumes that links are fixed. Durations are determined based on work quantity as taken off plan drawings and specifications, combined with the crew choice and their unit productivity. However, one must consider that forecasting durations is always loaded with uncertainty. While studies have explored distributions to provide realistic durations for probabilistic scheduling (Khamooshi and Cioffi 2013), project managers in the construction industry have not been oblivious to the need for realistic duration estimates as opposed to overly optimistic ones. In practice, how well it is accomplished depends on the expertise of individual project managers, who determine ‘raw’ durations (from productivity data) and empirically extend them to ‘realistic’ ones by including a contingency (Barraza 2011). Contingency refers to both time or cost (Xie et al. 2012), but here it means additional time. This research assumes that raw durations are known to a user of this new approach, here presumed to be the general contractor. Studies have explored how contingency aids in company performance (Deng and Smyth 2013). It “has been used in project planning to cover activities delays, oversights, and unknowns and as a cushion for possible time-estimating errors” (Barraza 2011, p. 259). Since time contingency is essentially float, it will be referred to as such for clarity. The nature, quantity, and most beneficial distribution of such contingency, or float, will be explored next.

2.2 Criticality Paradox

Whereas risk has been explored in detail, with many studies listing risk factors and how to rank or weigh them, often using survey methodologies (e.g. Tran and Molenaar 2012), its realization in form of delays has been studied primarily to create numerous competing or even contradictory approaches to distribute liability between owner and contractor (Yang and Kao 2012) after excusable delays have been forgiven, i.e. assigning blame, and pondering the vexing issue of concurrent delays (Ibbs et al. 2011). However, a posteriori analysis, while unfortunately necessary, is not even reactive, but merely inculpativ. In other words, delay liability appears has been the focus rather than delay mitigation or, even better, avoidance.

Rephrasing the definition of criticality as ‘an inability to absorb delays’ reveals that it is based upon an assumption itself, that activities in network schedules will necessarily have unequal capabilities to handle delays. However, schedulers control the manner in which activities are linked in network schedules (Zack 1992), so that criticality is essentially an artifact of the schedule itself. Criticality as it is currently defined
for critical path method is not an inherent quality of the activity based on its nature or risk, although this fact is often hidden, because long or difficult activities often actually turn out to be part of the critical path.

Artificially dividing activities into being critical or not by whether or not they have total float in fact creates a paradox (Thompson and Lucko 2012, p. 488): “By definition, noncritical subcontractors have float, but the critical ones have none, even though they need it most.” Such two classes, of which critical activities are designed to be on the verge of failure, run counter to what should be the optimum goal of a scheduler: Creating a schedule that attempts to minimize the overall risk level (or probability of local delays affecting any successor) of its activities by giving each the amount of float that it actually needs. In other words, this approach will advocate for a schedule that does not contain a ‘critical path’ in the traditional definition.

2.3 Float Ownership

Although a notion of overcoming the well-established concept of a critical path may sound ambitious, it is not out of line with project management in practice: Project managers already attempt to set contingency by considering which of the various activities ‘needs more time’. However, this is performed empirically by “subjective management of the project time contingency” (Barraza 2011, p. 260), influenced by various factors, including the contract type that is used (Smith and Bohn 1999), but lacking any rigorous scientific foundation. Thus realism and quality (in terms of predictive ability) of a schedule depend to a large degree on such an individual’s expertise. Quantifying and formalizing this wisdom is the purpose of this research.

If float can mitigate delays by being consumed, then it becomes a commodity with potential value to the project participants (de la Garza et al. 1991). A question naturally arises, who owns float? In practice the ‘first come, first serve’ approach of using float appears to prevail (Pasiphol 1994), which underlines the urgent need of a mathematical approach that is derived from a testable hypothesis. A multitude of studies in the literature has discussed float ownership, which continues to be contentious and unresolved. Among the arguments were that float should belong to the owner, who pays for a project, or the contractor, who is responsible for its schedule (Al-Gahtani 2006), and suggestions to share or split it (Prateapusanond 2003), but without any details on how it could be fairly and equitably accomplished. Splitting this Gordian knot once again can be achieved by rephrasing the initial question to overcome its implicit assumption: Who among the project participants should be allocated float, and how much? The dichotomy of owner and general contractor is not central to resolving this question, because in many cases the individual activities are performed by specialty subcontractors. As Al-Gahtani and Mohan (2007 p. 33) supported, float should be allocated by “linking the ownership with the party who carries the risk”. Subcontractors, being productive agents who perform the schedule activities, will therefore be the focus of this research.

2.4 Fair Allocation

The final step in the logical argument pertains to the question of how much? This is fundamentally an allocation problem, where float takes on the role of a valuable but limited commodity and subcontractors are competing parties who each desire to receive float to protect their individual activities against delays. Since such activities are very different, it is necessary to establish a quantitative measure of need for float (rather than binary criticality) by which the allocation can proceed to achieve a fair and equitable result.

3 RESEARCH METHODOLOGY

This research employs an analogy-adapting methodology to create a functioning mathematical approach and test its hypothesis. An unexpected intriguing analogy is found in the area of social choice (Thompson and Lucko 2011), which will be described in the following section. Different from previous work by these authors that first presented the idea; this research will compare three different possible measures of float allocation and visualize their respective performances regarding the goal of a fair and equitable allocation. The quantitative measure of need for float will use the activity duration, i.e. it is simplifyingly assumed that long activities are at a higher risk of incurring delays. While this is certainly true, characterizing the risk of delays by duration alone in practice likely is less realistic. It is envisioned that a weighted combination of e.g. duration, cost, and any other quantitative measure of relevant risk factors may be used, which will be
investigated under future research. It is assumed for the new approach that initially all durations are raw durations and that a regular calculation per the critical path method has been completed to obtain the raw project finish and a list of activities that are deemed critical. The difference between calculated raw project finish and the known contract turnover date is called contract float (\(CF\)), which is “post-CPM duration float that relates to the overall completion of the project” (Thompson and Lucko 2011, p. CN-002-7). While this approach may superficially resemble critical chain project management (CCPM) from the manufacturing industry, which intentionally accumulates all intermediate buffers into a single large one at the project finish (Steyn 2000), important differences exist, which counteract the simplistic assumptions of CCPM:

- CCPM does not explicitly distinguish raw from realistic durations, but simplistically assumes a generic 50% reduction of the planned duration to determine “the likely duration” (Zhao et al. 2010, p. 1056), which questionably assumes that on average all subcontractors inflate their estimates by as much;
- CCPM radically removes all ‘buffers’ from a schedule, even from the currently non-critical activities, into a single cumulative ‘project buffer’ (Rand 2000) at the project end, thus changing schedule dates;
- CCPM artificially and willfully generates severe criticality across a schedule, because it assumes that the subcontractors will only work timely if they have the impression that they work with zero flexibility;
- CCPM over-ambitiously seeks to minimize project duration (Herroelen and Leus 2001), but does not focus on reducing the project risk by increasing the consistency of achieving a realistic duration;
- “CCPM does not assign safety time to each individual activity” (Ma et al. 2014, p. 1), which is inverse to the philosophy new approach, and prevents determining any mathematically fair float ownership;
- CCPM reinserts ‘feeding’ buffers into non-critical paths (Rand 2000), changing schedule dates again;
- CCPM continues to ignore the critical path, whose risk has increased when all ‘safety’ was removed.

Besides such conceptual discrepancies, neither CCPM nor similar buffering approaches that were purely simulation-based (Gurgun et al. 2013, Barraza 2011) and essentially functioned by “taking off contingency buffers from individual activities and pooling them”, then “putting the resized or newly introduced buffer between activities” (Park and Peña-Mora 2004, p. 630), provided a rigorous scientific foundation for fair and equitable apportionment of buffers, or rather \(CF\). They can therefore be considered to be rudimentary attempts of solving a related ambition, but differed from the analogy-based approach that is presented in this research by turning away from, instead of improving, the vital backbone of a project – its critical path.

Note that this methodology and its assumptions and intended outcome – a project schedule ‘without’ any critical path – are not as radical as they may initially appear. Project managers already will ‘inflate’ the raw durations to what they consider realistic ones, but they do so in an individual and empirical manner. In the best case, this research will thus formalize and codify the best professional practice by providing it with a quantitative scientific foundation whose entire predictive and preventative approach can be validated.

### 3.1.1 Research Analogy

Arrow (1964) distinguished decision-making approaches into being voting (which is used in democratic systems to reach political decisions), and marketplace mechanisms (which are used in capitalist systems to reach economic decisions). Under these approaches, persons or groups engage in decision-making in several ways; e.g. dictatorially or unilaterally, forming a coalition to compose a majority of similar-minded individuals, or collective bargaining (hierarchical negotiation). Such approaches are often refined by extra rules and constraints, e.g. veto power – an ability to overrule a decision, per its Latin meaning “I forbid.”

Regardless of its detailed approach, any type of decision-making process seeks to reach a consensus by systematically aggregating many individual views. A rich body of research has examined decision-making under the heading of social choice; within it problems like fair division (of desirable assets or undesirable chores) and voting models (for parliamentary processes) have been explored mathematically. These offer analogies for the internal structure and operation of network schedule systems. Stated briefly, participants in such system (here: project) are voters (here: subcontractors), who jointly generate a decision (here: to expend float or not) by their actions (here: timely completion or delay) (Thompson and Lucko 2011). This conceptual analogy warrants investigation, especially exploring the applicability of their tenets to network schedule systems and project management in general for the problem at hand; namely float allocation.
A fundamental question emerges when participants are not of equal size (e.g. countries in the European Union), yet each of them should receive a fair weight within a decision-making process. To solve this vexing problem, two related mathematical voting models have emerged; the Penrose (1946) square root law and the Banzhaf (1965) power index. The former was inspired by the founding of the United Nations. It addressed problems of 'resolute' blocs that may dominate decisions and small nations, whose view either is irrelevant or who may become the tiebreaker. In other words, a truly fair balance is necessary to ensure that participants of small size are neither never nor always influencing the decision. Transferred newly to project management, Penrose (1946, p. 53) serves as inspiration for the new float allocation:

In general, the power of the individual vote can be measured by the amount by which his chance of being on the winning side exceeds one half. The power, thus defined, is the same as half the likelihood of a situation in which an individual vote can be decisive – that is to say, a situation in which the remaining votes are equally divided upon the issue at stake. The general formula for the probability of equal division of \( n \) random votes, where \( n \) is an even number, approaches \( \sqrt{2/n} \) when \( n \) is large. It follows that the power of the individual vote is inversely proportional to the square root of the number of people in the committee.

He distinguished voting weight (which is a simple factor) from voting power (how often a participant sways a decision). Of course, all participants should receive equal power, regardless of their size. For countries with population \( n \), a balance between the two unfair extremes of 'one vote per country' (proportional to \( n^0 \), which gives small ones too much power) versus 'one vote per person' (proportional to \( n^1 \), which gives small ones too little power) is required for a fair and equitable decision-making process (Pöppe 2007). He suggested that the newly formed General Assembly should allocate votes based on the square root (\( n^{0.5} \)) of country population. This somewhat counterintuitive principle that using direct proportionality to number of voters in each country is not the fairest possible approach remains a central insight of these studies.

Transferring this conceptual analogy to network schedules systems, political systems in representative democracies with two or more levels (federations like e.g. the United Nations, European Union, or United States) that make binary decisions provide the analogy, which correlates with critical subcontractors, who individually decide to consume their allocated float or not, and collaboratively build a project on time or not. Just as voters cast votes in an election (a decision forum), so subcontractors participate in a project with delay mitigation by deciding on the expenditure of float. “[V]oting typifies a possible determinant for the analogous behavior to those participating in large construction projects; and a potential mitigation approach to network schedule uncertainties and their impacts” (Thompson and Lucko 2011, p. CN-002-4). A question remains of whether \( n^{0.5} \) is the most appropriate value, i.e. a pure Penrose approach to float allocation, or if applying this analogy to construction projects warrants another value between \( n^0 \) and \( n^1 \).

### 3.1.2 Research Hypothesis

It is hypothesized that allocating float to the activities on the critical path based on the square root of the measure of float need leads to less need to project float than an allocation based on order zero or one.

### 4 SIMULATION CALCULATIONS

#### 4.1 Conceptual Approach

To efficiently perform the simulation calculations for the case example and derive comparisons, the entire new scheduling approach has been implemented in commercial computer software. Coding has followed a modular approach: Inputs are provided as a file that contains an activity list with name identifier for each activity as well as duration (distributions with its respective shape parameters) and point-to-point relations between the predecessors and successors that compose a network schedule. The number of repetitions of the simulation (i.e. runs) are specified separately. Output is written to another file and post-processed for analysis and interpretation. During each run the probability distribution of every activity is randomly sampled to determine its respective duration instance for one particular realization of the entire project.
Repeated simulation of a model that contains individual probabilistic variables to observe the probabilistic behavior of the entire system is known as Monte Carlo method (Chantaravarapan et al. 2004). It is often employed if the system (here a network schedule) is sufficiently complex to preclude a direct prediction of how exactly its elements will interact and cannot be solved by direct mathematical calculation. A distant conceptual relation of the new approach of this research exists to the so-called criticality index (Tang et al. 2013, p. 3238), which “is defined as the probability of an activity becoming critical”. However, several fundamental differences must be understood to contrast the criticality index with the new float allocation:

- A criticality index does not pre-allocate any contract float, neither to critical nor to any other activities;
- A criticality index is based on duration distributions for realistic durations, not raw ones, even though the former are more difficult to determine than the latter, which can rely directly on productivity data;
- A criticality index is performed within the calculated project duration, oblivious of its contract deadline;
- A criticality index analysis, using a Monte Carlo approach, tracks whether or not the critical path will pass through a particular activity within a single randomized realization of a given network schedule;
- A criticality index analysis is randomized across a single variable, the duration from the distributions;
- A criticality index analysis generates a single quantitative values to indicate a form of ‘meta-criticality’;
- The float allocation is randomized across two variables, durations and also increasing available CF;
- The float allocation generates a curve for each activity that indicates at what total CF that is available to all critical activities within a schedule said activity ceases to exceed its own allocated portion of CF.

For continuity, the case example is selected from Thompson and Lucko (2011). The left half of Table 1 lists its input with 15 activities that initially amount to a 72-day-long project from mobilization (Mob.) to turnover (T/O) per a CPM calculation of raw durations. Seven bold activities are deemed critical and will be the ones that receive float from the three allocation mechanisms. For simplicity, links have no leads or lags and no link types other than finish-to-start are used; these items will be explored in future research. In the subsequent simulation it is assumed that the duration distribution of activities has an asymmetric triangular shape with a minimum at 90% of the planned duration per Table 1 and a maximum of 125% to reflect that fact that activities rarely take shorter than planned, but often longer (Thompson 2012). Other probability distributions, e.g. beta (Fente et al. 2000), will be examined within the future research as well.

The following approach was taken for simulation. The first module performs the forward pass, backward pass, and float calculations of traditional CPM, which identifies critical activities. Afterward, it replaced the fixed planned durations with aforesaid triangular distribution and performs numerous repetitions (here 1,000) in a Monte Carlo type simulation of the now probabilistic schedule. Data analysis was performed on the list of seven critical activities only. Their actual durations as sampled from the distribution were compared per Equation 1 with the float that had been allocated, called distributed float $DF$ (Thompson and Lucko 2011) and is a portion of the contract float $CF$ itself that is available to the entire critical path.

$$\text{Actual duration} - (\text{planned duration} + \text{distributed float}) = \text{Float overrun}$$

Besides the actual duration of each activity, $CF$ was the second variable in the simulation. It was varied in integer increments between $CF = \{1 \text{ to } 40\}$ days. Efficiently, it was not necessary to re-run the simulation to count all of the individual cases of float overrun (or have sufficient float, which is of course desirable), or even to repeat it 30 times, once for each scenario of $CF$. Rather, only ‘actual duration’ in Equation 1 is randomized. ‘Planned duration’ is fixed and known from Table 1. And ‘distributed float’ depends only on the mechanism of float allocation, planned duration, and $CF$, but not actual duration. The reason for this uncoupling is that the entire approach is designed to function a priori, before actual durations are known.

Rounding presented an important challenge for float allocation, because it directly influenced how exactly the limited valuable $CF$ became $DF$ for each critical activity. It was rounded to integer days and any non-allocated single day of float was not explicitly assigned, but was left to ‘first-come, first-serve’. However, activities were rounded up so that each activity could only start at an integer time, to reflect the fact that if a subcontractor finishes before the end of a workday in construction practice, the next one will not arrive for merely a few hours, but on the morning of the next regular workday as Bashford et al. (2007) implied.
Table 1: Case Example Input and Float Allocation Output

<table>
<thead>
<tr>
<th>Traditional CPM Calculations</th>
<th>Duration(^{0.0})</th>
<th>Duration(^{0.5})</th>
<th>Duration(^{1.0})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Act. Dur. Succ. ES LS EF LF TF FF L R m s</td>
<td>L R m s</td>
<td>L R m s</td>
<td>L R m s</td>
</tr>
<tr>
<td>Mob. 7 A, B, E 0 0 7 7 0 0</td>
<td>3 11 4.80 3.85</td>
<td>4 13 5.87 3.52</td>
<td>4 14 6.34 3.82</td>
</tr>
<tr>
<td>A 19 D, I, J 7 13 26 32 6 0</td>
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<td>N/A N/A N/A N/A</td>
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</tr>
<tr>
<td>B 10 C 7 7 17 17 0 0</td>
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<td>3 16 5.62 3.65</td>
<td>3 15 5.60 3.79</td>
</tr>
<tr>
<td>C 6 D, F, J 17 17 23 23 0 0</td>
<td>3 11 4.24 3.05</td>
<td>4 14 5.43 3.32</td>
<td>5 16 6.52 3.64</td>
</tr>
<tr>
<td>D 18 L 26 33 44 51 7 7</td>
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</tr>
<tr>
<td>E 15 F, G 7 8 22 23 1 0</td>
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<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
</tr>
<tr>
<td>F 17 H, I, K 23 23 40 40 0 0</td>
<td>3 32 9.83 7.38</td>
<td>2 19 6.15 4.19</td>
<td>2 16 5.48 3.60</td>
</tr>
<tr>
<td>G 16 H, I, K 22 24 38 40 2 2</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
</tr>
<tr>
<td>H 6 M 40 53 46 59 13 0</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
</tr>
<tr>
<td>I 11 L 40 40 51 51 0 0</td>
<td>3 18 6.79 5.21</td>
<td>3 15 6.06 3.72</td>
<td>3 14 5.85 3.72</td>
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<tr>
<td>J 19 L 26 32 45 51 6 N 6</td>
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<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
</tr>
<tr>
<td>K 15 T/O 40 54 55 69 14 14</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
</tr>
<tr>
<td>L 18 T/O 51 51 69 69 0 0</td>
<td>3 32 10.69 8.36</td>
<td>2 18 6.60 4.75</td>
<td>1 15 5.17 4.04</td>
</tr>
<tr>
<td>M 10 T/O 46 59 56 69 13 13</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
<td>N/A N/A N/A N/A</td>
</tr>
<tr>
<td>T/O 3 N/A 69 69 72 72 0 0</td>
<td>3 4 3.50 0.00</td>
<td>6 9 7.56 0.37</td>
<td>9 12 11.07 0.69</td>
</tr>
<tr>
<td>Grand Average Across Activities</td>
<td>3.0 18.0 6.55 4.63</td>
<td>3.4 14.9 6.19 3.36</td>
<td>3.9 14.6 6.58 3.33</td>
</tr>
</tbody>
</table>

4.2 Results and Interpretation

Float overrun was plotted as the response variable in comparison to the CF as the explanatory variable. Figure 1 shows side-by-side the three different mechanisms of float allocation: Equal shares (planned duration\(^{0.0}\)), square root of duration (planned duration\(^{0.5}\)), and directly proportional (planned duration\(^{1.0}\)). The number of occurrences of float overrun was counted for each CF scenario and for every activity. Said counts were of course different under the three mechanisms. Shapes of the curves in Figure 1 represent the efficacy of each mechanism to protect the critical path against delays. For low CF the critical activities have not yet received sufficient DF to be individually protected. This explains the ‘plateau’ of their curves in the left half of the diagrams: While on this plateau, activities will consume more float than they own, or have not even received any DF yet. The latter is due to the fact that only integer days of CF become DF; and until the CF exceeds the number of critical activities, critical activities exist that have an allocation of zero. Next, activities experience a more or less steep drop-off or ‘cliff’, as float shows its powerful effect in absorbing any delays locally. If all activities will remain within their DF, the entire project will not exceed its planned raw duration plus CF. For each activity, a relatively narrow range exists, where DF changes from insufficient (on average) to sufficient (on average). After this cliff, a lower plateau is reached in the right half of the diagrams, where activities have excess DF and the project contains more CF than is needed.

To capture the cliff behaviour, which is of vital interest for this analysis, these parameters were calculated from the data and listed in Table 1: Left and right cutoffs \( L \) and \( R \) (the right edge of upper plateau and the left edge of lower plateau), and within this range a weighted mean \( m \) and weighted standard deviation \( s \) on the horizontal axis, which indicated where and how narrow the cliff was. For example, if an activity has a result of \( y = \{10, 10, 1, 0, 0, 0\} \) counts of overrun for \( x = \{0, 1, 2, 3, 4, 5\} \) days of CF, then \( L = 1; R = 3; m = [9 \cdot (2 - 1) + 1 \cdot (3 - 2)] / (9 + 1) = 1.6 \) (weighted by drops \( \Delta y \) within their integer ranges of \( x \)); and \( s = \sqrt{[9 \cdot (1.5 - 1.6)^2 + 1 \cdot (2.5 - 1.6)^2] / [10 \cdot ((2 - 1)/2)]} = 0.42 \) (average weighted distance of the integer range midpoints to \( m \)). Note that both \( m \) and \( s \) are only calculated across a cliff itself, not the plateaus besides it.
The ranges of $L$ and $R$ and weighted grand averages and standard deviations across all critical provided a quantitative comparison of the efficacy of the three mechanisms. The equal shares (planned duration$^{0.0}$) has a wide range {3.0 to 18.0} within which all activities exhibit their drop-off behaviour, a weighted mean of 6.55, and a weighted standard deviation of 4.3, which indicates a merely gradual saturation of critical activities with their urgently needed $DF$. This approach is not recommended, due to being oblivious to the relative risk of activities, which here is represented by the proxy of duration. More interesting is comparing square root (planned duration$^{0.5}$) versus proportional shares (planned duration$^{1.0}$) approaches of Figure 1. The former has a narrower average range {3.4 to 14.9} of width 11.5 for all critical activities per Table 1; the latter is even slightly narrower {3.9 to 14.6} of width 10.7. Weighted means and standard deviations give a more distinct view: The former has a weighted mean of 6.19 compared to 6.58 of the latter. Clearly the square root model on average provides all critical activities earlier with the $DF$ that is needed to satisfy their need. In fact, $m$ is almost identical for (a) and (c) in Figure 1, which supports the hypothesis that (b) is the balance approach between these extremes. Finally, weighted standard deviations compare nearly identical at 3.36 versus 3.33 per Table 1. Both are much lower than $s = 4.63$ for (a). Testing for statistical significance at an alpha-level of 0.05 finds the difference between means not significant; however, this is most likely due to the very small case example with only seven different activities. More experimentation is therefore needed to substantiate the positive indications of the square root approach for float allocation.

5 CONCLUSIONS AND RECOMMENDATIONS

This research has presented a vision for overcoming the long-standing and deeply entrenched paradigm within construction project scheduling by uncovering its various implicit assumptions. They have included focusing excessively on dissecting risk factors on the one hand and delay liability on the other hand; not explicitly distinguishing raw from realistic durations and basing criticality assessment on the latter, not the former; and artificially creating a paradoxical two-class society of critical versus non-critical activities that actively contradicts any desire to minimize the overall risk level. It is thus understandable that previous approaches to float ownership failed to solve the true underlying issue – minimizing risk by mitigating delays. This research stipulated that all critical activities should receive float, not by directly inserting it from its location between calculated and contract finish to being distributed along the critical path within a network schedule itself, but rather by providing an unambiguous approach to calculate optimum portions of ownership. This new approach is based on the premise that a directly proportional allocation to ‘size’ of the critical subcontractors’ contributions to the project would not fulfill the overall goal of being fair and equitable. Rather, three cases have been tested for numerical comparison; an allocation based on equal shares ($n^0$), the square root of size – or risk – ($n^{0.5}$), or proportional shares ($n^1$). Initial results are positive, but not statistically conclusive between the square root approach or proportional shares of float allocation. More experimentation with larger and more realistic examples of network schedules is recommended.
This research aids in fulfilling the unrealized vision of “Total Float Traded as Commodity” (de la Garza et al. 1991, p. 716). Only that it will not be the $TF$ of non-critical activities, but $CF$, and that it will be designed to benefit critical activities. And that it will require having completed a pre-allocation of $CF$. Combined with the creative analogy from voting mathematics, which provides the seminal inspiration for how to achieve a provable fairness between large and small subcontractors who compete for $CF$, a market of opportunities can emerge. More research is necessary on how to determine dollar value, which should be listed in the contract to give all subcontractors certainty. Future research should investigate how the emphasis that is placed on measures of ‘size’ – whether it is duration, cost, risk (depending on type and nature of activity) – can be weighted and converted into a single numerical metric (Thompson and Lucko 2011). The current approach has merely assumed that a numeric value of risk (or size) is available as input. Closely related to this, it should also be examined how the potentially different subjective monetary valuations of $CF$ by said contractors can be aggregated. Further analogies from areas of knowledge besides construction project management should be parsed to identify proven concepts that can handle subjective valuation.

Acknowledgements

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References


STUDY OF THE INFLUENCE OF PORTLAND CEMENT ON THE PROPERTIES OF CONCRETE WITH FLY ASH

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Abstract: Concrete made with Portland cement is one of the most used construction material in the world. Engineers and scientists are always looking to improve its sustainable properties. The durability of concrete is a determining factor in the service life of a structure. The durability of cement based materials is strongly influenced by its porous structure. Previous research has shown that the use of fly ash in concrete mixtures as partial substitution of Portland cement produces a pozzolanic reaction that changes concrete’s micro-structure. As a concrete mineral admixture, fly ash improves concrete’s mechanical properties and durability while providing economic and environmental benefits. The objective of this paper is to present the results of a study that investigated the influence of fly ash on the durability of concrete mixed with ASTM C150: Type I cements. The methodology included mixing three different ASTM C 150: Type I cements with three different percentages of fly ash each for a total of 9 different combinations. Durability, physical, and mechanical properties tests were performed on the concrete samples from each mix. The results indicate that the performance of concrete with fly ash varies based on the characteristics of the cement used and the amount of fly ash used in the mixture. Based on the results of this study, it can be concluded that the best result for experimental concrete with 25% fly ash substitution were obtained with concrete Y (C3S = 55.31%), while with 50% fly ash substitution the best results were obtained with cement Z (C3S = 77.04%). These combinations increase the concrete’s durability while reducing costs and providing environmental benefits. This paper contributes to the body of knowledge by increasing the understanding of the influence of cement properties in fly ash on the durability of concrete.

1 INTRODUCTION

Many concrete structures require repairs or reconstruction before reaching their expected service life. In the United States, the annual cost of repairs to parking structures and bridges exposed to de-icing salts has been estimated in a range between 325 million and 1 billion dollars (Kelting and Laxson 2010). According to Fernández Cánovas, placing good quality concrete is the best way to protect the steel reinforcement embedded in it. To reduce the costs of repairs and replacement of structures most experts coincide that the concrete durability must be improved (Fernández Cánovas 2004).

The American Concrete Institute (ACI) defines concrete durability as the ability to maintain its shape, quality, and utility under the exposure conditions for which it was design throughout their expected life span. The deterioration mechanisms such as expansion, retraction, or ionic penetration into the concrete are related to the exposure conditions (ACI 2008). Puerto Rico is an island, and the most relevant
exposure condition for concrete structures is the marine exposure, where chloride ions attack is the most aggressive.

It is widely known that fly ash as a mineral addition to concrete has positive effects on the concrete durability. Among the many benefits of using fly ash, its reaction with portlandite produces additional calcium silicate hydrate (C-S-H) gels (Pihlajavaara and Paroll 1995). Calcium silicate hydrate (C-S-H) gels are the main responsible for cohesion and mechanical properties of concrete. These additional C-S-H gels refine the porous network of concrete, providing additional protection against environmental exposure attacks, like the penetration of chloride ions. At the same time the formation of these secondary C-S-H gels consumes Portlandite, which is the most leachable compound of the hydrated cement. As a result the durability of the material is considerably improved (Naik and Hossain 1994), (Lorenzo García 1993).

Other benefits of using fly ash in concrete are pecuniary and environmental. Fly ash is usually less expensive than Portland cement, making the mixture with fly ash more economical than a mixture by using Portland cement only (Federal Highway Administration 2011). Some of the environmental benefits are the reuse of a by-product of energy production and the reduction of Portland cement production. This last aspect is very important as with a reduction of cement production, the energy required is reduced as well as the CO₂ emissions to the environment (Burden 2006). Also, the use of fly ash as an addition to concrete can help earn credits for the Leadership in Energy & Environmental Design (LEED) certification (King 2005).

In general terms, the effects of fly ash in concrete are widely known, but the effects of fly ash when used with the cements available locally are unknown. In Puerto Rico there are three brands of cement type I commercially available. All of them comply with the specifications of ASTM C150. Even though all of them are classified type I, each one has different chemical and physical properties. The main objective of the present work is to better understand the influence of the durability and mechanical properties of concrete of each type of Portland cement when a partial substitution of fly ash is introduced.

2 METHODLOGY

2.1 Materials

In this research, the materials utilized were those available for commercial use in Puerto Rico. The cements used are classified as type I according to the ASTM C150. They are distributed by Antilles Cement Corporation, Cemex Puerto Rico and Essroc San Juan. For each one of the three cements used, a chemical and mineral composition analysis was conducted according to the standard ASTM C114. The distribution of particle size was determined according to the standard ASTM C204. Tables 1 and 2 summarize the mineral and chemical composition for each cement used; these were denominated X, Y and Z.

The fly ash used in the study has a Type F classification according to ASTM C618, distributed in Puerto Rico by Ecológica Carmelo. The chemical composition analysis for fly ash was made according to ASTM C114. Table 3 shows the summary of the chemical composition of the fly ash used.

The coarse aggregates used are of siliceous origin, crushed with a maximum diameter of 20 mm (3/4"). The fine aggregates used are crushed limestone with a fineness modulus of 3.02. The particle size analysis of aggregates was conducted in accordance with the standard ASTM C33.
### Table 1: Partial mineralogical composition of used cements

<table>
<thead>
<tr>
<th>Mineral composition</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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</thead>
<tbody>
<tr>
<td>C₃S</td>
<td>74.82</td>
<td>55.31</td>
<td>77.04</td>
</tr>
<tr>
<td>C₃A</td>
<td>5.40</td>
<td>11.04</td>
<td>8.10</td>
</tr>
</tbody>
</table>

Source: Cement Chemistry Laboratory, Essroc San Juan

### Table 2: Chemical composition of used cements

<table>
<thead>
<tr>
<th>Chemical compound or property</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>19.47</td>
<td>20.29</td>
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<tr>
<td>Al₂O₃</td>
<td>4.54</td>
<td>6.40</td>
<td>4.75</td>
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<tr>
<td>Fe₂O₃</td>
<td>3.92</td>
<td>3.51</td>
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<tr>
<td>CaO</td>
<td>65.62</td>
<td>65.13</td>
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<tr>
<td>MgO</td>
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<td>1.86</td>
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<tr>
<td>SO₃</td>
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<td>K₂O</td>
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<td>Na₂O</td>
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<td>P₂O₅</td>
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<tr>
<td>TiO₂</td>
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<tr>
<td>SrO</td>
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<td>0.03</td>
<td>0.15</td>
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<tr>
<td>ZnO</td>
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<td>0.01</td>
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<td>Mn₂O₃</td>
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<td>0.04</td>
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<tr>
<td>LSF</td>
<td>105.142</td>
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<td>109.685</td>
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<tr>
<td>Silica Ratio</td>
<td>2.301</td>
<td>2.047</td>
<td>2.551</td>
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<tr>
<td>Aluminium Ratio</td>
<td>1.159</td>
<td>1.826</td>
<td>1.788</td>
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<tr>
<td>LOI</td>
<td>1.65</td>
<td>3.13</td>
<td>7.12</td>
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<td>Blaine</td>
<td>374</td>
<td>394</td>
<td>526</td>
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</table>

Source: Cement Chemistry Laboratory, Essroc San Juan

### Table 3: Chemical composition of the fly ash used

<table>
<thead>
<tr>
<th>Chemical compound or property</th>
<th>Fly Ash</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>53.84</td>
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<tr>
<td>Al₂O₃</td>
<td>36.64</td>
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<tr>
<td>Fe₂O₃</td>
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<td>CaO</td>
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<tr>
<td>MgO</td>
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<tr>
<td>SO₃</td>
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<td>Na₂O</td>
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<tr>
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<tr>
<td>TiO₂</td>
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<tr>
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</tr>
<tr>
<td>LSF</td>
<td>1.04</td>
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</table>
2.2 Dosages

The ACI Committee 211 method was used for the concrete mixture design. The reference concrete had 426.6 kg of cement and a water/binder ratio of 0.65. For the experimental concrete, Portland cement was substituted with fly ash by 25 and 50 percent. Table 4 shows the material amounts required for each dosage to produce a cubic meter of concrete.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Cement (kg)</th>
<th>Fly ash (kg)</th>
<th>Water (kg)</th>
<th>Coarse Aggregate (kg)</th>
<th>Fine Aggregate (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref (0% Fly ash)</td>
<td>426.6</td>
<td>0.0</td>
<td>277.3</td>
<td>992.4</td>
<td>661.6</td>
</tr>
<tr>
<td>25% Fly ash</td>
<td>319.9</td>
<td>106.7</td>
<td>277.3</td>
<td>992.4</td>
<td>661.6</td>
</tr>
<tr>
<td>50% Fly ash</td>
<td>213.3</td>
<td>213.3</td>
<td>277.3</td>
<td>992.4</td>
<td>661.6</td>
</tr>
</tbody>
</table>

For each Portland cement type used in the study, one reference batch and two experimental batches were mixed, reaching a total of nine batches. In all cases a concrete mixer with 0.38 m$^3$ of capacity was used. Each batch had a volume of 0.11 m$^3$ that produced 10 cylindrical specimens of 15 cm (6 in) diameter and 11 cylindrical specimens of 10 cm diameter (4 in). The process of mixing and curing was executed according to ASTM C192.

2.3 Testing

The specimens were subjected to different tests in order to characterize the concrete properties of all batches. The mechanical behavior was characterized by the compressive strength. In order to study the durability of the concrete rapid chloride permeability tests were conducted. Finally, to characterize the physical properties of the porous network mercury intrusion porosimetry and air permeability tests were performed, both of them in turn directly related with concrete durability. Table 5 summarizes the results of testing, the age of the specimens at the time of testing and the name of the standard procedure followed for each test.

<table>
<thead>
<tr>
<th>Test</th>
<th>Age of specimen at time of test (days)</th>
<th>Test standard</th>
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</thead>
<tbody>
<tr>
<td>Compressive strength test</td>
<td>X X X X</td>
<td>ASTM C39</td>
</tr>
<tr>
<td>Rapid chloride permeability test</td>
<td>X X X</td>
<td>ASTM C1202</td>
</tr>
<tr>
<td>Mercury intrusion porosimetry</td>
<td>X</td>
<td>ASTM D4404</td>
</tr>
<tr>
<td>Air permeability</td>
<td>X</td>
<td>UNE 83966</td>
</tr>
</tbody>
</table>
3 RESULTS

The results of the rapid chloride permeability tests are shown in Figures 1 to 6. Figures 1 to 3 show the passing charge of each concrete batch according to its percentage of fly ash substitution. In figures 4 to 6 the results are shown in accordance to the Portland cement mineralogical composition.

Figure 1: RCPT of concretes with cements X, Y, Z and 0% of fly ash substitution by cements X, Y, Z and 25% of fly ash substitution

Figure 3: RCPT of concretes with cements X, Y, Z and 50% of fly ash substitution

Figure 4: RCPT of concretes with cement X
Reference concretes show high permeability at all ages. Experimental concretes (with fly ash) have higher resistance to chloride ion permeability, especially during a long-term period. After analyzing the performance depending on the cement type, those mixtures with 50% of fly ash substitution improved their resistance to chloride ion permeability in all cases, although the results in the case of cement X were a little worse.

Figures 7 to 9 show the results of the compressive strength tests of concrete cylinders according to the percentage of fly ash substitution. Figures 10 to 12 show the results according to the cement mineralogical composition.
At early ages, the reference concretes show higher compressive strength than concretes with fly ash substitution. In all cases the best results were obtained by concretes mixed with cement Y.

Concretes with 25% of fly ash substitution reach the values of compressive strength of the reference concretes as time progresses. Concretes with 50% of fly ash substitution did not reach the values of compressive strength of the reference concrete at any age.

The results of the analysis of the physical properties of the concretes are presented in figures 13 to 19. Figures 13 to 18 show the results of the mercury intrusion porosimetry tests. The results are arranged by percentage of fly ash substitution and by cement type utilized. Figure 19 compares the volume of accumulated intrusion in macropores and mesopores of all concrete batches. Figure 20 shows the results of the air permeability tests.
The lowest mercury intrusion volumes were obtained with concretes mixed with cement \( Y \), as was the case in the compressive strength results. The best result obtained was the experimental concrete with 25% of fly ash substitution of cement \( Y \).

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**Figure 15**: Accumulated intrusion volume of concrete with cements \( X, Y, Z \), and 50% of fly ash substitution

**Figure 16**: Accumulated intrusion volume of concretes with cement \( X \)

**Figure 17**: Accumulated intrusion volume of concretes with cement \( Y \)

**Figure 18**: Accumulated intrusion volume of concretes with cement \( Z \)
Figure 19: Volume of accumulated intrusion of macropores and mesopores

In all cases of concretes mixed with cement Y, both the reference and experimental concretes, obtained the lowest volume of intrusion in macropores. The lowest volume of intrusion in macropores occurred in concretes with 50% of fly ash substitution.

Figure 20 compares the permeability to air constant for all concrete batches, arranged by the percentage of substitution by fly ash.

Figure 20: Permeability to air constant (average) of concretes with cement X, Y, Z

In reference concretes, the type of cement used in the mix does not affect the air permeability. On the experimental concretes variations were observed depending on the type of cement used for the mixture. The behavior of the results does not coincide with other tests carried out.
4 CONCLUSION

This study proves that the performance of concrete with fly ash varies based on the characteristics of the cement used and the amount of fly ash used in the mixture. Based on the results of this study, it can be concluded that the best result for experimental concrete with 25% fly ash substitution were obtained with concrete Y ($C_3S = 55.31\%$), while with 50% fly ash substitution the best results were obtained with cement Z ($C_3S = 77.04\%$). These combinations increase the concrete’s durability while reducing costs and providing environmental benefits.

The reference concretes have high permeability to chloride ions at any age. When compared by type of cement, concretes with the highest percentage of fly ash substitution performed better on the RCPT. This coincides with previous investigations. All experimental concretes improved their performance in RCPT and compressive strength test with age. Fly ash refined the porous structure of concretes. The porosimetry results show that in experimental concretes the accumulated volume in macropores decreases and the accumulated volume in mesopores increases when compared with reference concretes. The results show that even when all the cements used comply with type I classification according to ASTM C150, there is a tendency to performance variation of the concretes mixed with cement with different mineralogical composition.

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DEVELOPMENT OF AN AUTOMATED 3D/4D AS-BUILT MODEL GENERATION SYSTEM FOR CONSTRUCTION PROGRESS MONITORING AND QUALITY CONTROL

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Abstract: Automating the progress monitoring and control process is of great interest to industry practitioners to help improve the limitations associated with the current manual data collection and analysis practices. Two remote sensing technologies, namely, Light Detection and Ranging (LiDAR) and digital camera, are widely used to acquire 3D point clouds as a means of measuring the “scope of the work performed” of structural elements. However, to assign the collected 3D point clouds to their corresponding structural element, current object-based recognition models use the as-planned 4D model, which may not be reliable in cases where the locations of the as-built structure differ from those of the planned, and/or the planned 4D model is not available with sufficient detail. Here, a novel method is proposed to eliminate the dependency on the as-planned data by automatically generating the 3D/4D as-built model through a robust Principal Component Analysis-based (PCA) segmentation algorithm. The proposed system is also independent of the technology used to capture the 3D point clouds. To evaluate the reliability of the proposed automated as-built model generation procedure, two sets of LiDAR data from the "Mechanics of Materials" laboratory and the "Graduate Student Hall of Residence" construction site at the University of Calgary were collected. A novel method of automated registration of the as-built model to the planned model coordinate system is also proposed through which the compliance of the planned vs. actual dimensions of corresponding structural elements are examined. The results of the two experiments demonstrate the applicability of the proposed methods for the automatic generation of the 3D/4D as-built model and the dimension compliance control of structural elements.

1 INTRODUCTION

Project monitoring and control are vital to facilitate decision makers identify deviations between the planned vs. as-built states of the project and take timely measures where required (Maalek and Sadeghpour, 2012). Monitoring is the process of collecting onsite data as a means of measuring the Project Performance Indicators (PPI). Traditionally, onsite data are collected manually, a time consuming, error-prone and labor intensive task particularly on large scale projects (Golparvar-Fard et al. 2009a). In practice, to justify the time and cost associated with such manual approaches, a limited amount (and/or frequency) of onsite data are collected, which diminishes the ability of the project manager to identify the causes of delays and cost overruns on time. In addition, most onsite data collection processes are anecdotal without a proper monitoring plan/strategy (Golparvar-Fard et al. 2011), which influences the time, cost and reliability of the collected PPIs.
Project control involves the processing of the accumulated data for the determination of the performance of the current state of the project. Therefore, the reliability of the determination of the performance of the project is highly dependent on the strategy as well as the accuracy of the collected data during the monitoring process (Saadat and Cretin, 2002). Currently, site supervisory personnel spend 30-50% of their time on manually monitoring and controlling onsite data (McCullough, 1997, Golparvar-Fard et al. 2009). If this time is reduced by means of a novel approach to onsite data collection and analysis, more time can be allocated to improving vital construction related concerns such as safety (Maalek & Sadeghpour, 2011), and workforce productivity and communications (Choy and Ruwanpura, 2007). Therefore, automating the monitoring and control process is proposed in recent years to help overcome the aforementioned limitations of current manual practices.

2 LITERATURE REVIEW

The percentage of completion of an activity is suggested as the Key Performance Indicator (KPI) capable of providing progress information in activity-level (Maalek et al. 2014). In order to automatically extract this metric, the scope of the work performed for each activity is required to be identified by means of a remote sensing technology. Currently, two remote sensing technologies, namely, digital camera and LiDAR, are widely used to generate 3D coordinates of the surrounding surfaces. The overview of the previous research related to the application of these two technologies for progress monitoring of construction activities are presented in the following.

2.1 Digital Camera

In practice, photographs are commonly taken to record the progress of specific activities and/or to help minimize disputes/claims (Golparvar-Fard et al. 2009a). These images are stored without proper documentation and indexing (Brilakis et al. 2006). In addition, the KPIs are manually extracted from the large number of unordered/randomized images, constituting a costly, lengthy and challenging procedure. Current research aims at improving these aspects by means of automating the extraction of meaningful information from the accumulated images. These research studies can be subcategorized into two groups, namely, those using a single pre-calibrated fixed-location camera, and those using multiple cameras to determine the 3D coordinates of the surrounding surfaces.

2.1.1 Single fixed-location camera

Using a single camera at fixed locations, it is not possible to determine the 3D coordinates of the structural elements (Rougier and Meunier 2010); however, some researchers have innovatively used time-lapsed images to determine the completion and production rate of certain construction activities. Lukins and Trucco (2007), Zhang et al. (2009) Ibrahim et al. (2009) aimed at determining the completion of certain activities on site by detecting the changes between consecutive images. Golparvar-Fard et al. (2009a) aimed at visually identifying the deviations between the plan and the actual states of the construction work by means of color-coding the identified differentiations. Ranaweera et al. (2013) developed a system to automatically determine the productivity of tunnel construction by identifying the number of liners lowered into a tunnel during a shift.

2.1.2 Multiple cameras

As mentioned in the previous section, it is not possible to quantify the “scope of the work performed” (i.e. the progress) of construction activities using a single camera. In addition, since construction sites are dynamic environments with many moving objects, the presence of newly added obstacles may block the Line-Of-Sight (LOS) of the camera. Therefore, additional cameras are required to correctly determine the progress of construction activities. At least two camera exposures taken from different locations are required to estimate the 3D coordinates of a point relative to the image coordinate system using collinearity equations and triangulation (Kraus, 1993). In order to determine the position and orientation of each exposure station, at least three (3) tie-points (point correspondences) are required per image. Recent research studies aim at automatically matching similar features (tie-points) from unordered construction site photographs to generate the 3D coordinates of the surrounding surfaces (point clods).
Golparvar-Fard et al. (2009b, 2011a, 2011b, and 2015) developed an automated progress monitoring system, called D4AR, which uses the accumulated unorganized photographs to determine the 3D coordinates of structural elements on site. The system uses a dense pixel to pixel matching algorithm to link the similar features between every two image to create a 3D point cloud of the site at the time the monitoring is performed. The system then estimates the translation and rotation of each of the camera exposures with an arbitrarily defined scale via a bundle adjustment. The scale of the measurement is then identified by manually registering some corresponding key points from the planned to the as-built space. At least three point correspondences are required to solve for the seven parameters (including scale; Horn, 1987). It is to emphasize that the manual registration is mandatory since the true 3D coordinates of the point clouds can only be estimated if the scale is defined with respect to the true space. However, the method assumes that the 3D coordinates of the selected key points remain unchanged between the as-built and the as-planned models. In other words, the potential errors in construction are neglected. Therefore, it is likely that the expected accuracy of the generated 3D coordinates drops since construction errors may cause differences between the as-planned and the as-built structure, which consequently affects the scale of the measured point clouds. In order to overcome this challenge, the correctly-scaled coordinates of the key points should ideally be measured by means of an external measurement system (such as a reflector-less total station or a scale bar), which increases the time and cost of data collection as well as possibility of interruption with construction activities. In (Golparvar-fard et al, 2011a, 2011b and 2015), the constructed point clouds from the D4AR system, proposed above, are assigned to their corresponding structural elements by superimposing the as-planned 4D BIM model to the constructed point clouds.

As indicated above, at least two camera exposures are required to estimate the 3D coordinates of a point. Considering the limited Field of View (FOV) of a camera, a large number of manual photographs must be captured in order to cover every structural element on the site at least twice, which increases the time and cost of onsite data collection and analysis (Maalek et al. 2014). In addition, finding point-to-point correspondences between every image pair requires additional processing. In Golparvar-fard et al. (2011a), the processing of 288 images, constructing only 62,000 points, is shown to take approximately 7 hours. Furthermore, the quality of the images taken by a camera is a function of the lighting conditions and thus the accuracy of the generated point cloud can be highly affected by the lighting conditions (Golparvar-fard et al. 2011a). To summarize, the large number of images required due to limited FOV, the additional processing time due to the correspondence problem between the accumulated images and the need for adequate illumination (Dario et al. 2013) has led researchers to use LiDAR to help overcome the aforementioned limitations of implementing cameras on construction sites.

2.2 LiDAR

LiDAR is a remote sensing technology used to collect 3D coordinates of the surrounding surfaces in LOS using only a single scan-station without additional processing (i.e. directly). In addition, LiDAR is more likely to achieve more accurate data compared to those provided by photogrammetry (Golparvar-Fard et al. 2011b and Bhatla et al. 2012). Therefore, the feasibility of preparation of as-built 3D/4D models using LiDAR technology has been of great interest to researchers in recent years.

In the work of (Bosché, 2010, Bosché et al. 2009, 2015, and Turkan et al. 2013), the as-planned 4D CAD model is used to assign the accumulated point clouds to their corresponding structural elements. In their approach, first, the collected point clouds are manually registered to the planned model coordinate system. For each registered scan-station, the point clouds corresponding to the planned model are then generated by considering the potential random errors associated with the LiDAR equipment. If the distance between the two points is smaller than a threshold, the two points are equivalent. For the corresponding points, the Iterative Closest Point (ICP) registration is used to improve the results of the manual registration. In (Turkan et al. 2013), an earned value analysis on the data captured and processed in (Bosché, 2010) was performed. The point clouds were assigned to their corresponding structural elements; however, the “scope of the work performed” for each object was determined manually, which is a time consuming process, especially for in large scale construction projects. In (Bosché et al. 2015), the same procedure presented above was used to first generate the 3D as-planned point clouds on a piping project. A 3D Hough transform was then performed on both the as-planned and
as-built point clouds to determine the circular cross sections. These cross sections were then matched to identify the dimension compliance, location and the completion of the pipes. Zhang and Arditi (2013) also used the as-planned model in order to determine the completion of an object by counting the number of point clouds inside two predetermined boundaries, representing the tolerance region, of the object. Kim et al. (2013) also used the as-planned 4D Building Information Model (BIM) in order to report the progress of construction activities. In their approach the use of connectivity between components as well as sequence of activities were suggested in order to improve the classification results and to deal with misclassifications caused by missing data.

2.3 Some Limitations of Current State of Research

Current object-based recognition models use the planned 4D model as a-priori knowledge to assign the collected 3D point clouds to a structural element (Golparvar-Fard et al. 2009a, 2011a, 2012, 2015 and Bosché et al. 2009, 2015; Bosché, 2010; and Zhang and Arditi 2013), which may not be reliable in cases where the locations of the as-built structure differ from those of the planned (Shahi et al. 2013) or the Issue for Construction (IFC) plan with sufficient detail is not readily available. In other words, the assumption that there are no significant deviations between the as-built and the as-planned states of a project is contradictory to the nature of monitoring and control. In order to reduce this dependency on the details of the planned model, here, it is proposed to summarize the information carried by the accumulated point clouds (regardless of the method the point clouds are generated) into meaningful information that is comparable to the details presented in the planned model (not vice versa). The procedure is explained in more detail in the following sections.

3 OBJECTIVE AND METHODOLOGY

As mentioned previously, the goal of this research is to automatically summarize the accumulated point clouds into vertices that represent the boundaries of the structural elements, which can be used to determine the scope of the work performed. In other words, a novel method is proposed to automatically generate the 3D as-built model of structural elements. For this matter, the geometric primitives (only the 3D coordinates) are used to determine structural vertices from the collected point clouds. The procedure is as depicted in Figure 1. Each element of Figure 1 is explained in more detail in the following sections.

Figure 1: Point clouds summarization into meaningful vertices

3.1 Point Cloud Classification

Point cloud classification is the process of labeling points with similar physical attributes into predefined classes. Since the most generic building elements as well as most man-made objects (Nunnally, 2010; Vosselman et al. 2004) are constructed from the intersection of planar surfaces, the classification of point clouds into planar surfaces is the major focus of this study. There are two methods commonly used to classify point clouds into planar surfaces, namely, the Hough transform and Principal Component Analysis (PCA). However, the use of Hough transformation for planar classification is computationally expensive and the results of the classification are highly affected by the presence of outlying data (Lari, 2014). Therefore, PCA-based classification is used in this study.

PCA is used to summarize the variation of a multivariate data set into independent (orthogonal) axes. These axes are regarded as the principal components. The magnitudes of these axes represent the variation of the data set in the direction of the axis. This is accomplished by decomposing the covariance matrix of the data set into its eigenvalues and eigenvectors. In case of a 3-dimensional data set such as a point cloud, three orthogonal axes can be determined, which represent the maximum variations of the data set. For noise-free, coplanar points, the data has no variation in the direction of the surface normal. In other words, the eigenvalue corresponding to the direction of the surface normal is equal to zero. For
this matter, many researchers have used PCA for the classification of planar surfaces (Lari, 2014). First, a neighborhood is defined around each point cloud. The PCA is performed on the pre-defined neighborhood of each point. If the pattern of the neighborhood of the desired point forms a planar surface (i.e. smallest eigenvalue is close to zero), the point is classified as a plane. This can be further illustrated in Figure 2.

Figure 2: Classification of accumulated point clouds into planar surfaces

The classification of point clouds into planar surfaces is trivial in ideal, controlled conditions with no data contamination. However, in a construction, due to the data artifacts caused by moving objects, occlusions and dust, outliers are present in the data. The classical method of PCA, which uses the classical estimate of the covariance matrix, is highly sensitive to outliers (Hubert et al. 2012). Therefore, in order to help reduce the effects of outliers on the underlying pattern of the data, the Deterministic Minimum Covariance Determinant (DetMCD) estimate, proposed by Hubert et al. (2012), is used here to robustly estimate the covariance matrix of the data.

3.2 Point Cloud Segmentation

Segmentation is the process of grouping the points of a certain class that possess similar attributes. To segment the classified point clouds with similar characteristics, two methods are generally used namely, region growing and clustering. Region growing methods are widely used due to their computational efficiency; however, they are not considered as robust methods since the results of the segmentation is dependent on the selected initial seed point (Wang and Shan, 2009; Lari, 2014). Therefore, clustering methods are used in this research to provide more robust segmentation results.

Generally, there are four main clustering algorithms presented in (Jain and Dubes, 1988). In the research carried out by Milligan and Isaac (1980), the complete linkage method was shown to be more efficient than the others in identifying compact clusters. In this research, an iterative planar clustering method is proposed, using a novel robust complete linkage method, in order to robustly determine planar clusters from unorganized point clouds.

3.2.1 Boundary Detection to Ensure Surface Continuity

Using the proposed clustering algorithm, it is possible to clustered coplanar point which are spatially discontinuous. In order to enforce surface continuity within each cluster, the boundary points of each cluster is determined using the modified “convex hull” algorithm proposed by Sampath and Shan (2007). This approach ensures that the disconnected surfaces are segmented into different clusters.

3.2.2 Robust Plane Fitting

After the boundary detection, each cluster contains coplanar point clouds from continuous surfaces. All the information carried by the points within a planar cluster can hence be summarized into a normal vector and a point, which represent the plane parameters of the cluster. The robust PCA using the Deterministic MCD is used to robustly estimate the aforementioned plane parameters. The robust PCA ensures that local surface roughness due to construction errors and/or outlying data do not affect the result of the plane fitting.

3.3 Surface Intersection

As indicated in Section 3.1, most common structural elements are constructed by the intersection of planar surfaces. The method proposed above can theoretically determine the planar facets of structural
elements on a construction site. Therefore, to determine the vertices of these types of structural elements, the closest planes are required to be intersected. For this matter, the planes whose boundaries are closer than the pre-defined threshold are first identified. The line of intersection of every pair of adjacent planes is then calculated. The neighboring points on the two planar clusters are then projected on the intersecting line. The upper bound and the lower bound of the line will be determined based on the position of the projected points. For the two end points of every identified line-segment, the closest end points of the remaining line-segments (within a threshold) are determined. The closest lines are then intersected in order to refine the end points of the line segments. The resulting end points are the vertices of the object of interest.

4 EXPERIMENTS

In Section 3, a fully automated method was proposed to robustly determine the boundaries of structural elements that are constructed from the intersection of planar surfaces. In this section, two experiments designed to assess the effectiveness of the proposed method for automatic 3D as-built model generation are described.

4.1 Monitoring Technology

The benefits of LiDAR to photogrammetry in generating 3D point clouds of the surrounding surfaces were outlined in Section 2.1.2. In addition, the resolution achieved by photogrammetry may not be sufficient to accurately classify and segment the acquired point clouds”. Therefore, LiDAR is the preferred alternative to generate 3D coordinates of the surrounding surfaces (Maalek et al. 2014). The Leica HDS6100 is used in this study to capture the required data. This device has the ability to collect up to 508,000 points per second (Leica, 2009).

4.2 Experiment 1: Mechanics of Materials Laboratory

Using the Leica HDS6100, one set of LiDAR data, consisting of three scan-stations, was collected from the Mechanics of Materials laboratory at the University of Calgary (Figure 3). As illustrated in Figure 3a, the laboratory consists of many obstacles and metallic tables, which may increase the possibility of occlusions as well as loss of accuracy due to multipath reflection. Therefore, it may be considered as a fair representation of an actual indoor construction site. Approximately 30 million 3D points of the interior surfaces were recorded from the three scan-stations. The total data collection time was less than 15 minutes for all scan stations. As illustrated in Figure 3b, the lab consists of 26 different walls. The elevation of the ceiling relative to the floor is 2.7 m. The planned model suggests that the roof, floor and the surrounding walls are planar surfaces. The plot of the plan of the site represents a concave polygon.

![Figure 3: a) "Mechanics of Material" laboratory; b) plan view of the laboratory](image-url)
4.2.1 Floor and Flat Slab Ceiling Extraction

Here, a method is proposed to identify and extract the points on the floor and the flat slab ceilings without performing a robust PCA. This is especially beneficial to help reduce the calculation time of the segmentation process. It can be demonstrated that the histogram of point elevation for any room similar to the lab used in this study has the form shown in Figure 4a. As illustrated, the histogram of elevation consists of two major peaks, which represent the points of the floor and the ceiling. To determine the location of these two modes, the Median-shift algorithm proposed by Shapira et al. (2009) was used. The two modes are regarded as points Pf and Pc in Figure 4a. In order to robustly identify the points on the ceiling and the floor using the identified modes (peaks), first all the points in $\pm r$ (rc) from the mode Pf (Pc) are identified. rf (rc) is the difference of the minimum (maximum) elevation of the data set from the elevation of first (last) meaningful mode Pf (Pc). The Deterministic MCD algorithm was then applied on these specified points in order to identify the subset that complies with the majority of the dataset. The identified points with the least variation are then regarded as the points on the floor and ceiling.

![Figure 4: a) Expected distribution of the elevation of the point cloud; b) histogram of elevation of the actual point cloud.](image)

The histogram of elevation is as shown in Figure 4b, which complies with the hypothesis presented in Figure 4a. The objective is to determine the points of the floor and the ceiling, enclosed by the red ovals of Figure 4b. The results of the extracted points using the robust method described above are presented in Table 1. As illustrated, no Type II errors were detected during the extraction of the feature extraction, which indicates the robustness of the proposed method. In addition, the extracted points accounted for approximately half of the total accumulated point clouds, which suggest a significant reduction in the time of data classification and segmentation.

<table>
<thead>
<tr>
<th>Surface</th>
<th>$t_f$</th>
<th>$t_p$</th>
<th>$f_n$</th>
<th>$f_p$</th>
<th>Precision (%)</th>
<th>Recall (%)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>252392</td>
<td>3897455</td>
<td>0</td>
<td>361429</td>
<td>91.5</td>
<td>100.0</td>
<td>92.0</td>
</tr>
<tr>
<td>Ceiling</td>
<td>1917447</td>
<td>11633097</td>
<td>0</td>
<td>959045</td>
<td>92.4</td>
<td>100.0</td>
<td>93.4</td>
</tr>
</tbody>
</table>

4.2.2 Segmentation and As-built Model

Using the methods presented in Section 3, the remaining point cloud was segmented with 94.7% accuracy. The results of the segmentation are as shown in Figure 5a, where the different colours represent different clusters. The purple colour represents the boundaries of the segments. Figure 5b shows the as-built 3D model of the site after the nearest planar clusters are intersected.

4.2.3 Automatic Registration

Here, a novel method is proposed to automatically register the generated as-built model to the planned model coordinate system. Figure 6 shows the plan view of the 3D as-built CAD model. In order to automatically determine the point to point correspondence between the as-built and the planned, two metrics are defined for every vertex (Figure 6a). The first is the angle between the vector that enters and
exits the vertex ($\theta$). The second is the average of the magnitude of the vector entering ($V_1$) and exiting ($V_2$) the vertex. The point correspondences are then determined based on the similarity of the two metrics using a one-step complete linkage clustering method. The method proposed by Horn (1987) is then used to perform a rigid body transformation and completed the registration process. The results indicated a 9.4 cm Mean-Radial Spherical Error (MRSE), which represents the potential discrepancies between the planned model and the captured data. The horizontal and the vertical dimensions of the walls were 7.5 cm and 2.4 cm different respectively.

![Figure 5: a) Segmentation results (obstacles are removed for clarity); b) as-built 3D CAD model](image)

### 4.3 Experiment 2: Graduate Student Hall of Residence

The objective of this experiment is to generate the as-built model of the elevator shaft for the Graduate Student Hall of Residence construction site at the University of Calgary. The elevator shaft is a concrete structure consisting of four perpendicular planar surfaces. The as-built dimensions of the shaft were of particular interest to the contractor since these dimensions are required to comply with the specification of the ordered elevator. A \( \pm 2 \) cm tolerance from the planned dimensions was acceptable for the contractor. The as-built model of the elevator shaft was generated using method proposed in Section 3 as illustrated in Figure 6b &c. The results of this experiment indicated a Distance Root Mean Squared of 1.8 cm, which complies with the standards presented in the project plan and the acceptable tolerance region.

![Figure 6: Mechanics of Materials Laboratory: a) Plan view of the as-built model prior to registration; Graduate Student Hall of Residence: b) Collected LiDAR point clouds from the elevator shaft; c) automatically generated as-built 3D CAD model](image)

### 5 CONCLUSION

In this study, a novel method for the automatic generation of the 3D/4D as-built model of planar structural elements was proposed without using the as-planned data. As-built models are of particular importance to the owner for renovation, maintenance as well as demolition of the existing structure. The proposed
system is a stand-alone method that can be used to assess the progress of construction activities even at times when the planned model is not available. The planned model is however, required to assess the deviations between the planned and the actual states of the project. This approach uses a novel robust PCA to first classify coplanar point clouds. The classified points are then segmented using the complete linkage clustering method. The boundary points of each cluster are determined to break discontinuous surfaces into smaller segments. The planar surfaces are then intersected to determine the vertices of the objects of desire. A novel method is also proposed to robustly extract the floor and flat slab ceilings without the need for the aforementioned approach, which can help reduce the calculation time significantly. A new method of automated registration and point to point correspondence search is also proposed. The two experiments show the effectiveness of the proposed system in automatically generating the 3D as-built model in both a highly occluded laboratory and an actual construction site environment.

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INTEGRATING STOCHASTIC FUZZY-LOGIC DECISION SUPPORT WITH BRIDGE MANAGEMENT INFORMATION SYSTEM (BMIS)

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Abstract: Over the past few years, infrastructure restoration has been backlogged with multifaceted factors that engrossed the attention of municipal and federal authorities in North America and Europe. Several successful integrations of bridge management information systems with decision support systems and computer aided engineering design solutions had significantly leveraged downstream processes of bridge maintenance operations and inspired many researchers. The subjectivity nature of evaluating bridge conditions and deteriorations is the main factor that influences bridge maintenance, repair, and replacement (MR&R) decisions. In order to overcome this shortcoming, the main objective of this research study is intended to demonstrate the viability of integrating a decision support system with a stochastic gamma deterioration model by utilizing a probabilistic fuzzy-logic strategic approach at bridges network level. Results are anticipated to be of major significance to municipal and federal authorities as well as to bridge stakeholders and considered a vital contribution to bridge management integrated technologies with probabilistic fuzzy-logic decision support strategic approaches.

1 BRIEF INTRODUCTION

Predicting bridge deterioration conditions is the main constituent of infrastructure asset management techniques. Furthermore, a decision support system based on fuzzy-logic theory that assist asset managers in making appropriate MR&R decisions is a necessity for a successful bridge deterioration monitoring program. Given the above-mentioned, a time-dependent prediction of overall bridge deterioration requires the development of a thorough, reliable, and user-friendly fuzzy-logic decision support system to assist contractors in making decisions among maintenance, repair, and replacement strategies. Towards that goal, a wider insight into integrating a fuzzy-logic decision support system capable of assisting bridge assets managers in monitoring, scheduling, and proposing a strategic solution to deteriorating bridge infrastructures based on a standard probabilistic gamma deterioration distribution and comprising independent non-negative increments with identical scale parameters is artistically and objectively being created and deployed.

2 PROBLEM STATEMENT

Economically, it has been proven that often in many situations, maintenance costs exceed annual or semi-annual preventative maintenance costs. However, it is observed that most bridge stakeholders are frequently reluctant to pay for maintenance fees rather than early preventative maintenance costs, which appear to be of no benefit or was found, from previous experience, not successful in preventing a bridge structure from deteriorating. Therefore, integrating bridge performance indicators based on bridge
beneficiaries’ perception on technical parameters with stochastic bridge time-dependent deterioration modeling may be utilized for planning maintenance and deterioration monitoring programs and subsequently prioritizing MR&R activities; such as inspection, sampling, preventative and maintenance operations.

3 MOTIVATION AND OBJECTIVES

The proposed integration is a rationalized approach that justifies most of bridge stakeholders “ineffective” spending as the scale of subjectivity in quantifying bridge deterioration is considerably reduced. Moreover, the integration contributes towards not just reliability of a particular bridge element but also to the reliability of collected data and probability of the occurrence of deterioration benchmarks such as imitation of corrosion and elemental degradations. Therefore, the main objective of this paper is geared towards proposing a fuzzy-logic decision support system based on complex quality functions and a gamma stochastic deterioration model approach, which is based on the integration of the above probabilistic models in an attempt to improve the effectiveness of bridge maintenance management systems.

4 REVIEW OF THE LITERATURE

Highway and transportation authorities have often relied upon simple deterministic deterioration curves for predicting bridge maintenance programs. Recent bridge management systems; however, have implemented Markov chains deterioration models, which are considered as a major step forward towards incorporating stochastic-natured deterioration models. Proceedings and evolutions that tailored the Markov chain approach in bridge management systems were provided in a study published by Frangopol et al. (2001). In another study conducted by Van Noortwijk et al. (2007) gamma processes and peaks-over-threshold distributions for time-dependent reliability is illustrated. In their paper, a comprehensive discussion on the evaluation of structural reliability is presented where a methodology that integrated two stochastic processes originating from a Poisson process for obtaining the temporal reliability of a particular structural component was proposed. In another study conducted by Lounis (2000), it is argued that one advantage of Markov models application is the simplicity of allowing information pertaining to existing bridge conditions and bridge remaining service life to be determined at any given time. Another study conducted by Edirisinghe et. al. (2013) present the application of gamma process for stochastic deterioration prediction of building elements derived from discrete condition data obtained from the Victorian local government infrastructure asset database. Moreover, Reddy and Ramudu (2013) analyze a numerical arithmetic-geometric maintenance model for deteriorating system subject to a random environment. Furthermore, Pandey and Van Noortwijk (2004) investigate a gamma process model for temporal structural reliability and present a relative assessment of random variable deterioration models based on the first order reliability methods and temporal stochastic modeling based on the gamma process. Van Noortwijk et al. (2005) study a gamma process model for temporal structural reliability and presented a combined computational method comprising both deterioration resistance and variable load modeled as a stochastic gamma process. On the other hand, Lounis and Madanat (2002) present a two-level decision support system that amalgamates stochastic deterioration models to enhance efficacy of bridge maintenance management systems. Hence, the majority of these studies have not considered the integration of decision support systems with gamma stochastic process models to assist assets managers in capturing economical maintenance routes and making strategic MR&R decisions. In an attempt to overcome such limitation, reliability-based deterioration models that are based on fuzzy-logic decision support system by the deployment of complex quality functions originating from the house of quality (HOQ) model, presented latter, quantitative and qualitative fuzzy logic scorings that take into account diverse parameters (i.e. technical, functional, safety, etc) are proposed. Moreover, such models are powerful in the manner that they are capable of analyzing single or multiple simple spans of complicated bridge structures of a highway bridge network that possess multiple failure modes and diverse failure consequences. Therefore, the proposed methodology towards the development of the bridge management system incorporates a fuzzy-logic decision support system complete with MR&R solutions integrated with a reliability-based gamma stochastic process models for predicting temporal bridge deteriorations.
5 PROPOSED DEVELOPMENT METHODOLOGY

The proposed development methodology comprises an innovative bridge management information system (BMIS) based on a strategic framework that is capable of integrating bridge gamma stochastic deterioration modeling with a fuzzy-logic decision support system through the deployment of complex quality functions derived from bridge beneficiary-driven parameters and symmetrical triangular fuzzy numbers (STFN’s) to capitulate bridge evaluation ambiguities. Furthermore, the developed framework possesses a unique aspect of BMIS by including several bridge MR&R strategies into a probabilistic matrix factorization to derive competitive priority ratings. An overview of the model development is illustrated in Figure 1.

Model development methodology comprises the following six main steps. At first, data related to the bridge beneficiary-driven technical parameters module components are collected and strategically arranged into a database server. Next, a decision support system that assists the user in making MR&R decisions is implemented. Then, complex quality functions that analyze bridge beneficiaries/users relative perception on the multiple evaluation criteria are incorporated towards the development of a fuzzy-logic decision support system that assist the user in evaluating the condition of a bridge element. Afterwards, a mathematical model is employed to evaluate bridge MR&R scorings and provides solutions on the analysis. Later on, a gamma stochastic temporal deterioration model is created where MR&R ranking ratings are defined and incorporated into the model for prioritization of maintenance operations. At the end, prioritization and optimization of maintenance operation results are presented. Three main modules are then categorized according to actual bridge deterioration monitoring activity sequence. The modules are as follows: 1) selection of optimum MR&R strategy that comprises an automated quality function deployment (QFD), a client-based quality management system based on product beneficiaries/users.
relative importance perception on a set of defined competitors; (2) Multi-criteria decision making approach
equipment fleet cost optimization system that includes analyses of strategies for the selection of the best
bridge maintenance operation alternative based on a specified list of technical parameters; 3) gamma
stochastic process, which contains a time-dependent deterioration model with priority rankings obtained
from the previous module automatically linked to the BMIS software technical database followed by a
report module that displays instantaneous output reports of optimum MR&R strategic solutions.

6 FUZZY-LOGIC DECISION SUPPORT

Presently, bridge MR&R decisions are mainly influenced by the scale of subjectivity involved in bridge
condition assessments. Otayek et al. (2010) have studied the integration of a decision support system
based on a proposed machine technique as part of artificial intelligence and neural networks (NN). In their
study, the authors recommend continuous and further development in decision support systems in an
attempt to assist bridge designers in selecting bridge type at conceptual phases. On the other hand,
Malekly et al. (2012) have proposed a methodology of implementing QFD and TOPSIS for bridge
selection. Their methodology is integrated in a novel oriented approach while overcoming interoperability
issues among the disperse databases. Therefore, authors of this study propose an integration prototype
of a decision support system and MR&R-related attributes. Bridge MR&R decisions are found to be
significantly influenced by each of the following seven main (WHATs) criterion: (1) technical 'W 1'; (2)
functional 'W 2'; (3) safety 'W 3'; (4) construction 'W 4'; (5) economics 'W 5'; (6) aesthetics 'W 6'; and (7)
material 'W 7'. Selection of the WHATs criteria is based on earlier studies on critical factors that
infrastructure asset managers rely upon and authors' perception on bridge criterion importance and
successive bridge condition assessments. A 9-point symmetrical triangular fuzzy logic numbers (STFN)
range from one to nine, with one being very low and nine being very important, is adopted for assisting
the user in predicting bridge beneficiaries perception pursuant to the seven main criteria listed above. The
scoring system comprises crisp and fuzzy measures when uncertainty arises. On the other hand, bridge
beneficiaries are identified in this study and classified as follows: (i) stakeholders/government; (ii)
designers ENGINEERS; (iii) contractors/builders; and (iv) public/residents. Also, the following nine common
bridge types "competitors" are identified and incorporated into the database platform for QFD analyses:
(1) beam bridges 'C 1'; (2) truss bridges 'C 2'; (3) cantilever bridges 'C 3'; (4) arch bridges 'C 4'; (5) tied-arch
bridges 'C 5'; (6) suspension bridges 'C 6'; (7) cable-stayed bridges 'C 7'; (8) movable bridges 'C 8'; and (9)
double-decked bridges 'C 9'. Upon completion of beneficiaries' scorings on the seven WHATs, perception
on relative importance ratings of the seven WHATs is determined. In this study, Chan and Wu (2005)
mathematical expressions are deployed due to their efficiency, systematic characteristics, and ease of
use in competitive analysis of bridge type selection. Crisp and STFN measure forms of relative
importance ratings are obtained in accordance with Chan and Wu (2005) Eqs. 1 and 2.

\[ \text{[1]} \quad g_{mk} = \frac{g_{m1} + g_{m2} + g_{m3} + g_{m4} + g_{m5} + g_{m6} + g_{m7} + g_{m8} + g_{m9}}{9} \]

\[ \text{[2]} \quad \tilde{g}_{mk} = \frac{\tilde{g}_{m1} + \tilde{g}_{m2} + \tilde{g}_{m3} + \tilde{g}_{m4} + \tilde{g}_{m5} + \tilde{g}_{m6} + \tilde{g}_{m7} + \tilde{g}_{m8} + \tilde{g}_{m9}}{9} \]

Where; $g_{mk}$ is a bridge beneficiary relative importance perception on a WHATs criterion in ‘crisp’ form;
k is a bridge beneficiary; $W_{ni}$ is a WHATs criterion; $\tilde{g}_{mk}$ is a bridge beneficiary relative importance
perception on a WHATs criterion in ‘fuzzy’ form. In other words, $g_{mk}$ is the average "integer" crisp scoring
value of a bridge beneficiary on the relative importance of each of the WHATs criteria and $\tilde{g}_{mk}$ is the
average "integer" fuzzy scoring value of a bridge beneficiary on the relative importance of each of the
WHATs criterion. Following the determination of relative importance ratings, bridge beneficiaries’
competitive comparison matrix analysis is developed as per Chan and Wu (2005) Eqs. 3 and 4.
[3] \( X = \begin{bmatrix} x_{mk} \end{bmatrix}_{7 \times 9} \)

[4] \( x_{mlk} = \frac{(x_{m11} + x_{m12} + x_{m13} + x_{m14})}{4} \)

Where; \( X \) is the bridge beneficiaries’ comparison matrix; \( x_{mk} \) is a bridge beneficiary assessment on \( W_m \); and \( x_{mlk} \) is a bridge beneficiary assessment of a bridge competitor on \( W_m \). Afterwards, the probability distribution of each \( W_m \) on bridge competitors is calculated using Chan and Wu (2005) Eq. 5.

[5] \( p_{mk} = \frac{x_{mk}}{x_m} \)

Where; \( p_{mk} \) is the probability distribution of \( W_m \) on bridge competitors; \( x_{mk} \) is a bridge beneficiary assessment on \( W_m \) ‘result obtained from expression (4)’; and \( x_m \) is the total of bridge beneficiary assessment of all bridge competitors on each of \( W_m \). Following the determination of probability distribution of \( W_m \), its measure of entropy, which is a quantification of the expected value of a system with uncertainty in random variables, may be obtained using Chan and Wu (2005) Eqs. 6 and 7.

[6] \( E(W_m) = -\phi_9 \sum_{l=1}^{9} p_{mk} \ln(p_{mk}) \)

[7] \( \phi_9 = \frac{1}{\ln(9)} \)

Where; \( E(W_m) \) is the measure of entropy by a discrete probability distribution for \( W_m \); \( \phi_9 \) is the normalization factor that guarantees \( 0 \leq E(p_1, p_2, \ldots, p_L) \leq 1 \); \( p_{mk} \) is the probability distribution of \( W_m \) for the diverse bridge competitors. Higher entropy or \( (p_1, p_2, \ldots, p_L) \) implies smaller variances and lesser information in a probability distribution \( p_L \). At the end, it is possible to determine bridge competitors’ priority ratings on each of the seven \( W_m \) using Chan and Wu (2005) Eq. 8.

[8] \( e_m = \frac{E(W_m)}{\sum_{m=1}^{7} E(W_m)} \)

Where; \( e_m \) is the criterion weight of \( W_m \).

7 TECHNIQUE OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION (TOPSIS)

Upon determination of the seven WHATs, a multi-criteria decision making approach, TOPSIS, is undertaken. This approach takes into account the following criteria: (i) qualitative benefit; (ii) quantitative benefit; and (iii) cost criteria. As part of TOPSIS analysis, the following two most contradicting alternatives are surmised: (a) ideal alternative in which the maximum gain from each of the criteria values is taken; and (b) negative ideal alternative in which the maximum loss from each of the criteria values is taken. Towards the end, TOPSIS opts in for the alternative that converges to the ideal solution and opts out from...
the negative ideal alternative. Prior to undertaking the multi-criteria decision making approach, a TOPSIS matrix is developed using Eq. 9.

\[ X = \left( x_{ij} \right) \]

Where; \( X \) is the bridge beneficiaries comparison matrix; and \( x_{ij} \) is an “m x n” matrix with ‘m’ criteria and ‘n’ bridge competitors that display the score of bridge beneficiary ‘i’ on criterion ‘j’. TOPSIS analysis comprises the following consecutive five steps: (i) normalized decision matrix; (ii) weighted normalized decision matrix; (iii) ideal and negative ideal solutions; (iv) bridge competitors’ separation measures; and (v) relative closeness to ideal solution as shown in Figure 2.

![TOPSIS Process Flowchart](image)

In this study, Hwang et al. (1993) mathematical expressions are deployed based on their direct applicability to ranking bridge type alternatives and proven reliability. Generating the normalized decision matrix is intended to convert various parametric dimensions into non-dimensional parameters to allow for contrasting among criteria using Hwang et al. (1993) Eq. 10.

\[ r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \]
Where; \( r_{ij} \) is the normalized scoring value of bridge beneficiaries on bridge competitors’ criteria.

Afterwards, the creation of a weighted decision matrix is obtained by multiplying the criterion weights determined from Eq. 8 by its corresponding column of the normalized decision matrix obtained from Eq. 10 through the employment of Hwang et al. (1993) Eq. 11.

\[ v_{ij} = w_i r_{ij} \]

Where; \( v_{ij} \) is the weighted normalized element of the TOPSIS matrix; and \( w_i \) is the WHATs criterion weight value. Afterwards, the ideal and negative ideal solutions are determined using Hwang et al. (1993) Eqs.12 and 13 respectively.

\[ A^* = \{v_{i1}^*, ..., v_{ij}^*\} \]

\[ A' = \{v_{i1}', ..., v_{ij}'\} \]

Where; \( A^* \) is the positive ideal solution; where \( v_{ij}^* = \{\max v_{ij}\} \) if \( j \in J \); minimum \( v_{ij} \) if \( j \in J^' \); \( A' \) is the negative ideal solution where \( v_{ij}' = \{\min v_{ij}\} \) if \( j \in J \); maximum \( v_{ij} \) if \( j \in J^' \); where \( J \) is the set of beneficial attributes or criteria; and \( J^' \) is the set of negative attributes or criteria. Afterwards, bridge competitors’ separation measures from ideal and negative ideal solutions are calculated by using Hwang et al. (1993) Eqs.14 and 15 respectively.

\[ S_i^* = \left[ \sum (v_{ij}^* - v_{ij})^2 \right]^{1/2} \]

\[ S_i' = \left[ \sum (v_{ij}' - v_{ij})^2 \right]^{1/2} \]

Where; \( S_i^* \) is the separation from the positive ideal solution; \( S_i' \) is the separation from the negative ideal solution; and \( i \) is the number of bridge competitors. Finally, relative closeness to ideal solution is calculated by Eq. 16.

\[ C_i^* = \frac{S_i'}{S_i^* + S_i'} ; \text{ where } 0 < C_i^* < 1 \]

Where; \( C_i^* \) is the relative closeness to positive ideal solution. The recommended bridge competitor or alternative is the one with a corresponding \( C_i^* \) closest to the value of unity “1”. The developed model shall be capable of assisting the user with the MR&R decisions at a bridge network level provided the circumstances given.

8 GAMMA STOACHASTIC MODEL

The general equation for a gamma distribution probability density function is as per the Eq.17.
\[ f(x) = \frac{(x - \mu)^{\gamma - 1} e^{\frac{x - \mu}{\beta}}}{\beta \Gamma(\gamma)} \quad \text{where} \quad x \geq \mu; \quad \text{and} \quad \gamma, \beta > 0 \]

Where; \( x \) is the value of a time-dependent deterioration parameter; \( \gamma \) is the gamma probability density function (PDF) shape parameter, \( \mu \) is the location parameter, \( \beta \) is the scale parameter, and \( \Gamma \) is the gamma function defined Eq. 18.

\[ \Gamma(\gamma) = \int_{0}^{\infty} x^{\gamma-1} e^{-x} \, dx \]

A standard gamma distribution is determined by substituting the shape parameter, \( \mu = 0 \) and the scale parameter, \( \beta = 0 \) and; therefore, the general gamma distribution function reduces to the Eq. 19.

\[ f(x) = \frac{x^{\gamma-1} e^{-x}}{\Gamma(\gamma)} \quad \text{where} \quad x \geq 0; \quad \text{and} \quad \gamma > 0 \]

9 MODEL DEVELOPMENT

The model is being developed through an object-oriented programming (OOP) approach utilizing ‘C#’ and implemented in a classical .NET framework. The main purpose of the model is to facilitate the interface between bridge beneficiaries, MR&R attributes, and gamma shock model functions. At first, the user inputs bridge condition assessment survey results based on the developed fuzzy logic scoring system related to bridge MR&R attributes for the four distinct beneficiaries defined earlier into the QFD module as shown in Figure 3.
Afterwards, a beneficiary comparative matrix is established where parametric weights are assigned for commencement of TOPSIS analysis.

10 SUMMARY AND CONCLUSIONS

In this paper, the viability of developing an integrated fuzzy-logic decision support system with a gamma stochastic temporal deterioration model targeted towards assisting bridge stakeholders and assets managers propose strategic MR&R solutions for deteriorated bridge structures is presented. Comparative analyses of disperse bridge beneficiary driven attributes and MR&R solutions were conducted utilizing QFD systematic approaches. The actual accuracy of the model is highly dependent upon the technical and functional constraints as well as user-defined fuzzy-logic entries. It was concluded that the model possess some limitations pursuant to complex and joint elemental bridge time-dependent deteriorations. It is necessary to mention that the model is proposed as a tool that can be used to eliminate subjectivity in bridge performance assessment and predict the most appropriate maintenance solutions for a particular bridge project. The proposal presented herein may be utilized in bridge projects that involve major degradations where evaluating elemental deteriorations would be a subject to uncertainties. This capability provides the model a great advantage over other bridge performance indicator software packages, prototypes, or models published earlier in literature. Also, results presented in this paper are anticipated to be of major significance to the bridge assets managers and stakeholders and would be a novel contribution to bridge management system approaches and assortment of MR&R strategic solutions.

References

TRACKING CONSTRUCTION PROJECTS PROGRESS USING MOBILE HAND-HELD DEVICES

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Abstract: Recent studies have attempted to automate monitoring progress of construction projects using 3D laser scanning or image based reconstruction methods. This paper presents a new methodology for monitoring using mobile hand-held devices such as smartphones and tablet computers. This is done by proposing a new developed android application called “BIM track” that the end-user can use to record the progress of activities (actual dates, percentage complete, and actual cost) from a remote location. BIM track is cloud-based which ads in speeding up the production of construction progress reports and improves data accuracy as it’s connected with Google drive using fusion tables that make the user able to combine/edit the data on the internet. As such, it is capable to collaborate, visualize, and share data through the internet to export the results into an Excel spreadsheet from the mobile application to a remote computer. In addition, the data can be imported to the Navisworks to update the project’s 5D model. Accordingly, time schedules, cost performance (CPI) and schedule performance index (SPI) can be calculated easily. In addition, such results can be shown in 5D model using Navisworks to compare actual progress versus the planned progress. BIM track android application can have an access to any uploaded project’s 3D model using Autodesk 360 as this application is integrated with BIM track. A case study is presented below to demonstrate the use of the proposed methods to track the project and to make a comparison between the actual and the planned progress of the project.

1 INTRODUCTION

Nowadays, there is major developments in Mobile hand-held devices technologies that are highly prevailing that is no longer limited to personal use. Portability and accessibility granted the Mobile hand-held devices such as smartphones and computer tablets a great advantage that attempt recent studies to automate the process of construction site monitoring. A recent survey conducted by McGraw Hill reveals that 93% of random samples of general contractors and subcontractors are now using mobile devices on their jobsites to document workflows (Bernstein and Russo 2012). There are several aspects for improvement in productivity of onsite operations. Any onsite information management system should have the following characteristics (Bowden, et al. 2006) (Golparvar-Fard, et al. 2011) (Son, et al. 2012) (Bae, Golparvar-Fard and White 2013): 1) enable project monitoring capabilities 2) provide easy access to relevant information so that onsite resources could be managed more effectively, and 3) function in near real-time to share information and facilitate interactions among project participant. (Kim, et al. 2013) listed five different categories of studies for mobile computing of construction: 1) development of a framework or platform to demonstrate how mobile computing should be used for construction; 2) mobile computing as a toll for identification or general management; 3) mobile computing for defect management; 4) mobile computing for safety or disaster management; and 5) development of specific features of mobile computing.
As a step towards improving the productivity on site, it is required to perform beneficial reporting system to provide the opportunity for project management to detect the performance deviations. However, typical practice for progress tracking mostly depends on supervisors daily or weekly reports, which involve intensive manual data collection and entail frequent transcription or data entry errors. Field engineers and/or superintendents along with 2D as-planned drawings, project specifications and construction details to review the progress achieved by that date then study these reports. After that, they study the construction schedule to identify the work planned to be done by that date. This requires a significant amount of manual work that may affect the quality of the progress estimations (Kiziltas and Akinci 2005).

To overcome such limitations, recent researches trend moves towards improving construction monitoring through model-based assessment methods, where the expected performance is typically modeled with 4D Building Information Models (BIMs) and actual performance is sensed through 3D laser scanners (Turkan, et al. 2012) (Kim, et al. 2013) or a 3D sensing techniques called 3D image based reconstruction methods (Golparvar-Fard et al. 2009, Golparvar-Fard et al. 2011, Golparvar-Fard et al. 2012). In this paper, the proposed methodology makes benefit of the advantages of the mobile hand-held devices to develop an android application to monitor the construction projects through cloud based service. Time schedule is loaded along with the cost for each activity to generate a 5D model to calculate the planned, and actual values cost during the project. A case study is presented in which this application is deployed on a construction project to endorse its capability to track projects to compare the results.

2 DEVELOPMENT OF BIM-TRACK APPLICATION

This research aims at optimizing the built-in advents of smart phones with other technologies to provide an effective monitoring for progress on-site. (Kim, et al. 2013) listed the advents of smart phones that have become the standard of most smart phones can be classified into Global Positioning System, High-resolution color touch screen, sensors, camera, and high-speed data transfer. BIM-Track android application acquire from the aforementioned advents the High-resolution color touch screen to allow the user to read/add information through the high-speed data transfer to upload captured images integrated with its location as shown in the sections hereunder.

2.1 BIM-Track Structure

In the last few years, the trend toward the mobile computing has significantly increased in the construction management field. BIM-Track mobile application is developed using a combination of the following:

1) Primavera P6 R8.3 (Oracle 2015): P6 Professional is a comprehensive, multi project planning and control software, built on Oracle and Microsoft SQL Server relational databases for enterprise-wide project. Primavera is used to issue a time schedule using CPM (Critical Path Method) and to assign the activities cost for further cost control reports.
2) Revit 2014 (Autodesk, Revit 2015): Revit software is specifically built for Building Information Modeling (BIM), empowering design and construction professionals to bring ideas from concept to construction with a coordinated and consistent model-based approach. BIM Track used this program to create a 3D model.
3) Navisworks 2014 (Autodesk, Navisworks 2015): it is an application which allow the users to integrate the created 3D model with the time schedule and its assigned cost to produce a video that shows the 5D simulation in the project in various stages.
4) Autodesk 360 (Autodesk, Autodesk 360 2015): Autodesk 360 is service provided by Autodesk that allow to share and organize all project data, collaborate on 2D/3D model on the web or on the smart phone.
5) Fusion tables (Google 2015): It is an application similar to Microsoft Excel connected with Google drive that is able to combine the data on the web, collaborate, visualize and share. This service are used in this paper for updating the activities actual durations, actual start, actual finish, performance, and actual cost, etc. where these results can be filtered and summarized across hundreds of thousands of rows.
6) Matlab (Image Processing toolbox) (Mathworks, Image processing tool box 2015): provides a comprehensive set of reference-standard algorithms, functions, and apps for image processing, analysis, visualization, and algorithm development. Image analysis can be performed employing different
techniques including, image segmentation, image enhancement, noise reduction, geometric transformations, and image registration. This tool is used to analyze the progress of the captured images. 7) MIT App Inventor (MIT app inventor 2015) App Inventor is a cloud-based tool that can build android apps using web browser through Java programming language. This tool is divided into a group of blocks that have functions and a design interface for application designing to ease the use with the end-user.

Figure 1 illustrates the supportive applications that constitute BIM-Track” Application.

![Diagram](image)

**Figure 1: Supportive Applications for BIM-Track**

### 2.2 BIM-Track Data Flow

Tracking projects process, in a form of acquiring information and capturing images, is performed by visiting the field office and construction sites. The proposed BIM-Track application provides improved accessibility of project information and site images. Before updating the project’s information, the end-user of the proposed application can obtain the basic information of the preloaded projects that is prepared in the head office. Moreover, the integrated Building Information Model to the application can save time and help in taking fast decision on site, where these benefits are based upon the level of detail of the model. The level of detail (LOD) can be categorized through system published by AIA. (Bedrick 2008) defined five categories for Level of Details (LOD); the LOD 100 as a conceptual stage, LOD 200 as an approximate geometry stage, LOD 300 as a precise geometry stage, LOD 400 is fabrication stage, and LOD 500 as as-built stage.

However, the project information needs to be updated to track the project's status, this happens through the accessible devices as shown in Figure 2. First, the 2D/3D drawings provided by Autodesk 360 have an access to add any comments on the selected element to allow for interactive drawing sharing among the application users to provide the required information and this happens through Mobile computing system. Moreover, the captured image that is assigned to a specific element in the 2D/3D drawings can be used to track the performance in the project. RGB images are converted to binary images to calculate the actual performance using image segmentation. Second, data provided from the fusion tables can be used to update the Time Schedule and the actual cost of each activity to generate an actual 5D model to
be able to compare the actual/planned progress to see the difference between the Actual Cost of Work Performed (ACWP) and Budgeted Cost of work Scheduled (BCWS) through a 5D model.

![Data Flow in BIM-Track](image)

**Figure 2: Data flow in BIM-Track**

### 2.3 BIM-Track Interface

Effective tracking of site activities requires a friendly interface for the end-user to ease the usage of the developed android application. BIM-Track start screen shows the options available to the end-users. First, a button that open a preloaded 5D model is uploaded over the internet, which is updated periodically. The 5D model visualizes the difference between the planned and the actuals on the project as detailed in the sections hereunder, where this 5D model is updated after checking username and password of the user. BIM-Track has a button that shows the essential information such as the location, description, stakeholders, perspectives, and estimated cost of the project. In the proposed BIM-Track application, two tracking methods are used; fusion tables and the 3D model to capture the images for a specific location or leave a comment to the users (see Figure 3).

![BIM-Track Screens](image)

**Figure 3: BIM-Track Screens**
3 SITE MONITORING USING BIM-TRACK

3.1 Image Analysis for Progress Monitoring

Effective tracking for construction projects can have positive results in managing the projects. The developed BIM-Track application enables the users to: 1) visualize the project in 3D, and 2) open the construction project’s drawings to minimize time of acquiring hardcopy drawings. Autodesk 360 is used in viewing the drawings for different projects. For each project, it can be loaded with the 2D/3D drawings or both as per the exported .DWFX file extension using Revit 2014. However, Autodesk 360 is not only used for viewing the drawings or visualizing a 3D model, but it is used for tracking projects as well. Figure 4 depicts that progress can be added in comments where these comments can be added to a specific element in the drawings. Such elements can have markups as pin icon on the drawing, area highlighted, and freehand. Moreover, these comments are used to describe the state of work to perform an effective tracking for construction projects. Subsequently, these captured images are imported to MATLAB image processing toolbox to track the progress of works.

![Figure 4: Tracking project using Autodesk 360](image)

Images acquisition of construction sites is a preliminary step, where such images are attached to specific element in the 3D model. However, the image quality must be fine enough to recognize the objects in the image. Autodesk 360 transfers the captured image through the cloud mobile system effectively to be available through any accessed device. Once the captured site image is downloaded to the PC, it can be processed for progress monitoring. Figure 5 illustrates the procedure of image analysis to identify construction progress for executed typical floors in an administrative building. The RGB captured image using the smart phone shows both de-shuttered slab and other shuttered elements. The image processing tool using the MATLAB is capable to identify number of slabs in the image as a horizontal shapes after reducing the noises in the captured image, where, many of steel scaffolds as an example affect identifying the progress in any captured image. To achieve better results with respect to identification of number of performed slabs any noise should be removed or any element but the slab in the image.

Zou and Kim (2007) used HSV color space as the hue is less sensitive to different lighting conditions than RGB images to differentiate between objects with different colors. They stated that in HSV image, objects of different colors tends to be differentiated from another because hue represents the dominant wavelength of the color. However, the considered captured image colors have near RGB values especially for the shuttered slab. Thus, image segmentation takes place through converting the captured RGB image to grayscale image then to a binary image. Separation the grayscale image occurs to have three different planes 1) red, 2) green, and 3) blue. This process is called image segmentation, which is followed by adding this planes to one plane after adjusting the level of each plane to reduce the noise in the binary image to be complemented. In the complement of a binary image, zeros become ones and
ones become zeros; black and white are reversed. In the complement of an intensity or RGB image, each pixel value is subtracted from the maximum pixel value supported by the class (or 1.0 for double-precision images) and the difference is used as the pixel value in the output image. In the output image, dark areas become lighter and light areas become darker to fill image regions and holes, where these processes named image enhancement. Mathworks (2014) defined image enhancement as the process of adjusting digital images so that the results are more suitable for display or further image analysis.

Image analysis can take place by measuring properties of image regions using a logical operation in the Matlab as the function ‘find (X)’ that locates all nonzero elements of array X, and returns the linear indices of those elements in vector. If X is a row vector, then f is a row vector; otherwise, f is a column vector w. If X contains no nonzero elements or is an empty array, then f is an empty array. In our study X is the white part that is valued to be ‘1’ to detect the slab region and surround them by boundary boxes for users to count and identify the slabs.

![Image analysis procedure](image_analysis.png)

### 3.2 5D Model Development

During the execution of any mega construction project, cost control process takes place to track a project to conclude some parameters such as the budgeted cost of work scheduled (BCWS) which is known as the planned value, budgeted cost of work performed (BCWP) which is also known as Earned Value, and Actual cost of work performed (ACWP). BIM-Track application tends to show the difference between the aforementioned parameters through a 5D model and determine if the project is under or over budget and schedule to make the construction managers plan corrective actions (if any), and implement this corrective actions. A case study was conducted through BIM track android application to achieve this goal, where BIM track mobile has the access to add information to update the activities to enrich the tracked project by generating 5D model using Navisworks. First, information that can be acquired in the developed android application varies such as actual start, actual Finish, progress percent complete, WBS code, and the allocation of the activities responsibility to each Engineer on site. Second, BIM-Track transfers the results through google drive, which is a cloud storage service that allows the users to store the updated information using fusion tables. Third, the actual cost of each activity and budgeted total cost can be updated offsite after exporting the updated results from the android application onsite to a Microsoft Excel comma separated value file (.CSV) through the Google drive. Finally, the final results can be synchronized through the previous update which is imported to the Navisworks.

Now that Navisworks contains the time schedule, financial cost, and the 3D model imported. The final task is to attach each activity in the time schedule to the relevant task manually, or using a function called “Timeliner Rules”. Timeliner rules can attach the tasks to items with the same name, selection set with same name, and layers with the same name this is according to the generated 3D model technique, where the process of attaching the tasks is one time process as updating the 5D model will depends only on adding the information of each activity.
4 CASE STUDY

As a verification of image analysis for site monitoring, a case study for a construction Mega project for an administrative building located in Smart Village, Giza, Egypt with total area 13,000 m2 was performed to verify the usage of BIM track android application using a Sony Xperia C smartphone with 5 inches TFT capacitive touch screen, 8 Mega pixel front camera with Quad-core 1.2 GHz Cortex-A7 processor. Using mobile 3G/WCDMA networks that enable data transfer. A Joint Photographic Experts Group (JPEG) image format was captured on April 16, 2014 for a typical floor slab to apply image processing to track the project for the concrete skeleton, as the concrete works in the similar projects shall be critical activities. As shown in Figure 6, the converted binary image in figure 6c is noisy and such noise need to be removed, and the slabs shall be clearer. A manual trial and error process takes place for some variables to: 1) choose appropriate level of thresholded color plane to integrate the sum of all planes, 2) the intensity of the filled holes in the converted binary image. For evaluation process, the progress information represented with the user visual recognition compared with the Matlab results after trying different values for the variables to validate the counted number of slabs as illustrated in Figure 6. As a preliminary result, it was found an incorrect progress due to the disruption caused by the horizontal parts of the steel scaffolds and the shuttering, wherefore filled holes value between slabs has been increased to get the result as shown in Figure 6g.

![Image](image.png)

Figure 6: Case Study Image analysis procedure.

065-7
Moreover, it shall be mentioned that it’s recommended to fix the camera in same position and level to easily identify further progress without any trail and errors for image analysis to keep sure that the whole process is automated. This place recommended to be out of reach to keep sure that the position did not change every update. Tower cranes is highly recommended for this process. Whilst for the verification of generating a 5D model for the same project and scope of concrete works, BIM-Track android application was tested for sharing the updated activities to Google drive fusion tables over the internet, where the input data were activity name, performed progress percentage, actual start, actual finish, WBS code, and the site engineers allocated to the activity. These data were used to update the time schedule on the Primavera with data date May 17, 2014 to update the previous update with data date May 10, 2014. And thereafter, the updated time schedule was exported to the Navisworks in .CSV format to synchronize it with additional data calculated with the Primavera. This data were the planned value, earned value, and the actual cost of work performed for the activities. As such, the Navisworks was able to export three 5D model for May 17, 2014 data date to 1) Monitor project, 2) visualize the updated/planned 3D model where the process of fixing the steel reinforcement is presented in red color, shuttering for columns and slab is presented in yellow color, and at the end of pouring concrete activity is presented in the model final appearance (see figure 7) and 3) Compare the final total cost. These results were used to calculate important parameters for cost control management to check if the project is under or over budget, and ahead of behind schedule using the following functions, considering Cost Performance Index (CPI), and Schedule Performance Index (SPI), respectively as shown in Figure 7. The results show that the project is under budget, and behind schedule where the estimated CPI and SPI are 1.02 and 0.94, respectively. These results need a proper immediate action to recover within the next updates that is performed on a weekly basis.

Figure 7: 5D model visualization.

5 CONCLUSIONS

Mobile hand-held devices such as smart phones, and tablet computer with other computing technologies provided a powerful system for tracking construction projects. The objective of this study was to develop an android mobile application connected with other applications to aid in tracking projects through storing the updated data over a mobile cloud computing system. BIM-Track the developed application have two method of tracking which are image analysis for progress monitoring, and 5D modeling for the planned and actual progress. The application enables project monitoring and it provides easy access to project’s information, and facilitates the visualization interaction through the 3D model. Image analysis provided
information about the captured images using Matlab, whilst Navisworks used the updated information form the fusion tables to generate the 5D models. A case study for Administrative building under construction was presented to illustrate the use of the proposed application.

References

Abstract: Today, the demand of sustainable buildings is getting higher. The main purpose of buildings is to provide a comfortable living environment to their occupants, considering different aspects including thermal, visual and acoustic comfort as well as Indoor Air Quality. Life cycle assessments are related to many issues such as environmental concerns. Decreasing carbon foot print and energy consumption rates and increasing comfort level for the building users can help to achieve environmental improvements. This comfort level is related highly to Indoor Air Quality (IAQ). This research aims at improving environmental concerns using building information modeling. As-built BIM model is developed to act as a hub to allow transformation of information to an external database, extracted from the BIM Model in COBIE (Construction-Operations Building Information Exchange) format. The database is updated in a dynamic manner to reflect external environmental changes. The environmental changes are captured using sensors that can detect variations in temperature and humidity. Also, carbon emissions and energy consumption rates are reflected back on the model. A case study is presented to demonstrate the use of the proposed framework.

1 INTRODUCTION

Green building concept has been adopted by the construction industry as a response for the global environmental challenges leading to successful results. Abbaszadeh et al. (2006) found that thermal comfort, air quality, furnishing, cleaning and maintenance achieved higher rates for satisfaction in LEED-certified green buildings compared to those non-green counter parts. On the other hand, clients are looking for the added benefits coming from applying the concept of sustainable buildings as they have to increase the capital cost invested to perform their projects Paul and Taylor (2008). Previous research concluded that the aspect of sustainable and green buildings will become the most common among people when they get sure of the benefits and financial gains achieved from their projects as a result of the occupants improved productivity (Zuo et al. 2014). This improved productivity is assigned to the comfortable and satisfying environment provided for their users. Interoperable Carbon Information Modeling (iCIM) project provides an online tool to facilitate carbon assessment of a building by informing designers regarding their decisions and impact of their decisions throughout the building life cycle (iCIM 2011). According to the norms of building automations, it was found that comfort is an important characteristic compared to the usual security and safety issues. It was found also that thermal comfort and air quality are very important and significant factors in deciding the building sustainability and the human comfort level (Singh et al. 2011, Kang and Park 2000).

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 2013) and International Organization for Standardization (ISO) 7730, thermal comfort is defined as a
“State of mind that expresses satisfaction with the thermal environment”. Paul and Taylor (2008) performed a comparison between a green university office building and two conventional universities office buildings all located in Australia. They conducted a survey using questionnaires to examine comfort and satisfaction of users. The questionnaire included temperature, humidity, lighting, aesthetics, acoustics, serenity and overall satisfaction. The green building was having a level of thermal comfort higher than the two conventional buildings. A sustainable building is a function of comfortable and healthy spaces, reducing the generated waste, reducing the used natural resources and lower usage of energy. Kang and Park (2000) developed an integrated comfort sense system for indoor climate, three measurement environmental parameters were used in the system; temperature, humidity and air flow. ISO 7730 considered other parameters such as clothing level, activity level and mean radiant temperature. ZigBee technology-based environment was developed to monitor the indoor and outdoor environmental measurements. The procedures of thermal comfort analysis were proposed in literature (Kumar et al. 2010, Kumar and Hancke 2014-a, Kumar and Hancke 2014-b). Smart systems of thermal comfort sensing can be utilized as a practical tool for monitoring thermal comfort in homes, automobiles, office buildings, etc. (Kumar and Hancke 2014-a). Air conditioning systems can only sense air temperature as they are having obstacles in placating inhabitants in the building environment. But the technology in this area developed new methodologies and designs to achieve the demand of the best possible smart air conditioning system as it can provide the required value of comfort and control in an optimized environment (Kumar et al. 2010, Kumar and Hancke 2014-b). Ventilation is considered one of the effective systems that can improve the internal Air quality (IAQ) (Paul et al. 2010, Liu and Liu 2005), whereas, HVAC is having different control ventilation strategies. One of these strategies is called dual-mode ventilation control method it can save about 8.3-28.3% in electricity usage compared to the conventional fixed-rate controlling strategies (Chao et al. 2004). Other factors such as lighting, internal motions and activities also can play important roles in achieving the goal of occupants comfort level and would be taken into consideration.

Building Information Modeling (BIM) is considered one of the shining technologies developed to increase the efficiency of construction industry. Its function was extended to help in the facility management process by using the As-built BIM model and it is used also in monitoring the facility behavior over its life time as a way to increase the level of control on the building even in operations or maintenance. These great advantages are results of the comprehensive information stored in the model during the construction process. The functional and physical characteristics of a facility can be modeled digitally using BIM (Marzouk et al. 2010). COBIE (Construction Operation Building Information Exchange) is one of the IFC (Industry Foundation Classes) formats was developed in the aim of facility management improvement. It exports all model data in a manner that helps the facility manager to apply a high level of control, understanding all the building components, improve data quality and cut costs at projects turnover. Marzouk and Abdelaty (2014) proposed an integration between subways BIM-based models and Facility management process using a semi-automated inspection system. The system was developed using Wireless Sensor Network (WSN) inside the subway for detecting temperature and humidity. This paper presents a study that was performed on a university building located in Riyadh City the capital of Saudi Arabia. The building is a multifunction building where it has offices, laboratories and a lecture hall. The aim of the study is to evaluate the building behavior over the year regarding the Indoor Air Quality issues (temperature and humidity) and improving the occupants comfort level with respect to energy consumption rates and carbon footprint. The result may play a role in providing sustainable building and a higher convince for owners in achieving valuable benefits.

2 PROPOSED MODEL

The proposed model is developed to represent the idea of improving the IAQ in a certain facility building; the idea enhances the process of building design and management system with more data assessment for temperature and humidity taking into considerations their dynamic nature over the year due to the external environmental changes. The assessment results are used to improve the occupants comfort level inside the building with respect to the consumption and usage of energy and the carbon emissions produced. As-built BIM model is used to monitor the system behavior and weather the occupant’s comfort level is maintained or not. The model has to reflect any defects in the system behavior to the facility
 manager. Tracking the temperature and humidity changes is performed through sensors located in all the building spaces. These sensors are provided by (Dantec Dynamics 2012). The proposed model links the as-built BIM model to the assessment results through an external data base that is updated frequently with the sensors data and updating the As-built BIM model back with these data. The data are analyzed in the external database to ensure that they provide the required comfort level and notify the facility manager with any defects through the BIM model if the comfort level is out of the comfort range. The facility manager is then allowed to locate the problem and apply the required response plan immediately. The COBIE is considered one of the special information exchange tools that is designed to help in facility management. The COBIE sheet is chosen to be an external database. As such, the can manage the process easily and respond to any defects immediately to maintain the occupants’ comfort level. The designated procedure of the proposed model is illustrated in Figure 1.

![Figure 1: Proposed model procedure](image)

### 3 LOCATING SENSORS

At the model first stage, the process of measuring temperature and humidity had to be optimized by tracking the temperature and humidity behavior over the year and their effect on the IAQ and the occupants comfort level. In response to this problem, a thermal analysis was performed on the building. This thermal simulation was developed on the As-built BIM model with the help of the Revit and Ecotect software. The procedures of the analysis were first performed on the Revit as all the model spaces were defined and the model was exported in the GBXML format as shown in Figure 2. Then the Ecotect role started by importing the GBXML file. The non-defined spaces were remodeled on the Ecotect and the as-built materials were defined. Then, the building functional data were defined. Each space function was defined according to its function (office, laboratory or lecture hall) and according to the function the settings were adjusted. The thermal properties of the building were selected; the HVAC system was a Fan Coil System working on the concept of Constant Air Valve (CAV) with an assumed efficiency of 95%. Then, the thermostat range for environmental temperature range for comfort was defined, and then the lighting settings were set for each specified space. Then, the operation schedule was defined according to the hours of operations of each zone, these data were assumed according to the University working days.
After defining the space properties, the building was located on the map in its accurate location using Google Earth as shown in Figure 3. Then, the Riyadh city weather file was attached to the model and the solar path was defined according to the building orientation. Figure 4 shows monthly charts for the general effect of defined data on the building. After running the simulation, the critical spaces were identified due to their affection with external environmental changes through the year so that the analysis could be completed in an efficient way. The critical spaces were not all highest points of temperature and humidity in the building, but also lowest temperatures and humidity zones were critical so that it is possible to predict other building spaces data using interpolations and averages after receiving the actual data measured from the sensors located in the building.
4 LOCATING SENSORS

This section presents the experiment procedures and the methodology of analyzing the experiment outputs. The sensors were located in the building according to the performed thermal analysis. Ten spaces were chosen to monitor the internal air quality with respect to temperature and humidity. Three temperature probes and humidity probes were used in each space at the same time to improve the measurement accuracy Table 1. The experiment was performed in 23rd of November 2014 at 14:00 with a switched off Air Conditioning. Sample of the results are shown in Table 1. The sensors’ measurements were compared to the results of the thermal analysis that was conducted using Ecotect software. The thermal analysis was performed by applying the same experiment conditions. The thermal analysis results were approximately similar to the sensors measurements and that increased our trust in the performed thermal analysis even in defining the critical zones inside the building or in further capabilities in monitoring the indoor air quality. One of the critical spaces (named Space 5) was considered for the analysis (see Figure 2). A sample of the thermal analysis that shows inside and outside temperatures is depicted in Figure 5, taking into consideration conditions that are listed in Table 2.

Table 1: Humidity and Temperature probes measurements

<table>
<thead>
<tr>
<th>Probe</th>
<th>X [m]</th>
<th>Y [m]</th>
<th>Z [m]</th>
<th>Relative Humidity [%]</th>
<th>Operative Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hum. &amp; Temp. 1</td>
<td>3.00</td>
<td>1.74</td>
<td>5.60</td>
<td>30.92</td>
<td>31.79</td>
</tr>
<tr>
<td>Hum. &amp; Temp. 2</td>
<td>3.00</td>
<td>1.11</td>
<td>5.60</td>
<td>30.66</td>
<td>31.73</td>
</tr>
<tr>
<td>Hum. &amp; Temp. 3</td>
<td>3.00</td>
<td>0.68</td>
<td>5.60</td>
<td>30.49</td>
<td>31.56</td>
</tr>
</tbody>
</table>
Table 2: Conditions of thermal analysis

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. Temperature:</td>
<td>26.9°C</td>
</tr>
<tr>
<td>Total Surface Area:</td>
<td>270.085 m² (it represents 400.8% of floor area)</td>
</tr>
<tr>
<td>Total Exposed Area:</td>
<td>265.360 m² (it represents 393.8% of floor area)</td>
</tr>
<tr>
<td>Total Window Area:</td>
<td>1.858 m² (it represents 2.8% of floor area)</td>
</tr>
<tr>
<td>Total Conductance (AU):</td>
<td>676 W/m² K</td>
</tr>
<tr>
<td>Total Admittance (AY):</td>
<td>1384 W/m²K</td>
</tr>
</tbody>
</table>

![Graph showing Inside and outside temperatures for Space 5 (23rd of November 2014)](chart)

Figure 5: Inside and outside temperatures for Space 5 (23rd of November 2014)

5 ENERGY ANALYSIS

The energy analysis process was performed to monitor the efficiency of the building behavior in dealing with energy usage rates and carbon emissions. In this stage, the As-built model (GBXML format) was imported to Autodesk Green Building Studio software. The building systems were defined as stated before in previous stages and then the simulation experiments were conducted. The results of the simulation as shown in Figure 6 indicate the values of energy consumption due to different factors such as lighting, air conditioning, hot water and other factors. Simulation was carried out on the building by changing the internal systems to improve the energy usage and decrease the carbon emissions. The first simulation experiment was conducted to study the impact of changing the HVAC system from Fan Coil System to Variable Air Valves (VAV) system. This change improves the HVAC efficiency regarding the number of occupants in each space. The second simulation experiment was conducted to study the impact of using lighting occupancy sensors instead of manual lighting switched. Figure 7 shows that lighting efficiency and occupancy sensors can significantly contribute in more energy savings. These two extra simulations illustrated an improvement for the building behavior as shown in Table 3. The efficiency of building behavior was improved at the Variable Air Valve (VAV) simulation as the electrical and fuel usage and carbon emissions were decreased and went to their minimum rates at the second simulation.
<table>
<thead>
<tr>
<th>Simulation</th>
<th>Original Case (RUP-BIM Model.xml)</th>
<th>Simulation Experiment 1 (VAV Alternative)</th>
<th>Simulation Experiment 2 (VAV and Lighting sensors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Elec. Cost (SAR)</td>
<td>138,807</td>
<td>134,804</td>
<td>133,254</td>
</tr>
<tr>
<td>Annual Fuel Cost (SAR)</td>
<td>691</td>
<td>691</td>
<td>691</td>
</tr>
<tr>
<td>Elec. Demand (KW)</td>
<td>328.4</td>
<td>320.1</td>
<td>316.7</td>
</tr>
<tr>
<td>Annual Elec Use (KWh)</td>
<td>1,478,242</td>
<td>1,435,616</td>
<td>1,419,110</td>
</tr>
<tr>
<td>Annual Fuel Use (MJ)</td>
<td>93,062</td>
<td>109,767</td>
<td>93,062</td>
</tr>
<tr>
<td>Energy Use Intensity (MJ/m²/year)</td>
<td>767.7</td>
<td>748.3</td>
<td>737.5</td>
</tr>
<tr>
<td>Carbon Emissions (MG)</td>
<td>537</td>
<td>522.5</td>
<td>515.7</td>
</tr>
</tbody>
</table>

Figure 6: Annual energy consumption
6 UTILIZING COMFORT LEVEL

COBIE (Construction Operation Building Information Exchange) is considered one of the tools that can help in the process of facility management. It is used to provide two main advantages; the first is that the extracted COBIE sheet enables a full monitoring on the building objects and a system regarding their operations and maintenance, and the second is linking all the previous stages together to track and improve IAQ (see Figure 8). All measurements coming from sensors are imported into the COBIE sheet in a new tab in tabular form matching the COBIE format as the new tab could be linked with the Sheet using the unique element identifier. Also, the Energy analysis data are imported to the COBIE using the same procedures. The method of importing sensors measurements and Energy analysis to the COBIE is performed with the aid of Visual Basic for Applications programming language (VBA). The imported measurements are compared to the standard comfort range for temperature and humidity as stated by (ASHRAE, 2013): Temperature (22-25°C) and Humidity (31-41%) and if the sensors measurements were out of the comfort range the COBIE will reflect this back on the BIM model and give alert to the user with these out of range measurements so that the user can fix the problem immediately. Alerts would be a notification email to the responsible person. Another COBIE function is its ability to give the user alerts in case of any system expected shortage due to the end of its service life. These problems may be concerned with the HVAC system, lighting system or any system that could affect the users’ comfort level regarding the IAQ.
7 CONCLUSION

This paper presented a model for tracking IAQ using BIM. The model is performed with the aid of different tools such as Revit, Bentley AECOsim, Ecotect, Green Building Studio and COBIE to increase its functionality. COBIE is extracted from the As-Built BIM model to act as a database for different measurements conducted through the building service time such as temperature, humidity, energy usage and carbon emissions. This database is frequently analyzed to make sure that the measurements are fulfilling the occupants comfort level and reports any negative incidents to the BIM model giving alerts to the model user. The paper also proposed some optimized alternatives to the existing design such as using the Variable Air Valve HVAC system instead of Fan Coil Unit and using lighting occupancy sensors instead of manual switches. These alternatives maintained the required comfort level with decreasing energy consumption and carbon emissions.

8 ACKNOWLEDGEMENT

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References


Figure 8: Sample of COBIE sheet


STATE OF PRACTICE IN PORTFOLIO MANAGEMENT: A COMPREHENSIVE SURVEY

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Abstract: There has been an increase in the practice of managing multiple projects as the number of megaprojects has decreased and firms try to manage a larger number of smaller projects. The use of portfolio management is growing in the industry to allow firms to maximize the use of their limited resources. This paper reports on the outcome of a comprehensive survey, which was supported by the Construction Industry Institute (CII) and a team of 17 experts from various firms. The survey focused on identifying contemporary portfolio management practices by asking 28 questions on five topics: firm information, makeup of a portfolio, current practices, performance metrics, and implementation. The survey was designed to give an insight into what successful owners and contractors have done in implementing portfolio management. It was found that owners approach portfolio management differently from contractors. Owners generally establish strategic business objectives and select projects and form their portfolios using their available resources. On the other hand, contractors try to win projects and follow their clients’ regulations; however, they still need portfolio management to efficiently manage their projects. A major emphasis of this research effort was the list of performance metrics used in portfolio management. Owners who successfully implemented portfolio management within their firms have practiced the use of a formal project prioritization system in a portfolio. All of these firms use dashboards with performance metrics to show the performance of a portfolio. The Main indicators found on current dashboards include cost, schedule, safety, and overall success of the portfolio.

1 INTRODUCTION

The objective of the research was to identify recommended practices for project portfolio management. In this research, a portfolio is defined as a group of related or unrelated projects and/or programs managed by a single individual, hereafter referred to as a portfolio manager. This definition was decided by the research team and is different in some respects from the standard definition in the Standard for Portfolio Management (PMI 2013), which considers meeting strategic business objectives of a firm by implementing a portfolio approach. The research team consisted of the authors and a group of 17 industry experts from CII member firms.

The research goals were covered in three main stages as shown in Figure 1. The Survey is included in the “Collect Data” stage prior to interviews and case studies. The purpose of the online survey was to
help in identifying the principle drivers, metrics, tools, processes, and techniques, of successful portfolio management and also, the main barriers to successful implementation of portfolio management in various firms. Another purpose of the survey was to help in screening and identifying the most appropriate firms for in-depth face-to-face interviews. The online survey questions were designed with the help and participation of all team members. The research team finalized the 28 questions following two goals. First, the survey was designed such that respondents could complete it in 30 minutes or less. Second, the questions were organized in a logical way so that the respondents could see the continuity of questions.

![Figure 1: Three stages of the research methodology (CII RR303)](image)

The research team made a major effort to extend the data collection beyond the CII data liaisons. For this purpose, the members of Construction Management Association of America (CMAA) and Construction Users Round Table (CURT) were contacted to increase the response rate. The research team helped in identifying and introducing individuals who could contribute to this effort.

## 2 CATEGORIES OF QUESTIONS

The survey questions were divided into five categories: 1. Firm information, 2. makeup of a portfolio, 3. current practices, 4. performance metrics, and 5. implementation.

Six questions under the “firm information” category were designed to collect information regarding the firm type, industry sectors, and the name and role of respondents. The survey was intended to gather information from all types of firms, public and private, CII and non-CII, and owner and contractor.

The “makeup of the portfolio” category included six questions to get a perspective on formation of portfolios in terms of size, duration, and dollar value of projects. Moreover, other questions were asked about the availability of individuals who managed multiple projects and their titles.

The next category, “current practices,” included seven questions. These questions attempted to collect information regarding available tools on portfolio management in 13 various areas such as schedule, cost, cash flow, procurement, resource allocation, communication, quality, scope, change management, safety, risk management, issue management, and/or Key Performance Indicators (KPIs). Moreover, some questions were about using standard tools and practices, using CII best practices, prioritizing projects, and giving authorities to portfolio managers at the portfolio level.

One of the goals of the research was to identify useful applicable metrics in different areas. Six questions under the “performance metrics” category were designed to understand the available metrics in 15 areas including the 13 aforementioned areas and overall portfolio health and success. One question was about the areas that metrics could be included in a dashboard; moreover, respondents were asked about the importance of including these 15 areas in an ideal dashboard. A five points Likert scale with 1 (least important) and 5 (most important) was used to identify the importance of areas in an ideal dashboard.

Three questions were included in the “implementation” category. These questions were designed to measure the level of portfolio management success within firms, to understand the barriers in a successful application of portfolio management, and to understand any related suggestions or comments.
3 FIRM INFORMATION

The online survey was launched using the SelectSurvey™ tool provided by the CII. The survey was sent to 306 individuals in 251 firms. This included 130 CII and 121 non-CII firms. The response rate was 45% of email recipients and 36% of firms. These rates compare favorably with similar data collection efforts using the online survey tools (Nulty 2008; Hamilton 2011; Johnson and Owens 2003). Slightly over half of those interviewed were from CII firms as shown in Table 1.

<table>
<thead>
<tr>
<th>Firm Type</th>
<th>Respondents</th>
<th>#*</th>
<th>%**</th>
</tr>
</thead>
<tbody>
<tr>
<td>CII</td>
<td>49</td>
<td>54.4%</td>
<td></td>
</tr>
<tr>
<td>Non-CII</td>
<td>41</td>
<td>45.6%</td>
<td></td>
</tr>
<tr>
<td>Owner</td>
<td>53</td>
<td>58.9%</td>
<td></td>
</tr>
<tr>
<td>Contractor/Consultant</td>
<td>37</td>
<td>41.1%</td>
<td></td>
</tr>
</tbody>
</table>

* Number of Respondents ** Percentage of Respondents

The survey was designed to get a perspective on portfolio management in different industry sectors. Respondents could select as many industry sectors as they were active in. Table 2 shows the percentage of individuals responded to the survey in different firm types. More than three-fifths of those interviewed were in heavy industry sector. Several of the firms interviewed were engaged in more than one sector of the construction industry; hence the sum of percentages goes well over 100. The firms in “Other” sector were active as consultant, manufacturer, healthcare provider, software developer, and educator.

<table>
<thead>
<tr>
<th>Industry Sector</th>
<th>Infrastructure</th>
<th>Building</th>
<th>Heavy Industrial</th>
<th>Light Industrial</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Firms</td>
<td>31</td>
<td>28</td>
<td>58</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>Percentage of Firms</td>
<td>34.4%</td>
<td>31.1%</td>
<td>64.4%</td>
<td>27.8%</td>
<td>21.1%</td>
</tr>
</tbody>
</table>

4 KEY FINDINGS AND STATISTICAL TRENDS

The analysis of responses to other four categories of questions, makeup of a portfolio, current practices, performance metrics, and implementation, are explained in this section.

4.1 Makeup of a Portfolio

Almost all firms responding to the survey have individuals who managed a group of projects. Portfolio management was practiced in 87 (96.7%) firms, and only three firms did not use portfolio management extensively. The widespread use of portfolio management indicates the necessity and relevance of the research in all industry sectors. The three firms that did not have individuals to manage multiple projects usually have very large projects managed by one person. Two of these firms still have portfolio management for small projects with a total budget of less than $5 million.

Individuals who manage a portfolio of projects have various titles. The most common title is project manager following by project director, program manager, and portfolio manager. Many firms have several titles for individuals who managed a group of projects at different managerial levels; hence the percentages do not add up to 100 as shown in Table 3. The respondents had 48 other roles in the “other” category such as senior executive, global construction manager, vice president, etc.
Table 3: Titles of individuals responding to the survey (percentages)

<table>
<thead>
<tr>
<th>Project Manager</th>
<th>Program Manager</th>
<th>Portfolio Manager</th>
<th>Project Director</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>76.7</td>
<td>38.4</td>
<td>19.8</td>
<td>41.9</td>
<td>24.4</td>
</tr>
</tbody>
</table>

The survey asked about the extent of portfolio manager’s authority in the following four areas: 1. Budget, 2. Work force, 3. Procurement strategy, and 4. Sequence of execution (schedule adjustment). The level of authorities was different depending on the positions of respondents in various managerial levels. Contractors chose “work force” and “sequence of execution” as the top two areas where authority is given to portfolio managers. The authorities varied from portfolio to portfolio, client to client, and site to site for contractors. Owners selected “budget” and “sequence of execution” as the two top areas of authority given to portfolio managers.

The topic of formation of portfolios was investigated considering the typical duration, budget, and the number of projects in a portfolio. 54% of firms do not assign more than 10 projects in a portfolio. More than one-third of respondents do not typically allocate more than six projects to a portfolio. CII owners typically have more than 50 projects in their portfolios while the majority of other firms have less than 6 projects as shown in Table 4. CII owners were mostly active in heavy industrial sector with numerous periodic maintenance needs; therefore, the typical number of projects in their portfolios was more than 50. For other firms, less than 6 projects were dominant due to the large size of the projects. In each table, the largest figure on each row is bolded.

Table 4: Typical number of projects in a portfolio

<table>
<thead>
<tr>
<th>Less than 6</th>
<th>6 to 10</th>
<th>11 to 20</th>
<th>21 to 50</th>
<th>More than 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>%</td>
<td>#</td>
<td>%</td>
<td>#</td>
</tr>
<tr>
<td>CII Owners</td>
<td>8</td>
<td>25.8</td>
<td>2</td>
<td>6.5</td>
</tr>
<tr>
<td>CII Contractors</td>
<td>6</td>
<td>35.3</td>
<td>5</td>
<td>29.4</td>
</tr>
<tr>
<td>Non-CII Owner</td>
<td>9</td>
<td>47.4</td>
<td>4</td>
<td>21.1</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
<td>8</td>
<td>40.0</td>
<td>5</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Table 5 illustrates that the most common portfolio budget range is larger than $100 million among various types of firms. The size of portfolios was mostly in excess of $10 million. Comparing the portfolio budget range with the number of projects in a portfolio, it could be concluded that firms typically form their portfolios either with many small projects or a couple of large projects.

Table 5: Typical portfolio budget range

<table>
<thead>
<tr>
<th>Less than $5 Million (M)</th>
<th>$5M to $10M</th>
<th>$10M to $25M</th>
<th>$25M to $50M</th>
<th>$50M to $100M</th>
<th>More than $100M</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>%</td>
<td>#</td>
<td>%</td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>CII Owners</td>
<td>1</td>
<td>3.2</td>
<td>1</td>
<td>3.2</td>
<td>5</td>
</tr>
<tr>
<td>CII Contractors</td>
<td>3</td>
<td>17.6</td>
<td>1</td>
<td>5.9</td>
<td>4</td>
</tr>
<tr>
<td>Non-CII Owner</td>
<td>1</td>
<td>5.3</td>
<td>2</td>
<td>10.5</td>
<td>5</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
<td>2</td>
<td>10.0</td>
<td>4</td>
<td>20.0</td>
<td>2</td>
</tr>
</tbody>
</table>

The typical duration of projects is longer than one year for over three-quarters of respondents while majority selected 12 to 24 months. On the other hand, about one-third of respondents have projects that were typically longer than two years. Over 42% of non-CII contractors selected more than 24 months as the typical portfolio budget range.
4.2 Current Practices

The questions in this section were focused on portfolio management current practices. Three independent questions asked about using tailored, innovative, standard or customized (commercial or custom-built software) tools, and a fourth question asked about tools under development for portfolio project management. Moreover, the survey asked about the use of CII best practices for portfolio management. Then, the last two questions on this section were about the use of a formal prioritizing system for projects.

4.2.1 Tailored Tools

Almost all of the firms with portfolio management practices have tailored project management tools, techniques, and processes to manage multiple projects. Tailored tools are the customized tools, which are available in the market, adjusting with organizational processes. The graph in Figure 2 shows the percentage of tailored tools used in each area for portfolio management.

![Percentage of firms using tailored tools and processes in different areas](image)

Figure 2: Percentage of firms using tailored tools and processes in different areas

The thick dashed lines indicate that the non-CII firms had higher rates of customized tools in most of the areas except resource allocation, compared to CII firms. The thin dashed lines show that owners have slightly higher rates of using customized tools in cash flow, cost, procurement, and scope while contractors have considerably higher tailored tools in other areas.

4.2.2 Innovative Tools

In the majority of firms, 37 out of 55, use innovative tools and techniques on portfolio management. Table 6 illustrates the breakdown of respondents who used innovative tools within various firm types. CII owners used innovative tools more than other types of firms. It should be noted that the term "innovative tools" could be open to interpretation by the respondents. One person’s innovative tool can be a common practice to another. Reviewing the responses showed that most innovative techniques consisted of customizing existing off-the-shelf software, however, some firms had developed elaborate software systems for their portfolio management practice.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>CII Owners</td>
<td>16</td>
<td>84.2</td>
</tr>
<tr>
<td>CII Contractors</td>
<td>5</td>
<td>50.0</td>
</tr>
<tr>
<td>Non-CII Owner</td>
<td>8</td>
<td>61.5</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
<td>8</td>
<td>61.5</td>
</tr>
</tbody>
</table>
Firms mostly used customized software in the fields of cost, schedule, change order, and information management. Owners had some common processes and procedures such as outsourcing of software services, standard stage gate process, and balanced scorecard. The Microsoft Project Portfolio Planner was used only in one owner firm. On the other hand, contractors used several tools such as web based Primavera-P6, software on iPad, and the master integrated schedule tool. One of the contractors had his own portfolio management software for managing projects around the world. A comparison between owners and contractors highlighted that the use of Primavera-P6, Portfolio Contract Management, SAP portfolio management, and EVMS were common among owners and contractors.

4.2.3 Tools under Development

Several tools are being developed in firms. Two firms were customizing Unifier Portfolio Manager for portfolio management. This software is useful when a financial goal should be set for a group of projects. Other firms are planning to use server-based software such as PMWeb, repository Citrix, eBuilder, Capex, and custom access databases. Collaborated workflow using Microsoft SharePoint was also implemented to transfer information among divisions. Primavera-P6 or other ORACLE software for Portfolio Management (Oracle R12) and SAP were commonly used by both owners and contractors.

A comparison between contractors and owners show that both were trying to securely share data among their projects and define the work flows. The use of data sharing software such as eBuilder and SharePoint were common among owners and contractors while for this purpose some customized tools were being developed by owners. Owners also used Capex and Citrix for data sharing. They were working to customize software such as Oracle Unifier, Oracle R12, and SAP for managing a group of projects.

4.2.4 Use of CII Best Practices for Portfolio Management

Over two-thirds of respondents, 47 out of 70, had never adapted CII best practices for portfolio management. CII owners used more CII best practices for portfolio management compared to CII contractors. A CII best practice is a “process or method that, when executed effectively, leads to enhanced project performance” (CII Webpage).

A few firms used CII tools for portfolio management. For example, BMC (a software company) have developed some tools based on the CII best practices. The use of CII best practices on safety, PDRI, resource allocation, lessons learned, planning for start-up, team building, front end loading (FEL), and front end planning (FEP) were noted by respondents.

A comparison between the CII contractors and owners showed that the use of PDRI was common among them. One of the owners used the Independent Project Analysis (IPA) tools and processes that are similar to CII tools. Some contractors considered their clients’ viewpoints and needs to design a customized FEL or FEP process.

4.2.5 Project Prioritization within Portfolios

The project prioritization is crucial for the survival of firms to create the highest value using limited resources. 52.9% of firms did not use a formal system of project prioritization within their portfolios. The prioritization system was used by CII and non-CII owners more than contractors. The percentage of owners who used formal prioritization was higher than those who did not.

The respondents did not specify any standard prioritization method for the projects in a portfolio. Some firms have established criteria to prioritize projects, but the prioritization method was not stated. Some firms indicated simple methods for prioritization such as project deadlines, open communication with client, weekly project meeting, safety, revenue, operation improvements, turnaround date for installation, and resource requirements. Some systematic processes were also indicated using tools such as Work Load Planner, in-house risk-based system, SaaS, and StrataJazz.

Even though multicriteria decision making (MCDM) methods are available and many research reports and case studies have been published especially on Analytical Hierarchy Process (AHP) (Vaidya and Kumar
2006) and PROMETHEE (Behzadian et al. 2010), these were not widespread within the industry. Introducing the advantages of the MCDM methods to industries could motivate them to implement a formal process for project portfolio formation.

4.2.6 Standard or Customized Software

Schedule and cost received the highest rate of software usage by both owners and contractors. Procurement and Cash Flow got the third and fourth ranks for owners while Cash Flow and Resource Allocation had similar rank for contractors. Issue and Risk Management had the lowest software usage among owners; and Scope and Issue Management software for contractors. The two most common software in 7 different areas of project management are listed in Table 7. The term “Internal” means the software was developed in-house and could be based on off-the-shelf software.

<table>
<thead>
<tr>
<th>No.</th>
<th>Areas</th>
<th>Owners</th>
<th>Common among Owners and Contractors</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schedule</td>
<td>SAP</td>
<td>Primavera-P6, MSP</td>
<td>Internal</td>
</tr>
<tr>
<td>2</td>
<td>Cost</td>
<td>SAP</td>
<td>MS-Office</td>
<td>Internal</td>
</tr>
<tr>
<td>3</td>
<td>Cash Flow</td>
<td>SAP</td>
<td>MS-Office</td>
<td>Internal</td>
</tr>
<tr>
<td>4</td>
<td>Procurement</td>
<td>SAP</td>
<td>Internal</td>
<td>Smart Plant</td>
</tr>
<tr>
<td>5</td>
<td>Resource Allocation</td>
<td>MS-Office</td>
<td>Promavera-P6</td>
<td>Internal</td>
</tr>
<tr>
<td>6</td>
<td>Safety</td>
<td>Safety Training</td>
<td>Internal</td>
<td>MS-Office</td>
</tr>
</tbody>
</table>

4.3 Performance Metrics

Six questions were included in this section. The intent was to identify the metrics that firms used and what information could be included in an ideal dashboard. The questions focused on measuring portfolio performance in 13 areas, improving metrics on these areas, visualizing the portfolio performance on a dashboard, weighting the importance of different areas on a dashboard.

4.3.1 Portfolio Performance

More than 81% of firms have metrics to measure and monitor the performance of their portfolios. Over half of the CII firms who were using portfolio performance metrics were owners. The percentage of non-CII owners using portfolio performance measures was also higher than contractors, 37.5% compared to 34.4%. The top five areas to measure portfolio performance have similar ranks among both parties. Cost, schedule, cash flow, change management, and safety were the five areas that had similar ranks among owners and contractors. Figure 3 depicts the number of respondents selected each of the areas to measure portfolio performance.

![Figure 3: Frequency of metrics selected in various areas to measure portfolio performance](image-url)
### 4.3.2 Improving Metrics in Various Areas

Owners and contractors have different needs regarding developing metrics in various areas. Less than half of respondents expressed their needs to improve metrics for the 13 areas. The highest needs to metrics improvement were respectively on resource allocation, schedule, and cash flow for owners; and schedule, resource allocation, and KPIs were identified for contractors. Figure 4 depicts the number of respondents interested in having improved metrics in various areas to measure the portfolio performance. The rank of various areas differs for owners and contractors; however resource allocation and schedule are the top two areas that need improved metrics.

![Figure 4: Frequency of areas that need improved metrics to measure portfolio performance](image)

### 4.3.3 Dashboards

59.1% of firms use some sort of dashboard to visualize the portfolio performance. A higher percentage of CII owners and contractors have a dashboard compared to non-CII owners and contractors. Table 8 depicts the statistics of respondents using a dashboard.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>CII Owners</td>
<td>16</td>
<td>45.7</td>
</tr>
<tr>
<td>CII Contractors</td>
<td>8</td>
<td>22.9</td>
</tr>
<tr>
<td>Non-CII Owner</td>
<td>9</td>
<td>29.0</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
<td>6</td>
<td>19.4</td>
</tr>
</tbody>
</table>

Cost and schedule were the top two areas that owners and contractors include in their performance dashboards. Besides cost and schedule, contractors chose change management as the third top area, while owners selected safety and cash flow as third and fourth top areas. In this paper due to space limitations, a short list of metrics is shown in Table 9 for the five major areas that performance metrics are mostly used. A complete list of metrics for 9 areas (schedule, cost & cash flow, safety & environment, change management & scope management, resource allocation, procurement & supply-chain management, quality, risk management, and client satisfaction) is available in CII document IR303-2.

Safety, cost and schedule were the top three areas that owners and contractors chose in an ideal dashboard. Therefore, an ideal dashboard should at least cover these three areas.
Table 9: Suggested KPIs for measuring portfolio performance

<table>
<thead>
<tr>
<th>Areas</th>
<th>Suggested KPIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule</td>
<td>Number / percent of milestones completed (or missed) vs. planned</td>
</tr>
<tr>
<td></td>
<td>Total / average days ahead of (or behind) schedule</td>
</tr>
<tr>
<td>Cost &amp; Cash Flow</td>
<td>Cost variation (monthly and cumulative) – at project and portfolio level</td>
</tr>
<tr>
<td></td>
<td>Number / percent of projects with costs higher (or lower) than benchmarks</td>
</tr>
<tr>
<td>Change Management &amp; Scope Management</td>
<td>Number of requests for information (RFI)</td>
</tr>
<tr>
<td></td>
<td>Total cost of scope changes/ change orders</td>
</tr>
<tr>
<td>Safety &amp; Environment</td>
<td>Incident frequency rates</td>
</tr>
<tr>
<td></td>
<td>12-month rolling average of incident rates</td>
</tr>
</tbody>
</table>

4.4 Implementation

The survey asked about the level of success in implementing portfolio management by the firms. They were also asked about the barriers in implementing portfolio management. Almost half of firms, 42.6%, rated the portfolio management success as “Average” in their firms, while less than two percent rated the implementation of portfolio management in their firms as “Best in Class.” The barriers based on the respondents’ ideas are listed in Table 10.

Table 10: Barriers in implementation of portfolio management

<table>
<thead>
<tr>
<th>Lack of industry standards and best practices and available training</th>
<th>Unclear objectives and priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>• There are no comprehensive standards or best practices.</td>
<td>• There are no written objectives and the prioritization changes over time.</td>
</tr>
<tr>
<td>• There are some tools and best practices but they require customization so that they can be applied to each case.</td>
<td>• Sometimes the prioritization of criteria are not comprehensive and cause conflicts among departments.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lack of management support or direction</th>
<th>Cost of implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• There are conflicting ideas among managers at different levels.</td>
<td>• Software is expensive and needs too much customization.</td>
</tr>
<tr>
<td>• The managers’ knowledge is not the same and it causes resistance.</td>
<td>• Data is not centralized and cannot be passed among projects easily.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lack of awareness of value added</th>
<th>Lack of common code structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>• It is hard to quantify the value added to the company.</td>
<td>• There is no consistency between different departments within some firms regarding cost codes.</td>
</tr>
<tr>
<td>• The knowledge of senior managers is crucial for portfolio management improvement.</td>
<td>• There are no standard requirements for owners.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Management interference</th>
<th>Lack of previous success</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The objectives are not clear for managers.</td>
<td>• Commercial and custom tools have sometimes not been effective.</td>
</tr>
<tr>
<td>• The organizational structure is not appropriate.</td>
<td></td>
</tr>
</tbody>
</table>
5 CONCLUSIONS

Portfolio management is used by almost all of the firms that participated in this survey. The majority of firms are utilizing software tools to better manage their portfolios. The survey has identified various areas where these tools are used, with the top three areas being schedule, cost, and procurement. Primavera-P6 and MSP are the two major tools in the area of schedule while SAP and internally developed tools are used for cost. SAP, Smart Plant, and internally developed software are used in the area of procurement for portfolio management. In all of the areas except schedule, firms have tailored existing tools or developed custom-built software to better adjust with their processes.

Firms use a combination of KPIs to track and measure the performance of their portfolios. The most common KPIs on dashboards are in the areas of cost and schedule. Change management is important for contractors as the third KPI and safety and cash flow for owners. The ideal dashboard should include at least three KPIs, cost, schedule, and safety.

The survey showed that even though portfolio management has been practiced in firms for more than 30 years, it still has some barriers such as standardization of processes, centralization of databases, prioritization systems, customization of dashboards, and generalization of concepts, justification of benefits to cost of implementation. Removing these barriers, which may be the subject of future research, can assist firms to improve the efficiency of their resources while pursuing their strategies.

Acknowledgements

We gratefully acknowledge the financial support provided by the Construction Industry Institute (CII). The cooperation of a wonderful team of experts from nine owner and eight contractor firms is also acknowledged.

References


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Construction Industry Institute (CII). 2015. Managing a Portfolio of Projects – Metrics for Improvement, RR303, The Univ. of Texas at Austin, Austin, TX.


A FRAMEWORK FOR CLASSIFYING BIM DESIGN COORDINATION ISSUES.

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Abstract: Design coordination and conflict detection are the most common and highly valued uses of Building Information Modeling (BIM). The process is essential as critical design decisions are often made in this stage. BIM promises to support automatic evaluation of building design, rather than the manual, iterative and time-consuming evaluation of CAD drawings. However, we have observed that current BIM tools are unable to identify many types of design coordination issues and that these issues are particularly challenging to manage and resolve. This research is based on ethnographic field studies of two building design coordination processes, examining how practitioners identify, resolve and document design issues during design coordination process. We coded and analyzed over 60 meetings to investigate the characteristics of BIM design coordination issues, and developed a framework based on prior research and our own observations to classify design coordination issues. We classified design coordination issues into seven categories of spatial, clearance, physical, inquiry, systematic design errors and missing information. We also observed and analyzed design issues' frequency of occurrence, and investigated the resolution rate of design issues. We believe our characterization of design issues can help practitioners better identify, categorize, resolve, and document design issues, as well as re-using generated knowledge of resolving same type of issues throughout design coordination.

Keywords: BIM, Design Coordination, Design Issue, Errors, Clash Detection, Collaboration, Interactive Workspaces, Design Artifacts, Building Systems, MEP coordination.

1 INTRODUCTION

In complex building projects, design coordination is a critical and challenging task. It involves the detailed layout and configuration of the various building systems such that it complies with design, construction, and operations criteria (Tatum and Korman 2000). Recent advancements in Building Information Modeling (BIM) tools have had a significant impact on the efficiency and efficacy of the design coordination process. Studies have shown that design coordination and conflict detection with BIM is one of the most frequent and valued uses of BIM in the construction sector (Bernstein and Jones 2012). Communication of project information through paper-based information representations limits the team’s ability to work together, to solve problems and make decisions during design meetings (Fischer et al. 2002). In contrast, teams using BIM tools for Mechanical Electrical & Plumbing (MEP) coordination are
found more likely to be satisfied with the meeting process and spend less time arguing over issues compared to paper based design coordination meetings. (Liston, Fischer, and Kunz 2000).

BIM supports the automatic evaluation of building design, rather than the manual, iterative and time-consuming evaluation of CAD drawings (Lee, Park, and Won 2012). However, we observed that not all design coordination issues are identifiable using state of the art BIM tools, specifically the design issues that are not geometrically identifiable (using the geometry of building components to automatically detect conflicts). Prior research (e.g. Tabesh and Staub-French (2006), Wang and Liete (2014)) have addressed many aspects of design issues including their context and classification. However, they focused on design issues that are geometrically identifiable (e.g. conflicts between two components), rather than non-geometrically identifiable (e.g. inquiries, and missing model components).

We conducted two ethnographic case studies of complex building design coordination processes using state of the art BIM tools. We characterized the design issues practitioners identified, resolved and documented throughout design coordination, through developing a framework for classifying design issues based on prior studies and our own observations, analyzing their frequency of occurrence in both case studies, and investigating the resolution rate of the design issues in one of the case studies. We found that the case study in early construction stage, involved more design issues of constructability and incorrect design details whereas the one in late construction stage faced more design issues of inquiry, and as-built missing components.

2 MOTIVATING CASE STUDIES

We performed two ethnographic field studies of design coordination processes to gain a better understating of the current practice and identify its shortcomings. Over the course of design and construction, BIM was used extensively to coordinate designs involving different consultants and sub-trades. In both projects, the meeting participants consisted of representatives from the different trades involved in the project, including the owner, the construction manager, architect, engineering consultants and construction sub-trades. The meetings always had at least six active participants and in most cases the MEP coordinator and the BIM navigator were present. On some occasions, when a participant was not present, he/she participated remotely through conference calls or online video conferencing tools.

Case study A: The newly constructed Pharmaceutical Sciences Building (Figure 2) at the University of British Columbia, Vancouver campus is a 18,000 m² facility, providing a variety of teaching and learning spaces from lecture halls and seminar rooms, to a pharmacist clinic and three floors of research laboratories. The project had considerably complicated MEP systems along with a unique architectural design, which made design coordination and constructability the key concerns for this fast track project. Since the beginning of construction, weekly meetings were held in our BIM Trailer (Figure 1) on the construction site. The BIM Trailer was equipped with two large-screen touch displays, connected to separate computers displaying 2D and 3D digital information. Construction of the project started in June 2010 and the building was delivered on time for occupancy in September 2012. Most participants were the ones creating the BIM for trades, so they had considerable experience with BIM. However, few participants were less familiar with interactions with BIM and digital tools.

Figure 1: Meeting environment from a design coordination meeting in case study A.
Case study B: currently under construction (early construction stage), the Royal Alberta Museum (Figure 3) building project involves the construction of a 25,349 m² building located in downtown Edmonton, Alberta on a site measuring 20,024 m². The project, in its current state, was initiated in 2011 under a design-build procurement mode. The total budget for this project is $340M while the construction budget alone is $260M. The project is scheduled to be completed in June of 2016. In terms of level of expertise with BIM, most project participants have no experience (35%) or consider themselves as beginners (35%) while 22% consider themselves advanced BIM users. We remotely participated, recorded and observed participants conducting design coordination, as well as observing and analysing various design coordination issues participants identified, resolved and documented throughout design coordination.

2.1 Design Coordination Issue Resolution Process

Based on our observations, we have come to understand that resolving a design coordination issue using BIM involves a cycle of three interconnected steps: Issue preparation (identification) issue resolution and issue documentation (Figure 4). Each of these design coordination steps shown in Figure 4 are comprised of smaller (micro) steps that shape the current practice of identifying, resolving and documenting BIM design coordination tools. This section attempts to better illustrate the micro steps involved the process as well as highlighting the observed challenges practitioners face throughout design coordination process. We elaborate this by showing how one particular issue which we observed was identified, resolved and documented in a case study.

Figure 4 - BIM design coordination process

Figure 5 - image 1 shows an issue the BIM navigator picked among hundreds of geometrically identified issues. He examined it in detail, and communicated it with project coordinator. In the same figure - image 2, shows how the coordinator zoomed out to inspect the issue. He then communicated it with different building systems representatives and found the need for a group discussion. He prepares another view (Image 3) to better outline the issue and the systems involved prior to issue resolution meeting.
To better show the remaining steps involved in resolution of above design issue, Figure 6 – images 1 and 2 shows how that issue was presented, shown and discussed in the coordination meeting as well as how participants interacted with the design artifacts. In image 3, the architect sates that the issue needs to be further discussed as input from other project stake holders are required. At this stage the coordinator determines that the issue needs to be documented for future follow-ups.

In terms of issue documentation, once the discussion on a certain issue reached an end (e.g. resolved, required further input from a different source, or needed follow up in the future), depending on the importance of the issue, the coordinator documented the details of each issue including its status, location, involved systems, snapshot(s), entry and solution dates, proposed solution and details of how it could be resolved in a spreadsheet containing all issues (Figure 7). In both projects A & B, the same documentation format, and details were used to document the issues. However, in project A, participants kept all resolved and non-resolved issues in a single file, and in case study B they used multiple files.

Figure 7: Design Issue Documentation
2.2 Limitations of Current Practice

Although the current process of identifying and preparing Issues seem ad-hoc, often when two building systems are integrated using state of the art BIM tools, thousands of design conflicts are detected, including numerous false ones. As Table 1 shows, the issues involved in design coordination sometimes go beyond simply geometrically detected design issues. Such design issues involve practitioners' knowledge and expertise to be able to be identified. In prior research this is often called practitioner’s rationale (Tommelein and Gholami 2012), which requires deep understanding of different construction systems, requirements and the codes.

While attempting to classify the issues observed in both case studies, we were unable to classify observed issues using the current points of departure in the field. Although previous studies (e.g. Tabesh and Staub-French (2006), Tommelein and Gholami (2012), Wang and Liete (2014), and Lee, Park, and Won (2012)) have effectively addressed major geometrically identifiable design coordination issues (e.g. a mechanical duct conflicting with structural column caps), few research characterized issues that are more complex in nature and are not identified through model based automatic clash detection (we call these non-geometrically identifiable). Design issues such as inquiries about maintenance and installation, or wrong dedicated openings in different systems (Table 1) have a significant impact on the design coordination process.

Table 1: non-geometrically identifiable design coordination issue examples

<table>
<thead>
<tr>
<th># &amp; Case Study</th>
<th>Description</th>
<th>Snapshot</th>
<th># &amp; Case Study</th>
<th>Description</th>
<th>Snapshot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - A</td>
<td>Structural floor opening is not big enough for the mechanical duct (1025X350)</td>
<td></td>
<td>2 - B</td>
<td>Plumbing conflicts W/ access ladder – confirm if there is enough room to climb ladder.</td>
<td></td>
</tr>
<tr>
<td>3 - B</td>
<td>HVAC duct vs. cable tray vs. column cap. Ask UBC – if ceiling can be lowered.</td>
<td></td>
<td>4 - B</td>
<td>Electrical lighting conflicts W structural beams. Cannot fit any lights. Lighting system change required.</td>
<td></td>
</tr>
</tbody>
</table>

Most researchers (Inc. Tabesh and Staub-French 2006, Tommelein and Gholami 2012, Wang and Leite 2012) have focused on geometrically identifiable design issues, however, we believe there is a need for a wider framework that can address and classify both geometrically and non-geometrically identifiable BIM design issues. We believe having access to such framework can improve design issue identification and documentation for BIM based design coordination processes. We envision having a framework combined with a central repository for design issues for classifying design issues can help practitioners classify design issues from the beginning of issue identification, track issues throughout their resolution and help with issue documentation throughout the BIM design Coordination process.

3 RELEVANT LITERATURE

This research has built on findings of past research as a foundation of the framework we have developed in section 5.1. although different researchers have used different terminologies (including design errors, conflicts and MEP clash) for referring to what we call BIM design coordination issue (design issue in short) in this article, there are notable similarities between their research and ours that helped us
significantly to build the framework. In this section we aim to address these points of departures briefly and highlight what we have built on:

As one of the pioneers of design coordination issue characterization, (Korman, Fischer, and Tatum 2003) classified design issues into three main categories of design criteria, construction, and operations issues. They also identified design issue attributes as geometric characteristics (component dimensions) and topological characteristics (spatial relationships). This work later on became a foundation to which (Tabesh and Staub-French 2006) built on to further classify design issues as tasks of conceptual reasoning (i.e., design validation, detailing, and sequencing), spatial reasoning (i.e., layout, routing and positioning) and underlying reasons behind the constraints identified in each discipline (i.e., tolerance, productivity, space, performance, access, safety and aesthetics).

Other researchers such as (Wang and Liete 2014) attempted to address design issue resolution knowledge capture, they attempted to provide a formalized representation schema for MEP coordination to present factors involved in cash analysis, clash resolution and management. Similar to this study their schema was developed based on literature review and findings of two case studies. On the other hand, they solely focused on geometrically identifiable issues, covering clash description, clash context, clash evaluation, and clash management items. In another attempt, while proposing a structured method for analysing BIM’s return on investment other research (Lee, Park, and Won 2012) classified design issues in terms of their cause, likelihood of identification, impact on schedule, impact on quality and impact on direct cost.

Previous research mainly focused on characterizing geometrically identifiable design issues for BIM building design coordination meetings. Most issues identified in the previous research focused on the components itself. These included highlighting BIM’s capabilities and strength for visualization of design issues (Tabesh and Staub-French 2006), representing geometrically identified clashes (Wang and Liete 2014), and formalizing knowledge representation for clashes (Tommelein and Gholami 2012). BIM design coordination issues are comprised of both non-geometrically and geometrically identified design issues. Non-geometrically intedentified issues are mostly manually identified, often comprising of multiple geometrically identified design issues. Although the current research has provided a good point of departure for characterizing and classifying design issues, our findings suggest that there is a need a for a better design issue classification framework that can address all design issues in BIM design coordination processes.

4 METHODOLOGY

We observed (in-person and remotely) and video recorded weekly design coordination meetings from the early stages of design through construction of the building systems, recorded over 43 design coordination meetings of which 32 meetings were held in our BIM trailer on case study A, observed the design coordination process in case study B through design and early construction of building structures, and analysed design coordination meetings in both case studies A & B. We conducted a qualitative assessment of the meetings initially to determine our focus area for a detailed analysis. We had access to construction documents, BIM files, site progress, design issue spreadsheets and some of the communication between project participants.

In particular, we investigated how design issue were identified, communicated among project coordinators and navigators, presented and resolved issues, their documentation approach and their future follow-up regarding each issue. We considered each issue first and tracked how that issue was identified through checking the BIM files of each meeting, how it was resolved through observing specific segments of the meeting related to that issue and by analyzing participants’ notes and issue documentation spreadsheets regarding each issue. This methodology enabled us to conduct most of our research qualitatively, rather than the quantitatively.

In addition, in order to investigate issue identification process in detail, we conducted a think-aloud observation (Lewis, 1982) while a BIM Navigator performed issue preparations on a high-rise multipurpose facility in Vancouver, BC. We asked the navigator to say whatever he was looking at,
thinking, doing, and feeling as he performed task. This enabled us to see first-hand the process of task completion. We observed how the navigator performed 3D model integrations and clash detection, distinguished between true and false clashes, communicated with the project coordinator to discuss each issue and prepared the coordination meeting agenda. This observation method helped us to better capture how design issues are identified and how participants communicate and work together prior to meetings.

Throughout this study, we have aimed to build our research methodology based on recommendations of (Green, Kao, and Larsen 2010). We are following their research protocol to continuously compare collected data and search “for resonance with conceptual ideas derived from ongoing literature searches”. Figure 8 shows our adaptation of methodology for their suggested methodology for generating theory through ethnographic case study. This methodology has allowed us to continuously improve our findings as we studied the literature.

5 CHARACTERIZATION OF DESIGN COORDINATION ISSUES

5.1 Design Issue Classification Framework

As discussed above, through observation and characterization of design issues in both case studies A & B, we found essential points of departure to help us better shape our understanding of issue classification. In Table 2, we have shown various design issues we observed along with their identification (detection) method, category, sub description, example of an actual issue that we captured, as well as a snapshot of that issue, to better elaborate our classification of the design issues. We also have identified the design issues previously identified by each key point of departure. The key points of departure used in the framework are respectively (Korman, Fischer, and Tatum 2003),(Tommelien and Gholami 2012),(Wong and Lelle 2014), and (Lee, Park, and Won 2012).

To elaborate further on what we have built on in terms of classification of design issues from the existing knowledge, we have adopted he most common classification of design issues: hard (actual) and soft (extended) ((Korman, Fischer, and Tatum 2003) and (Tabesh and Staub-French 2006)). As well as the time clash which refers to constructability and order of components being installed (Tommelien and Gholami 2012). We also built on (Lee, Park, and Won 2012)’s identification design issue causes: illogical design, discrepancies between drawings, and missing items. These classifications are explained below.

5.2 Analysing Design Issues in Case Studies A & B

We have classified the observed issues in both case studies A & B based on our developed framework (Table 2). The issues in each case study were investigated independently based on what the practitioners have documented and our own observations of the meetings. Having two case studies helped us to validate and evaluate the framework. During the analysis of the issues, the framework was re-iterated multiple times, revisiting issue categories, terminology and examples multiple times to ensure all design issues in both case studies could be classified using the developed framework. Also, having two case studies helped us achieve a wider generalizability for the developed framework. In total we analysed 98 issues from case study A and 120 issues from case study B (Figure 9). The figures show each design issue sub-category using different colours, as well as their frequency of occurrence in relation to total number of issues in each case study in a percentage format.

As Figure 9 shows, both projects nearly equal proportions of issues due to systematic design errors, these include illogical design, trade design conflict, and multiple systems conflicts. However, due to the stage of each case study the design issues handled by each team differ.
Table 2: Framework for classifying issues in BIM design coordination

<table>
<thead>
<tr>
<th>Geometrically Identified</th>
<th>Spatial</th>
<th>Time</th>
<th>Components occupying the same space-constructability / operability</th>
<th>Duct connecting to level 2 runs in corridor along same route as cable tray</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Spatial</td>
<td>locations of components jeopardize the intended function of component</td>
<td>Location of heating unit next to HVAC duct. Interferes W function of systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Functional</td>
<td>Components interfere with extended spaces (e.g. Access)</td>
<td>Plumbing conflicts W access ladder – is there enough room to climb ladder?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Functional</td>
<td>Physical interferences BW 2 single components</td>
<td>HVAC duct collides W column</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Functional</td>
<td>Physical interferences BW components , multiple times</td>
<td>Column colliding with Ducts in all floors.</td>
</tr>
<tr>
<td>Non-Geometrically Identified</td>
<td>Systematic Design Error</td>
<td>Illogical design</td>
<td>System wide conflicts Due to lack of coordination BW trades.</td>
<td>Mechanical duct conflicts with structural concrete beam.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple Systems Conflict</td>
<td>Multiple building systems are involved in a single area.</td>
<td>HTG, CHW, sprinkler main, FCU, cable all required to fit in ceiling under slab band</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trades Design Conflict</td>
<td>Condensed Systems, Essential change of type, systems required</td>
<td>Electrical lighting conflicts W structural beams. Cannot fit any lights.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incorrect Design Details</td>
<td>Not design to fit, too big, to small openings. Too big to bring in</td>
<td>Structural floor opening is not big enough for the mechanical duct</td>
</tr>
<tr>
<td></td>
<td>Missing Information</td>
<td>As-Built Missing</td>
<td>As built missing/ installation info not provided</td>
<td>Location of mechanical duct openings in metal wall panels.</td>
</tr>
<tr>
<td></td>
<td>Missing Information</td>
<td>Object Related Info Missing</td>
<td>Details related to specific components missing</td>
<td>Dimensions of mechanical component not specified</td>
</tr>
<tr>
<td></td>
<td>Missing Information</td>
<td>Modeled Component Missing</td>
<td>Model of component not ready yet, or needs remodeling.</td>
<td>Pipework clashing with duct- waiting for final Architectural model</td>
</tr>
<tr>
<td></td>
<td>Inquiry</td>
<td>Inquiry</td>
<td>More info needed regarding model details</td>
<td>Is cable tray required along south side of room?</td>
</tr>
</tbody>
</table>

Since, case study A was in the handover phase whereas case study B only had its major structure built at the time of this study, it is not surprising to see case study A’s time design issues (constructability) twice the size of design issues in case study A. On the other hand, we can see more inquiries in case study A, which could be due to the final stages of the project where multi project stake holders require different things.

In addition, it is not surprising to see no design issues relating to as built models, since there were little mechanical components installed at the time of design coordination. However, it is noticeable that incorrect design detail issues (e.g. wrong opening sizes) were almost 3 times higher in case study B. this could reflect the miss-coordination between different system prior to construction phase. In addition, missing model components contributed to an average of 7% of design issues in both case studies, which can emphasis on the importance of having every discipline meeting the coordination deadlines.

5.3 Analyzing Issue Resolution Rate

Classifying the design issues in the previous section, we found that in some issue resolution meetings, participants identified and resolved more issues than others. Also, towards the end of construction on case study A, a large number of design issues remained un-resolved on the documents. Therefore, we conducted an issue resolution rate study to better understand how often design issues were added, resolved and how many of them remained unresolved by the end of each meeting. We performed this study by tracking and analyzing issues of 12 consecutive design coordination meetings (Figure 10). These 12 meetings were the last design coordination meetings for case study A.

Furthermore, it is surprising that 20% of the design issues remained unresolved by the end of design coordination stage (final days of construction). We believe some of these issues could have been resolved on site, or they were not on the priority to-do list. Also, we observed that participants often spent
Finally, in terms of design issue documentation, we observed when design coordination meetings were poorly documented, the result had a direct influence as to preparations of the next meeting. For instance, in one occasion, the meeting coordinator could not attend the meeting and no other participant was in charge of the meeting documentation and task assignment, as a result the first 30 minutes of the next meeting was dedicated to revise prior progress and the meeting ended early as the necessary models were not prepared by responsible trades for design coordination.

6 CONCLUSION AND FUTURE WORK

We have conducted two ethnographic field studies to understand how participants identify, resolve and document design coordination issues in BIM based building design coordination processes. We developed a framework to classify both geometrically and non-geometrically identifiable design coordination issues, analyzed two case studies based on developed framework, investigated design issue resolution rates, and highlighted the role of documentation on issue preparations of subsequent meetings. Our characterization identified the non-geometrically identifiable design issues that were rarely identified in the previous research.

We believe further validation strategies are required at this stage in order to highlight the shortcomings of the developed framework. In particular we envision conducting feedback sessions with practitioners to ensure that the developed framework resonates with their knowledge. Other strategies could include performing industry workshops, in order to capture insights of other practitioners specifically not those in Feedback Sessions to achieve wider generalizability.

References


MULTI-OBJECTIVE SCHEDULE OPTIMIZATION USING CONSTRAINT PROGRAMMING

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Abstract: This paper describes the development of a constraint programming (CP) model for schedule optimization to satisfy both deadline and resource constraints in large-scale construction projects. Unlike many meta-heuristic methods in the literature, the CP model is fast and provides near-optimum solutions to projects with hundreds of activities. The IBM ILOG modeling software and its CPLEX-CP solver engine have been used to develop the proposed CP optimization model for solving the multi-mode resource-constrained project scheduling problem. The model takes many constraints into account, including project deadline, penalty (liquidated damages), incentive, and multiple resource constraints. The paper compares the CP results with the results of other methods, such as heuristic and genetic algorithm optimization, on case studies from the literature to prove the practicality and usefulness of the CP model. The paper also reports the results of CP optimization on larger projects of 1,000 to 2000 activities, which is common in construction practice, and is too large to be solvable by other methods. This research contributes to developing a practical decision support system for resolving real-life constraints in construction projects.

1 INTRODUCTION

Optimizing construction schedules has concerned many researchers in the past decades. In the literature, a broad category of schedule optimization models are referred to as multimode resource constrained problems, when each activity has more than one mode of execution with different resource requirements and costs. In the multimode problems, the main optimization objective has been either:

(a) Minimize the total project duration, while not exceeding resource limits. This problem has been referred to as (Multimode resource constraint scheduling problem, or MRCSP), or

(b) Minimize the total project cost, while not exceeding resource limits or a deadline constraint; which is referred to as (Multimode resource constraint time-cost trade-off, or RC-TCT).

While both cases involve multi-modes and resource constraints, case (b) is more general as it considers both cost and time in its formulation. Despite the extensive research in the literature in both aspects, no commercial software includes any time-cost trade-off (TCT) heuristic to help meet deadlines, let alone any procedure to resolve both deadline and resource constraints. One of the main contributing reasons, perhaps, is that both of these problems are known to be nondeterministic polynomial-time hard (NP-hard), which are very difficult to solve, particularly for large-scale problems.

In the literature, there is a large body of knowledge related to resolving either the RC-TCT or MRCPS problem. Each problem by itself is considered a large-scale problem that has a large number of possible solutions, even when few activities are considered. In general, however, each of these problems has been addressed by three types of techniques, as follows: (1) traditional mathematical (exact), (2)
heuristic, and (3) metaheuristic (artificial intelligence-based). Good surveys of the exact, heuristic, and metaheuristic procedures for the MRCPS P and the RC-TCT problems are found in Peteghem and Vanhoucke (2010), and in Menesi and Hegazy (2014), respectively.

To the writers' knowledge, none of the literature efforts of the three solution types have addressed large-size problems. Most efforts discussed small demonstration examples of 10 or 20 activities and the few efforts that handled medium-size problems (a few hundred activities) required an unreasonably large time to provide a solution. Kandil and El-Rayes (2005), for example, reported a GA processing time of 55 h for a case study of 360 activities, which was reduced to 9.3 h using a system of parallel computing with 50 processors. One of the latest efforts to handle large-scale problems is the heuristic model of Hegazy and Menesi (2012) for resolving the RC-TCT problem. Their case study of 360 activities required 32 minutes to be solved, which is much faster than GAs, for the same size problem. However, even this heuristic method is expected to take many hours in the case of much larger problems than 360 activities, thus the key drawback of these methods is that finding near optimal schedules for large scale is very time-consuming and solution quality greatly degrades with problem size (Hegazy and Menesi 2012; Menesi et al. 2013; Ling and Fang 2011). The primary objective of this paper, therefore, is to introduce a new model using constraint programming (CP) to provide fast near-optimum solutions to much larger-scale multimode optimization problems, thus providing a practical approach to optimize construction schedules.

2 CONSTRAINT PROGRAMMING

Constraint programming (CP) has been successfully used to solve complex combinatorial problems in a wide variety of domains (Chan and Hu 2002; Heipcke 1999) by combining operations research and logic programming techniques. To facilitate the use of CP algorithms in scheduling problems, IBM developed a powerful software library, called IBM ILOG CPLEX Optimization Studio (Beck et al. 2011). It incorporates a CP engine (with IBM ILOG CPLEX CP Optimizer) that has specialized syntax for modeling scheduling problems and other combinatorial problems that cannot be easily linearized or solved using traditional mathematical programming methods. The CPLEX-CP optimizer defines the scheduling problem by: a set of time intervals representing activities to be completed; a set of constraints that apply during these intervals or between intervals; and an objective function. Once the model is coded using the modeling language of the IBM ILOG tool (as discussed in the next section), the problem is solved by the CPLEX-CP solver engine using two techniques to find a solution: constructive search and constraint propagation (initial and during search). The initial constraint propagation removes the possible variable values that will not take part in any solution, thus reducing the search space. The constraint propagation during the search, on the other hand, removes all values that violate the constraints. The CP optimizer then uses a constructive search strategy to guide the search for a solution in the remaining part of the search space. The CP optimizer engine continues to search using constructive search and constraint propagation until a solution is found. In the literature, various researchers reported the advantages of CP in scheduling problems. Efforts include Liess and Michelon (2008) for solving the resource-constrained project scheduling problem; Liu and Wang (2008) for solving resource-constrained project scheduling problems considering cash flow; Liu and Shih (2009) for construction rescheduling optimization; Liu and Wang (2011) for optimizing overall profit and satisfying various resource constraints; and Menesi et al. (2013) for time-cost-resource optimization in large-scale projects.

3 CP MODEL FOR SCHEDULE OPTIMIZATION

3.1 General activity representation

Consider a construction project with \( n \) activities, each activity \( i \) has a set of associated construction methods \( (M_i) \). Each method \( k \) (from 1 to \( M_i \)) represents a construction mode or a way of carrying out activity \( i \). Associated with this method \( (k) \) is a specific duration \( (d_{ik}) \), cost \( (c_{ik}) \) and resources \( (r_{ik}) \). Naturally, these construction methods vary from cheap-and-slow to fast-and-expensive, thus offer ways to speed the activity, if needed. Based on these construction options, the planned duration \( (D_i) \) and direct cost \( (C_i) \) of each activity \( i \) can be expressed as a function of which method is used, as follows:
Where, \( X_{ik} \) is a binary variable that indicates which method \( k \) is planned for activity \( i \). Thus, if \( X_{ik} = 1 \), then method \( k \) is the one used for activity \( i \), while \( X_{ik} = 0 \) for all other methods. To make sure only one mode of construction is used for each activity, one constraint is needed for each activity, where the sum of the method indices \( X_{ik} \) s should equal to 1.

\[
\sum_{k=1}^{M_i} X_{ik} = 1 \quad i = 1, 2, \ldots, n \quad (3)
\]

**Network Logic Constraints:** The network logic is defined in a set of hard constraints. The logical relationship between any activity \( i \) and its immediate predecessor \( p \), is expressed as:

\[
SS_i - SF_p \geq 0 \quad p = 1, 2, \ldots, NP \quad (4)
\]

Where \( SS_i \) is the scheduled start time of activity \( i \); \( SF_p \) is the scheduled finish time of the predecessor activity; and \( NP \) is the number of immediate predecessors for activity \( i \).

**Resource Constraints:** The project resource constraints are expressed in the model as follows:

\[
\sum_{i \in S_t} r_{ikl} \leq R_{lk} \quad l = 1, \ldots, L; \quad t = 1, \ldots, T \quad (5)
\]

Where, \( S_t \) is the set of eligible activities in time period \( t \), \( r_{ikl} \) is amount of resource \( l \) required by construction method \( k \) of activity \( i \), \( R_{lk} \) is the amount of resource \( l \) available in time period \( t \), \( L \) is number of resource types, \( t \) is the time period \( (t = 1, \ldots, T) \), and \( T \) is project completion time.

### 3.2 Problem-specific formulation

**Case of MRCPSP problems:** Objective Function is to minimize the project duration \( T \), as follows:

\[
\text{Minimize } T \quad (6)
\]

Where \( T = \) Maximum scheduled finish time \( SF_p \) among all activities

**Case of RC-TCT problems:** At the project level, the direct cost of the project is noted as \( PDC \) and the indirect cost as \( PIC \), thus, the total project cost \( (TPTC) \) can be expressed as:

\[
TPTC = PDC + PIC \quad (7)
\]

Where, the project direct cost is the summation of the activities’ direct costs in Eq. 2, as follows:

\[
PDC = \sum_{i=1}^{n} C_i = \sum_{i=1}^{n} \sum_{k=1}^{M_i} c_{ik} X_{ik} \quad (8)
\]

The project indirect costs, on the other hand, are project-duration dependent; the longer the project duration, the more indirect costs are incurred and vice versa. The relationship between \( PIC \) and the project duration \( (T) \) can be expressed as:

\[
PIC = IC_0 + IC \cdot T \quad (9)
\]

Where \( IC_0 \) is the fixed indirect costs (e.g., permits, mobilization cost, temporary hookups, temporary facilities, purchase advances), and \( IC \) is the indirect cost per time period (i.e., daily expenditures), and \( T \) is the total project duration. To consider practical scheduling situations, the model adjusts the total project
cost considering penalty and incentives amounts. If the project schedule is delayed beyond a defined
deadline, the delay cost \( C_{pd} \) is expressed as:

\[
C_{pd} = Y \times C_d \times (T - \text{deadline duration})
\]  \hspace{1cm} (10)

Where: \( Y \) is a zero-one variable representing if a project delay occurred (i.e., \( Y = 1 \) if the project duration \( T \) is greater than the deadline duration), and \( C_d \) is the cost of project delay per day (i.e., delay penalty).

On the other hand, if the project is scheduled to finish before the deadline, the incentive for early completion is expressed as:

\[
IN = Z \times B \times (\text{deadline duration} - T)
\]  \hspace{1cm} (11)

Where \( Z \) is a zero-one variable representing if the schedule is completed earlier than the deadline (i.e., \( Z = 1 \) if project duration \( T \) is less than the deadline duration), and \( B \) is the incentive per day saved.

**Project Completion Constraint:** The project completion constraint is expressed as:

\[
SF_e \leq \text{Deadline Duration} \quad E = 1, 2, \ldots, NE
\]  \hspace{1cm} (12)

Where: \( SF_e \) is the finish time of ending activities, \( NE \) is the number of ending activities.

Objective Function is to minimize the sum of the costs described above, formulated as follows:

\[
\text{Minimize } C = TPC + C_{pd} - IN
\]  \hspace{1cm} (13)

### 3.3 Multi-objective CP Model

In addition to the above single-objective multimode model in which the objective was to minimize the total duration or cost, another bi-objective multimode model was developed to include a secondary objective to minimize the fluctuations in the resource usage (resource leveling). The resource leveling problem itself is also a NP-hard problem and aims at achieving the most efficient resource utilization by reducing the peaks and valleys in the resource usage profile, without increasing project duration (Ponz-Tienda et al. 2013). One of the benefits of CPLEX-CP is that it has an internal function staticLex that can define an objective function with multiple objectives, with the first objective being most important, and so on. Utilizing this function, a multi-objective version of the CP model was developed with two objectives: (1) minimize project duration for MRCPSP problems or minimize project total cost for RC-TCT problems; and (2) minimize the peak resource demand. This is based on the fact that reducing the peak use of resources results in a more levelled resource profile.

### 4 IMPLEMENTATION AND RESULTS

Both of the proposed single-objective and multiple-objective CP formulations have been modeled in IBM ILOG CPLEX Optimization Studio, as shown in Figure 1. The figure shows a portion of the CP code and the ILOG modeling environment. Once developed, the CP models were applied to literature case studies.

#### 4.1 Experiments on the MRCPSC problem

The developed CP models for MRCPSC was applied to a 10-activity project reported in Zhang (2012) who compared the solutions among three metaheuristic methods, and thus can be readily compared with those of the CP model of this paper. Each activity in the project has up to three modes of execution and one type of renewable resource. The project network and the three modes for each activity are shown in Figure 2. The available amount of resources is limited to 5 resource units per day.

#### 4.2 Single-Objective Experiments on Small Projects

The results of single-objective CP optimization were compared with the results of three metaheuristic methods for the case study reported in Zhang (2012): ant colony optimization (ACO); particle swarm optimization (PSO); and genetic algorithm (GA). The comparison of results shows the superior performance of the CP model in terms of solution quality and processing speed. Repeating the
experiments several times for this 10-activity case, the ACO algorithm could achieve the best result (14 days) only 81% of the time, which is better performance than PSO and GA. The CP solution, on the other hand, achieved the 14-day optimum solution in all experiments. To verify the CP solution, the resulting activities’ start and finish times were entered into Microsoft Project Software, as shown in Figure 3a. The figure verifies that project duration is shortest, non-critical activities are not crashed, and that the resource-loaded schedule does not exceed the resource availability limit.

![Figure 1: ILOG CPLEX Optimization Studio](image1)

![Figure 2: Project network and activity modes for a 10-activity case study project](image2)
Single-Objective Experiments on Medium and Large Projects: Experiments on medium and large-scale projects were carried out. The 10-activity project of Zhang (2012) was used as the basis for creating larger projects with 100, 500, 1,000, 1,500, and 2,000 activities. The results of three experiments for the case of 100 activities experienced processing time of 1 s, 1 min, and 3 min, respectively. In the 3-min case, CP reached the optimal solution and, thus, its deviation from the optimal solution is zero. Also, for a 500-activity project, the CP model was able to reach a solution with a duration deviation of only 4.6% within 10 min. The quality of the CP solution for the same 500-activity project was then greatly improved when the processing time was extended to 30 min, reaching a deviation of 2.57% from the optimal solution. Therefore, for medium-size projects, the CP model can reach within 3% from the optimal duration, without violating resource limits, within a reasonable processing time (can be much faster if experiments were done on a desktop machine). For the 1,000-activity case, increasing the processing time to 2 h reduced the deviation from 18.9 to less than 5%, whereas in the 1,500-activity case; the deviation was greatly reduced from 21.0 to 7.3% when the processing time was increased from 1 min to 2 h. For the 2000-activity case, which is extremely large, the deviation remained at about 9.6% even with a processing time of 3 h. This result is considered practically reasonable. A deviation of 4.78 or 9.61% from optimum in the cases of 1,000 and 2,000 activities are not high. Without optimization, solutions are expected to be much worse or cannot be achieved. Figure 4 summarizes CP solutions for different problem sizes. Based on these results, the CP model proved to provide good solution quality with
reasonable processing time (20 min), thus, proving the practicality of the CP model in handling large-scale projects.

![Figure 4: Solution quality and processing time for different sizes of MRCPSC problems](image)

**Multiple-Objective Experiments:** The bi-objective model was then tested on the 10-activity case study and was found to work extremely well and does not require additional processing time. The resulting resource profile of the bi-objective optimization for the 10-activity project (Figure 3b) shows a much better resource profile than the single-objective solution in Figure 3a. The bi-objective model was also tested on the 1,000-activity case, with a processing time of two hours. The optimization reduced the solution deviation to 5%, with a standard deviation of daily resource usage being 1.018 (as compared with the single objective case that produced a 4.78% solution deviation and 1.030 standard deviation of resource usage). This shows the ability of the CP model to correctly trade-off among the objectives used.

### 4.1 Experiments on RC-TCT problem

**Single-Objective Experiments on Medium and Large-Scale Projects:** The case study of Chen and Weng (2009) was used as the basis for creating larger-size projects (1000, and 2000 activities). The base case study project consists of ten activities having up to 4 discrete options that use varying amounts of one limited resource. The experiments using the CP model and the heuristic method were performed for the base case of 10 activities and for the projects of 300, and 2000 activities. Table 1 presents the optimization results for each experiment, including the solution’s total cost, project duration, processing time, and deviation from optimum solution. As shown in Table 1, the CP solution for the 10-activity project (involving 38 variables and 51 constraints) reached the optimal solution in one second. For large-size projects with 2000 activities, which is extremely large, the deviation remained at about 6.5% even with longer processing time (up to 2 hours). This result is considered practically reasonable and the CP model proved to provide good solution quality with reasonable processing time (30 minutes), thus, proving the practicality of the CP model in resolving the combined schedule constraints in large-scale projects. This result represents a benchmark for further research to improve upon.
Table 1: Results of the CP model on different project sizes

<table>
<thead>
<tr>
<th>Project Size</th>
<th>Expected Optimum Solution</th>
<th>CP Solution</th>
<th>CP Deviation *</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Activities</td>
<td>Duration = 56, Cost = $244,000</td>
<td>Dur. = 56, $ = $244,000</td>
<td>1 Sec, 0%</td>
</tr>
<tr>
<td>300 Activities</td>
<td>Duration = 1680, Cost = $7,320,000</td>
<td>Dur. = 1820, $ = $7,751,700, Dur. = 1698, $ = $7,426,900, Dur. = 1686, $ = $7,384,900</td>
<td>15 Sec, 5.90%, 10 min, 1.46%, 20 min, 0.88%</td>
</tr>
<tr>
<td>2000 Activities</td>
<td>Duration = 11200, Cost = $48,800,000</td>
<td>Dur. = 12353, $ = $52,053,100, Dur. = 12298, $ = $51,969,200, Dur. = 12274, $ = $51,916,400</td>
<td>40 Sec, 6.67%, 30 min, 6.50%, 120 min, 6.39%</td>
</tr>
</tbody>
</table>

* Deviation from optimal = (CP cost in column 3 – Optimum cost in column 2) / Optimum cost in column 2

5 CONCLUDING REMARKS

Project managers usually have different options to complete activities with different resources and different production rates. Widely used scheduling software, such as Primavera P6 and Microsoft Project, do not have an option to enter more than one construction method or mode for an activity. In other words, using these software systems, project managers have to manually enter one option at a time in order to see the impact of using different activity modes on the project completion date. Currently, more owners are asking the contractors to submit and use resource-loaded schedules to manage their projects. While resource loading schedule may be a difficult exercise, it enables management to assess the amount of resources available and avoid risks early in project planning. If the resource-loaded schedule alerts decision makers that the available resources will not suffice to execute the work on time as planned, management can begin negotiating for additional resources early in the project.

This paper presents a fast and powerful tool for project managers based on constraint programming to perform what-if analysis for large-size projects and enables them to efficiently utilize their resources. Although it is possible to load the activities modes automatically into the CP process, a full automated process is not yet developed. This process automation is currently an ongoing task by the authors to fully link the CP model with Primavera P6 or Microsoft Project software, which are the industry most-used scheduling software systems. Another limitation of the current CP model is the fact that it is designed to optimize the schedules before construction starts. Serious modifications are therefore needed to modify the model so that it accepts actual progress information and then produces an optimized corrective action plan that does little disturbance to the already selected modes for the activities. This is in addition to considering other constraints related to cash flow and other requirements, during the optimization. One final note is that despite the fact that the CP modeling tool is easily programmable, requiring the scheduling expert to have computer programming skills is a serious obstacle to implementing CP models, until full automation is achieved. The encouraging results of this paper, therefore, may motivate the producers of industry standard software systems to incorporate some optimization features into their tools, so that optimization becomes a mainstream tool in the industry. The focus of future work in this area should then be on introducing efficient methods to handle practical size problems. Tweaking existing methods to achieve minor performance improvement on small problems has less practical value.

References


DESIGN CHANGE MANAGEMENT USING A BIM-BASED VISUALIZATION MODEL

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Abstract: Building projects frequently experience a number of changes in design development to satisfy owners’ space and functional needs within allocated budgets. These iterative changes, while necessary, individually and collectively have ripple effect on what appears to be the unchanged scope of projects work, with varying impacts on project delivery time and cost. Efficient management of design changes requires scope rendition and minimization of time and cost impacts of these changes. This paper presents an automated model, developed to help design professionals and owners visualize the ripple effect of contemplated design changes. This visualization covers those design changes requested by owners after completion of the design phase and before commencement of the construction phase. The developed model is expected to help owners and their agents to better grasp the ripple effect of design changes and consequently, to make better decisions as to approving or rejecting contemplated changes. The model is also able to calculate the impact of changes on projects cost and time. The model is developed on the basis of comparing the original model of a building to its revised model, which incorporates the introduced changes. The changes included in the developed model encompass addition, deletion as well as changes in quantities and specifications of building components. The model is then integrated with Building Information Modeling (BIM) to provide visualization and documentation of the design changes. The use of BIM provides significant benefits in coordinating changes across different views in the model, thereby enabling users to study the ripple effect of a change from different views, such as plans, elevations and 3D views. The model is capable of illustrating the ripple effect in architectural, mechanical, electrical and HVAC systems. For evaluation purposes, the model has been applied to a case study.

1 INTRODUCTION

Owners of construction projects have become more and more demanding, continuously changing their project’s design to suit their evolving needs, particularly in non-traditional project delivery systems. They may request changes at any phase of a project to respond to new market demands (Ibbs, 2012). Almost 20 years ago, studies had revealed that 20-25% of the construction period was lost as a result of inadequate design (Undurraga, 1996). In addition, lower-quality construction was attributed in 78% of projects to percentage of design changes (Koskela, 1992).

A change is any additional work added to the scope of a project that causes the project to incur delays and/or additional costs to the original contract. As such, a change can take many forms. However, it is owner-initiated change that must receive more attention than any other types of change, as this sort of change could present a risk to both the owner and the contractor. A change may be simple in an owner’s
mindset, but that perspective (most likely) does not consider the multiple affects that one change can have on many other areas of a project. Each change could add to the cost of the original contract and/or cause a delay in the project’s execution, even though there could be cases where a change does not add to a project’s cost and time. Some changes can even be beneficial to both owner and the contractor, but that situation is rather rare. A system that can manipulate changes would thus be a valuable tool in the construction industry. Owners should be involved in their projects, and the role and responsibility of an AEC (Architectural, Engineering, and Construction) team is to provide guidance, giving the owner all the required information about the requested change and its impacts on the project. If this new system could visualize the change and illustrate its impacts, then the owner would be able to see the ‘big picture’ and make an informed decision. This system should avoid unnecessary conflicts and disputes between the owner and the contractor, and thus greatly reduce the recourse to lawsuits.

A successful management system for applying, visualizing, analyzing and organizing change orders requested by owners would clearly be beneficial. Dealing with change orders in the traditional fashion, using paper-based printouts of 2D drawings, is no longer adequate, as it does not allow all of the ramifications of a change to be discovered. Moreover, with projects becoming increasingly complex, the ripple effect analysis of design changes is becoming much more challenging and time-consuming. This problem is being addressed by the development of Building Information Modeling (BIM) to provide real-time dynamic databases. BIM makes it possible to apply a change to a building model and to determine the impacts of that change in the design model, in every view and in real time. In other words, it can self-adjust a model’s database whenever a new change is applied. However, the user is only able to see a change, and the newly-affected model, but not the ripple effect of that change. BIMs only visualize the new model design; they do not highlight the components that are affected by the changed component(s). This limitation illustrates the need to develop a BIM-based change management system to provide effective management of a multi-disciplinary model through the dynamic procedure of building design. This study presents an integrated BIM-based automated model for design professionals and owners. It is designed to improve the visualization capabilities to help in analyzing a change’s ripple effect and in tracking the consequences, and to help owners and designers to communicate with each other in selecting beneficial changes that respond to the owners’ desired criteria, prior to the construction phase.

2 BACKGROUND

Understanding the meaning of change management is as important as knowing its process. Voropajev (1997) defined it as “an integral process related to all project’s internal and external factors influencing project changes: any possible change forecast; the identification of already-occurred changes; planning preventive impacts; to the coordination of changes across the entire project” (Voropajev, 1997). Tiog (1990) said, “a change order management system should be established for the ultimate benefit of owners” (Tigon, 1990). Sun et al. (2006) stated “the aim of project change management is not to seek the elimination of all project changes, but to minimize the negative impact of necessary changes and to avoid unnecessary ones” (Ming Sun A. F., 2006). Mirshekarlou (2012) reported that “by implementing a project change management system, a project’s involved parties would be able to reduce deleterious changes and encourage beneficial changes. Also, the project’s work performance and its chance of success should increase” (Mirshekarlou, 2012).

A change order process can be qualitative or quantitative, and sometimes a system can be a combination of both. Both systems would help the project participants to have a bright outlook on the possible changes and their impacts. Qualitative methods focus on how to process change orders once a change request is made, and how to make it beneficial for both the owner and the contractor. All the available best practices, guidelines and change management process steps can be classified as quantitative methods. These steps guide the change management process from the time the change is initiated to the completion of the project. However, there is no guaranty that a project will benefit, as none of these qualitative methods can identify the ripple effect of the changes that result from a single change. Current industry practice uses this type of change management process. To identify a changes’ ripple effect, experts must go through the all of a systems’ 2D printouts to see if the change could cause ripple effect in other parts of the project. This is very time-consuming and requires a number of highly-experienced
experts to use their knowledge to identify the change consequences. On the other hand, there are many quantitative methods that can be used to study the impact of changes. Quantitative methods concentrate on the impacts of the change order on time, cost, quality and/or productivity, and calculate everything numerically. All of the theoretical models and information models can be utilized in the quantitative change management system.

The first leaders in quantitative models were Leonard et al. (1991); utilizing the data from 57 different construction projects, they developed a regression model to quantify the impact of change orders on productivity (Leonard, 1991). Mokhtar et al. (1998) implemented an information model to help project participants coordinate design information when design changes occur by using a central database that of active building components. The model can transit design changes, track past changes, plan and schedule future changes and improve design change management (Mokhtar, 1998). Hanna et al. (2002) presented a new methodology, an integration of statistical regression and fuzzy logic, to quantify the cumulative impact of change orders on construction projects. The output of a fuzzy membership function would be the expected loss of labor productivity and its standard deviation (Awad S. Hanna. P. M.-J., 2002). Moselhi et al. (2005) developed a neural network model for quantifying the impact of change orders on labor productivity. The model is integrated with four other models, developed by others, to make a prototype software system that evaluates the percentage loss of labor productivity due to change orders (Osama Moselhi, 2005). Zhao et al. (2010) developed a change order prediction model as a beneficial tool for project management teams to manage changes proactively and efficiently. The model uses an activity-based dependency structure matrix (DSM) to identify the ripple effect of changes. It uses Monte Carlo simulation to analyze the change probability of activities involved in construction projects (Zhen Yu Zhao, 2010). Langroodi et al. (2012) evaluated existing BIM tools through a case study to determine if how BIM could be capable of aiding change management during the design and construction of fast-track projects. An ontology for change was developed in order to provide a common understanding of change characteristics for those when using BIM to manage changes (Behzad Pilehchian Langroodi., 2012). Most of the current quantitative models are designed to calculate the impact of change on productivity. Some of them are only applicable to the mechanical and electrical aspects of projects. These do not have any computer implementation and their limited number of variables reduces their practical utilization. None of them is able to visualize the ripple effect of the changes.

3 PROPOSED METHODOLOGY

This paper introduces a BIM-based model to support design change management; particularly to visualize the ripple effect of design change. Integration and automation methods were applied to the model development process to support change management. The main purpose behind the developed model is to provide decision makers with a tool to visualize the ripple effect of owner-requested design changes.

The process of project design change management begins when the owner requests design changes after completion of the design phase and before commencement of the construction phase. The design change is divided into four different categories: adding, removing and modifying one or more components in the original model, as well as any combination of these categories. These changes have their unique ripple effect on a project.

The developed model consists of three main frameworks, utilized for change management and owner decision-making. The first is a data acquisition framework, the second is a data analysis framework, and the third is a reporting framework as it is illustrated in Figure 1.


3.1 Data acquisition framework

For data acquisition, the project 2D drawings are needed in order to generate the original 3D BIM model. For the purpose of change impact analysis, project systems, such as architectural, structural, electrical, mechanical, piping and plumbing and HVAC should be part of the BIM model. The other required data are the owner’s design change requests. All requests are presented in a meeting with design team who applies them in the developed model in order to visualize their impact and share that with the owner. Meanwhile, the changes are introduced to a copy of the original 3D BIM model, which results in the creation of the 2nd model. The analysis is performed to trace the ripple effect of that change can begin.

3.2 Data analysis framework

In the data analysis framework the purpose is to visualize the ripple effect of an owner’s design changes in all of a project’s systems. By the time that a component has changed, the change may affect the other components that are connected to that first-changed component. Current BIM tools can update the whole model according to the first change. This means that when a change is happening in the attributes of a component, all the other components’ attributes related or connected to the first-changed component will be adjusted automatically. The problem with this model fixation is that it is not easy to follow or to use to evaluate a subsequent improved design change analysis. This process gets even more complicated when a project is more complex, as there will be more components and attributes.

The developed model should be able to trace the relationship between the changed component and the other components that are connected to it, which means finding the change path or the change sequence. For example, a wall is attached to a window, a door, the roof, floor, etc. The component not only has a connection to the other architectural components, it also has a connection to the components of other systems, such as mechanical, electrical, HVAC, piping and plumbing.

Therefore, determining these relationships and connections is the main step involved in discovering the ripple effect of a change. In this model, work breakdown structure (WBS) is defined at a micro level in the scheduling, which means that every component in the model has its own data information. Having a micro WBS will ease this process. When a change occurs at a component level by having micro-level WBS, the model will detect the area that a changed component is located in. It will then detect all the components that are connected to the changed component to discover if there are any other changes occurring based on the first change, which is the main source of impact. This action will continue until there are no longer any changes being found in the other components in the architectural system or any other systems.
available in the model. The same procedure also occurs in the other areas that are connected to the area where the main change is located.

The proposed model begins the analysis of all the ripple effect by a comparison method, which means that the model starts to compare the original BIM model with the modified BIM model. The analyzing procedure is based on a component-by-component comparison between the two BIM models. Every component in both models has an ID, which simplifies the comparison, and the procedure will provide an immediate result. The comparison model will detect the following:

- If the components are found in one model but not in the other. This detection will be for those types of design changes where the owner decides to remove one or more component from the original model.
- If the components are found in both models, but the components’ specification have changed in one model. This type of detection covers those types of design changes where the owner changes the specifications of one or more components in the original model.
- If the components are found in both models, and they have not changed from one model to the other.

3.3 Reporting framework

After the proposed model has visualized the change ripple effect, the next step is to provide a report to the user to assist in the change decision-making process. This model produces a report that shows all the affected components with their newly-assigned specifications such as length, height and width. The report also includes information about the original components, so that the user can see the differences between the original and the changed components. This report should be opened in the BIM interface and provide the visualization of the project model simultaneously, in a different window.

4 CASE STUDY

The proposed methodology is implemented and applied via BIM technology an actual project. In this study, the BIM platform is defined in Autodesk Revit 2014. The Revit.NET Application Programming Interface (API) allows users to program with any.NET compliant language, such as VB.NET and C#, as a way to add extensions to the originally generated BIM model. The developed model is merged with plugins that are coded in Microsoft Visual C#.Net programming language, which is in compliance with Revit APIs. The developed Revit add-In is named “Check Change”. Check Change provides the user with a change order ripple effect visualization of the owner-requested design change(s). At the same time, it also provides a report of the change ripple effect and a list of all the components that would be changed as a result of the owner’s change request(s).

In the data acquisition part, the BIM model is developed from the project’s architectural drawings; this model is called the Original model. After generating the Original model, the user opens the second model, which is a copy of the original model and is called the Copy. The user then modifies the Copy model according to the owner’s design change requirements. Both models will be shown in the same interface. Thus, the user can see both the Original and the Copy models in the Revit interface, as shown in figure 2. The program is designed so that the user cannot open more than two models at the same time.
Figure 2: Architectural System Data Acquisition

The Revit program also provides the ability for the user to see the Original and the Copy models from different viewpoints, such as plan, elevation, and section and 3D views. Having this access to the different views improves and facilitates the visualization process and a more complete understanding of the design changes. After uploading the models in the Revit interface, the next step is to click on the Check Change add-In to visualize the change ripple effect, visualized when the coded Revit add-In starts to compare the Original and the Copy models to detect the differences between the two models’ components. Clicking on Check Change tells the system to start the component-by-component comparison between the two models, as illustrated in Figure 3.

The visualization procedure is shown in Figure 4. At this stage of the model development, all of the visualization is shown in one color. Part of this study plan is to define different colors for the different results of the comparison between the two models.
For example, the components that stay the same in both models after applying the owner’s design changes appear in one color, and the components that exist in both models, but whose specifications are changed in the copy model, are indicated in another color. The components that are in the Original model and not in the Copy model are visualized in another color in the Original model.

The add-In can also provide a report of the changes detected after the component-by-component comparison. After the user applies the Check Change command, the model provides the change ripple effect visualization as well as a report. The report presents its information side-by-side; one side is for the Original model, and the other is for the Copy model, modified according to the design change requirements. The comparison model provides a report that shows all of the components that are changed due to the first source of change, the owner’s design changes. The components that have some modification in their specification will get a check sign in the report. By looking at the report, the user can observe that the reason for a change in a component could be due to a change in the height, width, length or a change in the material of that component. A sample of this report is given in Figure 5. The report and the visualizing process do not yet work together; the user would get either the report of the impacted components or a visualization of the change ripple effect. This study proposes to make a connection between the report production and the ripple effect visualization, so that the user would be able to see both at the same time and in the same interface after applying the Check Change command. In addition, the user would be able to click on a component in the report to highlight that component in every view of the model: plan, 3D, elevation or section. The user (and other interested parties) would thus be able to understand and appreciate the implications of the change ripple effect much easier.
5 CONCLUSION

Design changes initiated by owners are common and they can impact project’s cost, time, quality and overall performance. A single change in one location in a project can easily cause a series of changes in other parts of the project. Finding the sequence of change or change path via 2D drawings is time-consuming and demanding, and the result might not be accurate enough. This paper presents an automated BIM-based model to visualize the ripple effect of owner-requested design changes as they are applied to a project after the design phase has finished and before the construction phase has started. The developed model uses a component-by-component (ID-to-ID) comparison technique between the original model and the modified model to extract the list of affected components and highlight them in the Copy BIM model. The model is expected to allow project owners to make better decisions after being presented with the ripple effect of their requested changes in the architectural, mechanical, electrical and HVAC systems of the project.

References


RELIABILITY ANALYSIS OF WATER DISTRIBUTION NETWORKS USING MINIMUM CUT SET APPROACH

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Abstract: Canadian Water and Wastewater Association (CWWA) estimated the cost to replace 112,000 km of water mains in Canada to be 34 billion Canadian Dollars. Reliability analysis of water distribution networks (WDNs) is an important aspect in planning and operation of a WDN and hence plays an important role in the efficient use of allocated budget. In general, reliability analysis is classified into mechanical reliability and hydraulic reliability. Mechanical reliability is defined as the ability to function even when some components are out of service or there is any mechanical break. Hydraulic reliability is concerned with delivery of the specified quantity of water to a specific location at the required time under the desired pressure. This paper introduces a methodology for evaluating mechanical reliability of WDNs using the minimum cut set approach. The methodology involves the computation of mechanical reliability at the component (pipe, hydrant etc.), segment (collection of pipes and components) and network levels. An illustrative example is worked out to demonstrate the use of the developed methodology.

1 INTRODUCTION

Water distribution networks (WDN) are complex interconnected networks consisting of sources, pipes, and other hydraulic control elements such as pumps, valves, regulators, tanks etc., that require extensive planning and maintenance to ensure good quality water is delivered to all customers (Shinisthe et al., 2002). These networks are often described in terms of a graph, with links representing the pipes, and nodes representing connections between pipes, hydraulic control elements, consumers, and sources (Ostfeld et al., 2002). They are vital part of urban infrastructure and require high investment, operation and maintenance costs. The main task of WDN is to provide consumers with a minimum acceptable level of supply (in terms of pressure, availability, and water quality) at all times under a range of operating conditions. The degree to which the network is able to achieve this, under both normal and abnormal conditions, is termed its reliability. (Atkinson et al., 2014). Hence, reliability is considered as an integral part in making decisions regarding the planning, design, and operation phases of WDNs.

Many researchers defined reliability based on different conditions. Al-Zahrani and Syed (2005) defined reliability of WDN as its ability to deliver water to individual consumers in the required quantity and quality and under a satisfactory pressure head. Kalungi and Tanyimboh (2003) defined reliability as the extent to which the network can meet customer demands at adequate pressure under normal and abnormal operating conditions. In general reliability of any network refers to its ability of performing a mission placed on it, adequately under stated environmental conditions and for a prescribed time interval.
No network is entirely reliable. In every network, undesirable events, i.e. failures, can cause decline or interruptions in the network performance (Ostfeld 2004). Reliability of WDNs relates to two types of failure, (1) mechanical failure of network components and (2) hydraulic failure caused by changes in demand and pressure head. Mechanical reliability reflects the degree to which the network can continue to provide adequate levels of service during unplanned events such as mechanical failure (e.g., pipe bursts, pump malfunction). Hydraulic reliability reflects how well the network can cope with changes over time, such as deterioration of components or demand variations (Atkinson et al., 2014). Some authors (Islam et al., 2014; Gupta et al., 2012) have also argued about water quality reliability which is assessed with respect to a predefined level or range of selected water quality parameters (e.g., residual chlorine concentration). If the water quality parameter is within the prescribed range, the WDN is considered reliable, otherwise it is considered unreliable for water quality. However, the scope of this paper is limited to the evaluation of mechanical reliability of WDN and its components.

According to Su et al. (1987), reliability of components in a WDN such as valves, hydrants, controls etc. has an effect upon, and must be used to determine, the overall network reliability. However, no model has been found in the literature evaluating reliability of components. In this paper, a methodology is developed to assess the reliability of components in a WDN, and using reliabilities of these components, segment reliability is evaluated. Then the overall network reliability is assessed using minimum cut set method.

2 BACKGROUND

A review of the literature reveals that there is no universally acceptable measure for the reliability of water distribution networks. It gained considerable research attention over the last few decades. This research has concentrated on methodologies for reliability assessment and for reliability inclusion in optimal design and operation of WDNs. This section provides a summary of these efforts.

As reliability is not a network property that can be measured directly, it should be assessed based on other characteristics of the network that can be directly measured or calculated. Ostfeld (2004) categorized reliability assessment methods into (1) connectivity/topological, (2) hydraulic and (3) entropy as a reliability surrogate. The reliability which is based on the concept of connectivity refers to measures associated with the probability that a given network remains physically connected by taking into account the topology of the network. This type of measure mainly serves the purpose of evaluating mechanical reliability. Shamsi (1990) and Quimpo & Shamsi (1991) incorporated the use of node pair reliability (NPR) as the network reliability measure. The NPR is defined as the probability that a specific source and demand nodes are connected. This definition corresponds to the probability that at least one path is functional between the source node and the demand node considered. Yannopoulos and Spiliotis (2013) focused on topology of network as a measure for analyzing mechanical reliability. They developed a methodology based on adjacent matrix of graph theory in order to determine connectivity among different nodes. Measures used within this category do not consider the level of service provided to the consumers during a failure. The existence of a path between a consumer and a node is only a necessary condition for supplying its required demands (Ostfeld, 2004).

The second category of reliability assessment i.e., hydraulic measure is concerned with the conveyance of desired quantities and qualities of water at required pressures to the appropriate locations at the appropriate times. Xu and Goulter (1999) used a probabilistic hydraulic approach, based on the concept of the first-order reliability method (FORM), to determine the capacity reliability of the water distribution network, which is related to the hydraulic and demand variation failures, and is defined as the probability that the nodal demand is met at or over the prescribed minimum pressure for a fixed network configuration under random nodal demands and random pipe roughnesses. Shinistine et al. (2002), coupled a cut-set method with a hydraulic steady state simulation model that implicitly solves the continuity and energy equations for two large scale municipal water distribution networks in the Tucson Metropolitan Area. The measure of reliability was defined as the probability of satisfying nodal demands and pressure heads for various possible pipe breaks in the water distribution network at any given time. Zhuang et al. (2011) presented a methodology for reliability and availability assessment of a WDN based on an adaptive pump operation. In response to a pipe break, pump operations were adapted using
various sizes of pump combinations. In their method, they evaluate hydraulic reliability in terms of available water to fulfill desired demand.

Entropy, as a surrogate measure for reliability is the third category which has been used by several researchers for reliability assessment during recent years. The fundamental idea is to use Shannon’s (1948) entropy measure of uncertainty that quantifies the amount of information contained in a finite probability distribution, to measure the inherent redundancy of a network. In this regard, entropy is more related to the category of connectivity/topological analysis than to that of hydraulic reliability. It is assumed that distribution networks, which are designed to carry maximum entropy flows, are generally reliable (Ostfeld, 2004). A WDN with higher entropy is expected to cope better with simultaneous multi-pipe failure (Gheisi and Naser, 2014). Prasad and Tanyimboh (2008) used Flow Entropy, a statistical entropy measure for WDNs to show that surrogate reliability measure can be used effectively to improve reliability of multi-source networks. Tanyimboh et al. (2011) used statistical entropy and other surrogate measures such as network resilience, resilience index and modified resilience index, for the reliability assessment of WDN to assess the effectiveness of surrogate reliability measures in relation to more rigorous and accurate hydraulic reliability measures.

Among the most well-defined processes to determine the topological/mechanical reliability of a network is the process of minimum cut-set (Yannopoulos and Spiliotis, 2013). Tung (1985) discussed six techniques for WDN reliability evaluation and concluded that the cut-set method is the most efficient technique in evaluating the network reliability. The minimum cut-set approach is usually applied in order to investigate the topology of a WDN and the detection of its critical elements the failure of which will affect the network operation. The minimum cut-set is a set of network components which, when failed, causes failure of the network; but if just one component of the set has not failed, no failure of network occurs. Following the cut-set method, an estimation of mechanical reliability of the WDN can be achieved.

2.1 Identification of minimum cut sets

To identify the minimum cut sets of a network in a reduced computational time, a method generally used in power transmission networks for the same purpose has been adopted (Zhou et al., 2012). It involves 1) finding all possible paths from the source node to the demand node, 2) Constructing a path matrix and 3) getting minimum cut sets from the path matrix.

A path is a connection between a source node and a demand node. This model considers a node to be adequately supplied as long as there is at least one link connecting it to the rest of the network which means that the network is not considered as failed even if there is a single path from the source node to the demand node. After finding all possible paths, a path matrix is constructed in which, number of rows is equivalent to the number of paths from source node to demand node under consideration, and number of columns is equivalent to the number of segments (or combinations of segments) in a network. This matrix is a zero-one matrix with 1 as its entry if the segment is present in the path to the demand node, and 0 as its entry if it is not. For example, there are 3 segments A, B and C in a network and the possible paths from the source node to the demand node are AB and AC. Then the path matrix is expressed as

\[
[1] P = \begin{bmatrix}
A & B & C \\
1 & 1 & 0 \\
1 & 0 & 1 \\
\end{bmatrix}
\]

Once the path matrix is constructed for the demand node under consideration, the network is analyzed for minimum cut sets. First order cut set is a single segment which when fails, causes the failure of entire network. Similarly, second order cut set is the combination of two segments, the combined failure of which causes the failure of entire network. If any column in a path matrix contains all elements as 1, then the segment corresponding to that column is recorded as a first order cut set. For example, all the elements of the first column are 1 in the matrix 1. Hence segment \{A\} is recorded as a first order cut set. To find the second order cut sets, create all combinations of 2 segments and construct a new path matrix by merging the elements as per the combinations. For example, combination of 2 segments for the above example network are \{A, B\}, \{B, C\} and \{C, A\}. New path matrix would be
From the matrix 2, combination of B and C results in a column with all elements as 1. Hence \( \{B, C\} \) is recorded as second order cut set. Note that, any combination with A is neglected because A is already a minimum cut set. The same procedure is followed for finding third and higher order cut sets with combinations of corresponding segments.

3 METHODOLOGY

This section discusses the various computing measures adopted to develop the methodology.

![Network reliability flowchart](image)

Figure 1: Network reliability flowchart

3.1 Failure rate

Most researchers have chosen failure rate as the primary indicator of reliability. Quantitatively, it is defined as the number of breaks per year per unit length. Breaks are considered one of the significant factors contributing to water losses and require substantial human effort and cost to repair such failures. As the number of breaks increases, the reliability of a WDN decreases. The most often applied formulae for estimating the pipe failure rate have been obtained using simple regression models on the available pipe failure data from a limited time period. In this paper, the pipe failure rate or breakage rate is
computed using a regression model based on age of pipe, being developed in an ongoing research work at Concordia University. According to this model, the failure rate can be expressed as

\[ \lambda_{\text{pipe}} = 6 \times 10^{-6} X^2 + 0.0004X + 0.0026 \]

Where X is the age of pipe in years and \( \lambda_{\text{pipe}} \) is the failure rate of pipe expressed in number of breaks per year per unit length of pipe.

The failure rate of other components (hydrants, valves, controls) can be expressed as

\[ \lambda_{\text{component}} = \frac{N_f}{\text{Length of segment}} \]

Where \( N_f \) is the number of failures per year and \( \lambda_{\text{component}} \) is the failure rate of component expressed in number of failures per year per unit length of segment.

### 3.2 Component reliability

After determining the failure rates of pipes and other components, the reliability is assumed to follow negative exponential distribution which would mean that reliability decreases exponentially as the failure rate increases with time, and can be computed as

\[ R_c = e^{-\lambda t} \]

Where \( R_c \) is the reliability of a component or pipe and \( \lambda t \) is the failure rate of a component or pipe.

### 3.3 Segment reliability

A segment is a single water main pipe or a group of connected pipes (along with all the associated components) which are usually located between two nearest intersections at which isolation valves may exist (Salman A., 2011). According to the definition, the segment reliability can be expressed as

\[ R_{\text{seg}} = \sum \lambda \]  

The above equation represents segment reliability where components have the same weight which is not true. Each component has its relative importance in a segment. To be more specific in determining segment reliability, a relative weight component (\( w_i \)) is included in equation 4 to adjust it.

\[ R_{\text{seg}} = \sum_{i=1}^{n} R_c w_i \]

Where \( i \) is the water main component, \( n \) is total number of water main components and \( w_i \) is the relative weight of component.

The relative weight of component (\( w_i \)) is the ratio of weight of component under consideration to the total weight of components in that particular segment. The weights of components are obtained from Salman A. (2011).

\[ \text{Relative Weight } (w_i) = \frac{\text{Weight of component}}{\text{Sum of weights of all components}} \]
### Table 1 Component Weights (Salman A., 2011)

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe</td>
<td>38%</td>
</tr>
<tr>
<td>Hydrant</td>
<td>31%</td>
</tr>
<tr>
<td>Isolation Valve</td>
<td>28%</td>
</tr>
<tr>
<td>Control Valve</td>
<td>3%</td>
</tr>
</tbody>
</table>

### 3.4 Network reliability

The procedure for determining the network reliability of a WDN based on the minimum cut-set method is as follows.

#### 3.4.1 Probability of failure of segments

Quantitatively, the probability of failure of a segment is the complement of the reliability of a segment. It can be expressed as

\[ Q = 1 - e^{-kt} \]

These segment failure probabilities are computed so that they can be used later for determining network reliability using minimum cut set method.

#### 3.4.2 Identification of minimum cut sets

As described earlier in the literature review, all the minimum cut sets have to be identified to serve the purpose of evaluating network reliability.

#### 3.4.3 Mechanical reliability of WDN based on Minimum Cut Set

According to Shinstine et al. (2002), for \( n \) components (segments) in the \( i_{th} \) minimum cut set of a WDN, the failure probability of the \( j_{th} \) component (segment) is \( Q_j \), which can be obtained by Eq. 7. The failure probability of the \( i_{th} \) minimum cut set is

\[ Q(MC_i) = \prod_{j=1}^{n} Q_j \]

Where \( n \) is the number of segments in corresponding minimum cut set.

Assuming that the occurrence of the failure of the components within a minimum cut set are statistically independent. For example, if a water distribution network has four minimum cut sets, \( MC_1, MC_2, MC_3, \) and \( MC_4 \), for the network reliability, the failure probability of the network \( Q_N \), is then defined as follows (Billinton and Allan 1983):

\[ Q_N = Q(MC_1 \cap MC_2 \cap MC_3 \cap MC_4) \]

By applying the principle of inclusion and exclusion, equation 9 can be reduced to:
[10] \( Q_N = Q(MC_1) + Q(MC_2) + Q(MC_3) + Q(MC_4) = \sum_{i=1}^{M} Q(MC_i) \)

Where \( M \) is the number of minimum cut-sets in the network.

Finally, the mechanical reliability of the network can be expressed as:

[11] \( R_N = 1 - Q_N = 1 - \sum_{i=1}^{M} Q(MC_i) \)

### 4 CASE EXAMPLE

The hypothetical network shown in figure 3 is utilized for the demonstration of the developed methodology. The network consists of 8 segments named alphabetically and 7 nodes named numerically. Node 7 is a source node while the other nodes are demand nodes. Assuming the repair data for the network as shown in table 2, reliability of each component, each segment and whole network can be calculated. To calculate the reliability of presented hypothetical network using minimum cut sets method, network should be analyzed for the identification of minimum cut sets.

![Network model of case study](image)

Figure 3: Network model of case study

Let us consider node 3 as the demand node. The possible paths for the water to reach demand node 3 from source node 7 are found to be ABD, ACFED, ACFGH, and ABEGH and there are 8 segments. Therefore the path matrix can be constructed as

\[
[3] P = \begin{bmatrix}
A & B & C & D & E & F & G & H \\
1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\
\end{bmatrix}
\]

The elements in column A of matrix 3 are all 1. Hence \( \{A\} \) is recorded as a first order cut set. Note that, while finding second order cut sets, combination of segment A with other segments is not needed. Because the failure of A, alone causes the failure of network. It does not need combination of any other segment to cause failure of network.

To find second order cut sets, combinations list of 2 segments out of 8 segments is generated using WOLFRAM MATHEMATICA 10.1. Total number of combinations are found to be 28 and are listed in table 3. Hence the new path matrix contains 5 rows (No. of paths) and 28 columns (No. of combinations of segments) and can be constructed as

\[
[4] P = \begin{bmatrix}
A+B & B+C & B+F & C+D & D+E & D+G & D+H & E+F & G+H \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]
(All the combinations with segment A are not needed and hence they are neglected. Dotted columns
represent that there are few combinations that are not shown here because it's a large matrix and could
not be fit to page.)

Table 2 Hypothetical Network (Data and Results)

<table>
<thead>
<tr>
<th>Seg.</th>
<th>Comp.</th>
<th>No. of Failures</th>
<th>Age X(yrs)</th>
<th>Seg. length(m)</th>
<th>Failure rate (λt)</th>
<th>Comp. reliability</th>
<th>Weight</th>
<th>Relative weight</th>
<th>Seg. reliability</th>
<th>Probability of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>I.Valve 1</td>
<td>5</td>
<td>N.A</td>
<td></td>
<td>0.0125</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2979</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>3</td>
<td>8.4</td>
<td>400</td>
<td>0.0064</td>
<td>0.9936</td>
<td>0.38</td>
<td>0.4043</td>
<td>0.990</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>I.Valve 2</td>
<td>5</td>
<td>N.A</td>
<td></td>
<td>0.0125</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2979</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>I.Valve 1</td>
<td>5</td>
<td>N.A</td>
<td></td>
<td>0.0125</td>
<td>0.9876</td>
<td>0.28</td>
<td>0.2240</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>5</td>
<td>9.6</td>
<td>400</td>
<td>0.0070</td>
<td>0.9930</td>
<td>0.38</td>
<td>0.3040</td>
<td>0.989</td>
<td>0.011</td>
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<tr>
<td></td>
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<td>N.A</td>
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<td>0.28</td>
<td>0.2240</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrant 1</td>
<td>6</td>
<td>N.A</td>
<td></td>
<td>0.0150</td>
<td>0.9851</td>
<td>0.31</td>
<td>0.2480</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>I.Valve 1</td>
<td>3</td>
<td>N.A</td>
<td></td>
<td>0.0033</td>
<td>0.9967</td>
<td>0.28</td>
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<td></td>
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<td>Pipe</td>
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<td>17.6</td>
<td>900</td>
<td>0.0115</td>
<td>0.9886</td>
<td>0.38</td>
<td>0.2969</td>
<td>0.993</td>
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<tr>
<td></td>
<td>I.Valve 2</td>
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<td>0.9956</td>
<td>0.31</td>
<td>0.2422</td>
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<tr>
<td></td>
<td>Hydrant 2</td>
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<td>N.A</td>
<td></td>
<td>0.0067</td>
<td>0.9934</td>
<td>0.31</td>
<td>0.2422</td>
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<td>D</td>
<td>I.Valve 1</td>
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<td></td>
<td>0.0100</td>
<td>0.9900</td>
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<td>0.3918</td>
<td>0.990</td>
<td>0.010</td>
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<tr>
<td></td>
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<td>0.9841</td>
<td>0.31</td>
<td>0.3196</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>I.Valve 1</td>
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<td>N.A</td>
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<td>0.0056</td>
<td>0.9945</td>
<td>0.28</td>
<td>0.2240</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
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<td>900</td>
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<tr>
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<td>0.9967</td>
<td>0.28</td>
<td>0.2240</td>
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</tr>
<tr>
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<td>N.A</td>
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<td>0.28</td>
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</tr>
<tr>
<td></td>
<td>Pipe</td>
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<td>8.4</td>
<td>400</td>
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<td>0.38</td>
<td>0.4043</td>
<td>0.990</td>
<td>0.010</td>
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<tr>
<td></td>
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<td>0.9900</td>
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<td>G</td>
<td>I.Valve 1</td>
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<td>N.A</td>
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<td>0.9851</td>
<td>0.28</td>
<td>0.2240</td>
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<td>Pipe</td>
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<td>12</td>
<td>400</td>
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<td></td>
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<td>0.2240</td>
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<td>N.A</td>
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<td>0.9827</td>
<td>0.31</td>
<td>0.3196</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It can be observed that the elements in columns of matrix 4, representing combinations of {B, C}, {B, F},
{D, G} and {D, H} are all 1. It means that combined failure of these segments can cause failure of network
and hence {B, C}, {B, F}, {D, G} and {D, H} are recorded as second order cut sets. Note that, while finding
third order cut sets, any combination containing first order cut sets and second order cut sets are
neglected. Because they don’t need more segments to cause failure of network.

Same procedure is repeated for finding third order cut sets with combinations list of 3 segments. Total
number of combinations are found to be 56 as listed in table 3. Hence the new path matrix contains 5
rows (No. of paths) and 56 columns (No. of combinations of segments) and can be constructed as
As we can see, elements in columns of matrix 5, representing combinations of \( \{B, E, G\}, \{B, E, H\}, \{C, D, E\} \) and \( \{D, E, F\} \) are all 1, which means that the combined failure of these segments can cause failure of network and these are recorded as third order cut sets. The same procedure is repeated for each and every demand node in the network and all the cut sets are recorded. Note that any cut set is recorded only once. If the same cut set is identified while performing network analysis considering another demand node, it is not recorded as a cut set again.

Finally, the minimum cut sets after analyzing the network for all demand nodes are listed in table below.

### Table 3 Possible combinations of segments that can cause combined failure

<table>
<thead>
<tr>
<th>No. of segments to be combined</th>
<th>Possible Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{A}, {B}, {C}, {D}, {E}, {F}, {G}, {H}</td>
</tr>
<tr>
<td>2</td>
<td>{{A, B}, {A, C}, {A, D}, {A, E}, {A, F}, {A, G}, {A, H}, {B, C}, {B, D}, {B, E}, {B, F}, {B, G}, {B, H}, {C, D}, {C, E}, {C, F}, {C, G}, {C, H}, {D, E}, {D, F}, {D, G}, {D, H}, {E, F}, {E, G}, {E, H}, {F, G}, {F, H}, {G, H}}</td>
</tr>
</tbody>
</table>

### Table 4 Minimum Cut Sets

<table>
<thead>
<tr>
<th>Order of cut sets</th>
<th>List of cut sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{A}</td>
</tr>
<tr>
<td>2</td>
<td>{B, C}, {B, F}, {D, G}, {D, H}, {C, F} and {G, H}</td>
</tr>
<tr>
<td>3</td>
<td>{B, D, E}, {B, E, G}, {B, E, H}, {C, D, E}, {C, E, H}, {C, F, G}, {D, E, F}, {E, F, G}, {E, F, H}, and {E, F, G}</td>
</tr>
</tbody>
</table>

Hence the reliability of the presented hypothetical network can be calculated as

\[
R_N = 1 - Q_N = 1 - \sum_{i=1}^{M} Q(MC_i)
\]

\[
Q_N = Q(MC_1) + Q(MC_2) + Q(MC_3) = 0.0107
\]

\[
\therefore R_N = 1 - Q_N = 0.9893
\]

### 5 CONCLUSIONS:

Mechanical failure of pipes in water distribution networks has been studied by numerous statistical models in the past. But none of these models focused on mechanical failure of other components of water distribution networks which may also affect the reliability of the whole network. This paper presents a
methodology to evaluate mechanical reliability of water distribution networks along with its components, using minimum cut set method. The accuracy of a developed model depends on the accuracy of the data used to build it. The proposed model requires very detailed historic break data of all the components including pipes. But many municipalities are not equipped to collect such detailed data. In this paper, the failure rate of pipes is based only on a single parameter i.e., age of the pipe and the failure rate of other components is obtained using a more general formula. Consideration of as much parameters should lead to more realistic failure rate predictions. Research should be extended to also predict the failure rate of components other than pipe. Municipalities are required to collect detailed break data of all the components of water distribution networks. The availability of such data would assist in evaluating reliability more accurately.

Acknowledgements

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References


SHIFTING LOGICS OF CONSTRUCTABILITY AND DESIGN: A STUDY OF EMERGING AEC INTEGRATED PRACTICES FOR ENERGY PERFORMANCE

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Abstract: In this paper, we analyze the practices of translation and synthesis for energy performance in building design. We use grounded theory method to collect and analyze qualitative interview and observation data to examine the difficulties of knowledge sharing and problem solving between builders and architectural and engineering designers. Extending the theory of disciplinary specific “institutional logics,” we show that designers and builders integrate their work in three ways: 1) by addressing gaps in their own knowledge that require information from a knowledge domain different from their own, 2) by synthesizing design and construction issues holistically, and 3) through integrating construction and design work practices. These insights offer evidence of shifts in the institutional logics that structure the construction and design disciplines.

1 INTRODUCTION

In the traditional model of architecture, engineering, and construction (AEC) practice, architects and engineers prepare documents for builders to construct buildings in a temporally linear relationship. The “hand-off” between disciplines at the time of bidding establishes professional boundaries with significant cultural differences between the disciplines of design and construction, and transferring knowledge across these disciplinary boundaries is difficult and resistant to easy technological fixes (Neff et al., 2010). Like all industries, AEC industries follow what sociologists have called institutional logics, “the socially constructed, historical pattern of material practices, assumptions, values, beliefs, and rules” which act as “a set of assumptions and values, usually implicit, about how to interpret organizational reality, what constitutes appropriate behaviour, and how to succeed” (Thornton, 2004:69-70). For AEC industries, this means the different cultures of architecture, engineering, and construction are shaped in large part by a set of social logics that are larger than any one company or individual. For example, people on projects have conflicting obligations to company, scope or profession, and to the building project (Dossick & Neff, 2010). These emerge out of different sets of institutional logics at work within the AEC industries.

In this paper we examine work practices of translation and synthesis of energy performance design to examine the difficulties of knowledge sharing and problem solving in integrated AEC teams. We use the notion of institutional logics to help explain the challenges that designers and builders have in collaborating and communicating across the gaps in their professional knowledge. Our findings suggest that designers and builders integrate their work in three ways: 1) knowledge gaps that require accessing builder or designer domain knowledge, 2) holistic thinking that requires synthesizing design and builder
knowledge, and 3) integrated construction and design work practices that occur within and between
designer and builder firms. Together, our insights offer evidence of incremental shifts in the institutional
logics that structure the construction and design disciplines as they develop new work practices.

The worldview and decision-making processes of designers and builders are shaped by institutional
logics such as professionalism and market that overlap, intersect, and sometimes contradict one another.
Builders and designers often employ or evoke certain logics depending upon the type of activity taking
place and the social, cultural, and organizational context of the actors engaged in these tasks. For
example, builders are often expected to evoke the logics of market and cost; they analyze building
elements, turn design documents into cost estimates, view their work processes through quantification
and linearity, and consider themselves business people engaged in the capitalist market. Comparatively,
designers are often expected to evoke logics of professionalism; they synthesize across building
elements, turn ideas into form and documentation, view their work processes through qualification and
ambiguity, and consider themselves as professionals mandated to serve the public.

Closer collaboration between builders, engineers, and architects has benefits both for project efficiency
and for improving the quality of building outcomes (Kent & Becerik-Gerber, 2010), particularly for high
performance buildings (Reed, 2009). However, builders and designers have very different ways of talking
and thinking about their work which often frustrates good collaboration (Carrillo & Chinowsky, 2006). One
of the substantive challenges to contemporary integrated AEC work practices is the translation and
interpretation necessary for interdisciplinary teams to communicate and share domain knowledge. To
realize the benefits of integrated work practices, collaborative teams need to bridge across their
disciplinary differences in two parallel directions; builders need to engage the logic of design and
designers need to engage the logic of constructability.

2 LITERATURE REVIEW

Institutional logics include such things as the demands of the market, needs of a company or practice,
and commitment to a profession. These conflicting obligations can be described using the theory of
institutional logics (Thornton, 2004; Thornton et al., 2013). On all building projects, "conflicting obligations
push people away from as well as towards good collaboration" (Dossick & Neff, 2010:463). These
obligations include legal, professional, and ethical responsibilities for the scope of work and sense of
professionalism to a specific role on the project (e.g., structural engineer, lead architect), a “tentative
temporary alliance to the project,” and “a more permanent obligation to their company” (Dossick & Neff,
2010:466). AEC team members must routinely bridge the knowledge boundaries among the different
design and building disciplines. In these settings, different institutional logics can be used as justifications
for actions or cause conflicts among different members of the team. For example, new skills can offer
value, efficiencies, and increased authority but change the way that people collaborate and rely on
institutional logics to guide or justify their behavior (Smets et al., 2012). Because communication practices
are central to how institutional logics are constructed and changed (Green et al., 2008), how people talk
within integrated teams—whether through coordinating, translating, sense making or theorizing—has the
power to make and reshape these institutional logics (Ocasio et al., 2015).

Integrated AEC projects ask collaborating team members to manage gaps in their own knowledge with
information gained from other disciplines. This process requires that connections be continually made and
unmade between an individual’s domain of expertise and the expertise of other team members.
Integrated project practices encourage AEC professionals to acknowledge, interpret, accommodate, and
adopt the approaches of people from other AEC disciplines. Theories of “conflicting obligations” and
“institutional logics” seem to suggest that these connections are where we might expect to see
incremental shifts of institutional logics and predict why some integrated projects are more successful
than others.

To test this we conducted a qualitative study to see how people on integrated AEC projects talk about
different institutional logics on these projects to suggest ways these shifts are occurring with the rise of
integrated practice.
3 METHODS

3.1 Data

The data used in this study derived from three interviews (one engineer and two contractors) and twenty-one hours of field observations of participant meetings and work sessions between energy consultants, architects, engineers, and builders across four months and 12,978 words in written field notes. Our interview questions focused on collaboration, communication, translation, and synthesis of energy modeling data, including respondents' collaboration strategies and best practices for increasing team integration. Our observation data consist of conversations about new construction projects, renovation projects, and the submission of design-build proposals where energy performance was a key issue. This select dataset emerged from a larger dataset focused on issues of knowledge and translation and synthesis for energy performance in building design (10 interviews across the U.S., 19 projects, 195 hours of field observations, 141,000 words of written field notes). From a grounded theory analysis of this large data set, we found patterns in our smaller set of interview and observation data that opened up questions of shifting logics of constructability and design.

3.2 Qualitative Open Coding of Themes

Our data analysis relies on coding the team interactions that took place in our observations and in the detailed stories told during interviews. These interactions and stories reflect a stated desire for disciplinary knowledge that research participants imagined other professionals have or that they wish that they could access in the moment. We used a modified grounded-theory approach for open coding (Strauss & Corbin, 1990) for themes where designers and builders engaged in logics of “professionalism” and “market” evidenced in these interactions. For example, we coded for moments when someone expressed the desire for builder knowledge, raised questions about the constructability of a design, or acknowledged or engaged in discussion of specific construction methods or constructability costs.

We clustered themes found in our qualitative data around three key concepts showing the shifting institutional logics brought about by integrated practice: 1) designers using ideas about constructability, 2) builders using ideas from design, and 3) the evolution of builders’ thinking.

4 FINDINGS

4.1 Designers engaging the logic of construction

Our data suggests that designers engage in the logic of construction when they encounter gaps in their knowledge connecting design to construction, where they see holistic thinking that synthesizes design and construction issues, and where domain knowledge acts to link design and construction. In some cases, designers may request or suggest receiving a contractor or builder’s input to come to a shared resolution on a constructability issue. In other cases, designers appear to engage in the logic of construction during interactions where they demonstrate their ability to cross into the knowledge domain of construction and incorporate concerns of constructability into their design.

4.1.1 Gaps in knowledge connecting design to construction

At times, designers realized that input from a builder would assist in problem definition and would provide details that could help make decisions among design options. These moments frequently occurred when the contractor was not yet working with the design team, but the team anticipated gaps in their knowledge or expertise that the contractor could fill.

While working on design development, designers will direct their staff to detail elements to engage constructability issues. For example, an engineer working on a design-build contract for a renovation project pointed out to a new employee how to use a ductulator to transcribe duct measurements onto floor plans in Revit. The engineer advised the staff member that he shouldn’t use “weird dimensions. Six inches is the limit, anything else confuses contractors.” He then advised the staff member to “try to think
like a sheet metal guy. Ask, is it easy to make?” (Field Note 140808). The engineer told his staff member to anticipate questions, expectations, and concerns in the design work.

In one example, a design team was having a conversation about an ongoing HVAC assessment in an older building. This assessment would culminate in a final report advising what would need to be replaced or fixed on each floor along with cost estimates. They realized that changing out the dampers would be difficult. During this conversation, one of the participants realized that the entire design solution rested on a consideration of the repair and installation process by the contractor—an activity not fully understood by the design team—and suggested getting feedback from a contractor:

*Engineering Consultant:* I have a feeling this is a lot more challenging to change out than the [dampers] downstairs.

*Client Representative:* I agree. They’re not easy to get to.

*Consultant:* How do we handle the pricing on this? . . . We need a mechanical contractor’s input. It would be a real Rube Goldberg to fix these and to get these from the inside. We need feedback. It’s not clear what the approach is. (Field Note 141107)

Here designers tried to imagine conditions of constructability in the absence of builder input. Designers frequently arrived at these boundaries of domain knowledge as a consequence of their design efforts. However, these moments were also highly unpredictable, and questions of constructability appear to arise out of many different types of design conversations. In these design process contexts where constructability questions impacts the definition of the design problem and its potential solution, having immediate access to construction domain knowledge—as in the case of integrated project practice—can be of significant importance in terms of knowledge exchange.

### 4.1.2 Holistic thinking synthesizing design and construction

Designers and builders are trained to think differently about problem solution processes. Where the knowledge management strategies of builders could be characterized by processes of quantification, designers have more general knowledge management strategies that could be characterized by qualification. The design methodology of qualification can be seen where designers focus on performance metrics and outcomes that could be answered by any number of potential solutions. Sometimes, conflicts between quantification and qualification can lead to poor building performance where building elements that the design team intended to work together are compromised by builder choices and value engineering.

One architectural group and its energy consultants coined “bundles” to get around this problem by joining building elements as a performance package. The bundle protected building elements designed to work together from being cut individually from the final design. This was an effort by the design team to protect interconnected system choices for operational efficiencies and energy savings. This strategy required builder logics to move from building element quantification to building system qualification. This represents an institutional logic shift by builders from quantification to qualification. Another way of defining this shift is a move to synthesize design and construction issues through more holistic thinking.

Designers are not always convinced that this type of holistic team thinking is possible or available from builders. The design team was split on the idea that they needed the contractor to provide an initial review and cost for the first proposed bundle on a large hospital project. The architect suggested that the design team present the energy bundle options to the client as well as an economic analysis of each bundle. The energy modeler responded that it could be difficult to do an economic analysis for the client before having internal discussions with other team members, including the contractor. The architect suggested that the energy modeler has the knowledge expertise to “put numbers on things.” The energy modeler disagreed: “I would want to discuss that in a larger meeting with a contractor. I would want them to at least look the numbers over and put their blessing on it or note what they don’t like about them” (Field Note 141219).

The fear the architect had was that the contractor would be unable to think qualitatively and would start picking apart the constituent elements in the proposed design bundle using cost as a weapon. In turn, the energy modeler was accepting the challenge of holistic team thinking and anticipating that the
contractor’s cost estimates could act as a “blessing” for the entire bundle of strategies, a potential resolution.

Later in the same meeting, one of the energy modeler consultants noted that certain systems that they might use to increase building performance also cost less, and that there is a need to “rethink how comfort systems work and move things from one [budget] pot, like mechanical, to another. So [the owner] would not pay more to save more, but pay less to save more” (Field Note 141219). An engineer challenged this assertion, suggesting that a contractor’s domain of expertise and normative institutional logics are stuck in categories of budgeting that make it difficult to design holistically: “The challenging aspect is getting the right baseline and accurate pricing. The contractor won’t be billing to go beyond the cost per square foot.”

4.1.3 Domain knowledge linking design and construction

Our data showing benefits to builders in domain knowledge links between design and construction are slightly more robust than the benefits seen to designers. For builders, construction knowledge is now included in design activities early in integrated projects and thus builders participate more closely with design work. Compared to this general phenomenon for builders, we saw fewer new design-construction knowledge links for designers. One mechanical engineer explained how valuable it was for his own design knowledge base to take a job in a collaborative environment focused on construction: “My career didn’t take off... or, I didn’t understand things until I became a design-build engineer. [Until I] became a... I actually started working as a mechanical contractor.” (Field Note 141114). We have found some initial evidence that this kind of cross-disciplinary hiring—designers hired by contractors or builders hired by designers—is associated with firms invested in integrated project delivery.

4.2 Builders engaging the logic of design

We have found in our initial data that builders engage in the logic of design in ways that are parallel to how designers engage in the logic of construction. For builders, this occurs when they encounter gaps in their knowledge connecting construction to design, where they are asked to think holistically and synthetically between construction and design issues, and where domain knowledge between construction and design link the two disciplines.

4.2.1 Gaps in knowledge connecting construction to design

We saw examples in the data where builders often want to know more about the design performance requirements of building elements than is typically provided in traditional design-bid-build. This includes new problems like the lack of design intent in specification documentation which reduces the efficiency of constructability reviews. One builder noted:

What we often get is specs... where it’s “we’re using this light fixture.” And we don’t know if that light fixture is chosen because the owner likes the way it looks, or if it provides the right lumen output, if... you know, it’s the only one that’s available, or they think that’s available in the time that we have in order to procure. So, we get a product package that’s kind of ambiguous. And, so, if we’re going to go back to the team with seven recommendations, we’re going to pull some information from that product spec that may or may not be right. (Field Note 141111)

Here we see that traditional methods of contract document production through specifications by the design team are creating a knowledge gap for the construction team when faced with collaborative activities like iterative cost comparisons. This suggests a need for greater knowledge exchange between builders and the design team.

Another long-time construction director called these design intentions created by the design team the “whys” of a building project. He noted how understanding design intentions would allow his construction team to be “self-adjusting.” He said,
We don't know the “whys” enough . . . “Whys” are great. “Whys” would be helpful for everybody. And a lot of people don’t even know what the “whys” are. But that would be good too, right? To know where you are so you could self-adjust . . . ” (Field Note 141107)

Later, he pointed out in concrete terms how design performance knowledge helps builders be leaders on integrated project teams with architects. He said that knowing “why the data is the way it is”—what the design intentions were—“that's really super important if you’re going to lead . . . be a leader amongst that [integrated] team.” (Field Note 141107)

Builders see the usefulness of design intentions as a tool for bettering their own efforts, and that they have a desire for greater knowledge exchange with designers on integrated teams. Given that design intentions are often qualifications rather than quantifications, it suggests that builders may need to integrate more ambiguous information into their problem solution processes than traditional construction work practices may have required.

4.2.2 Holistic thinking synthesizing construction and design

Through the evolution of construction delivery processes, new modes of working have created challenges to the traditional domain boundaries between design and construction. As building information modeling (BIM) has become more widespread among construction teams as a tool for management, we find some instances where BIM has encouraged builders to find ways to have input early in schematic design to reduce subsequent problems during construction.

One large construction firm realized that it was very inefficient to wait for MEP details to be complete before they could do clash detection, and that a better proposition was to reserve spatial volumes through the building for systems development, a strategy they called “internal space planning.” This idea leveraged the 3D capacities of the BIM model produced by the design team but was actually modeled by the construction team. This effort on the part of builders is wholly dependent on their understanding of the full arc of the design effort and their capacity to integrate design activities within construction domain knowledge.

A particularly powerful aspect of holistic thinking on the part of builders is seen in design activities that are dependent upon cost information. This is an important contribution in situations where designers are less focused on cost. An engineer who had moved to a position as a mechanical systems specialist for a large contractor had a particularly clear viewpoint: “Engineers inherently are going to design the best system possible. Period. Without regards to cost. That’s just the way that they’re wired” (Field Note 141114). Another builder explained the improved benefits between “rules of thumb” costs by designers and actual cost estimates and scheduling information from their collaborating builders:

We find the engineer of record is kind of using more rules of thumb, like “oh that’s, we've typically see that would be ten percent more, and the lead time is generally six weeks.” Well, if we change that one little piece, a condenser, it can go to ten weeks . . . . You know, so when we’re involved in a more integrated process we can . . . we can talk a little bit more intelligently about that. (Field Note 141111)

By being able to offer highly accurate costs, this builder sees the benefits of integrating design and construction knowledge and a holistic engagement with the problem solving processes of both.

This same builder told us how his firm was able to offer more value to design processes by leveraging design information through a constructability lens. When asked to provide add-alternatives to a project, he explained how his firm puts this deliverable into the language of qualifiers and performance metrics aligned with the project’s design intentions found in the project program, its sustainability goals, or its life-cycle assessments. This builder uses services like life-cycle and energy calculations and operations and maintenance information—typically considered to be the responsibility of the design team—to contribute value to these iterative project development activities.
4.2.3 Domain knowledge linking construction and design

In certain construction markets, the increasing demand for preconstruction services and integrated project design early in projects makes having construction staff with design capabilities a necessity. This is a function of how building projects are contracted and how collaboration is advanced in the particular market. One mechanical engineer working as this kind of design specialist for a large contractor said of his market: “Here, if you don’t have, like, thirty people on your staff designing, you’re not even going to be in business” (Field Note 141114). This suggests that the change toward integrated design and construction practice is being taken seriously within the field.

A sustainability director for a large contractor was blunt about how builders can integrate the domain knowledge between design and construction:

So the people you’re seeing doing integrated design well from the construction perspective are the people who saw the benefits of it before there was a title. And, so they’re the frontrunners. I think you’re going to see everybody... they’re going to try to follow... And they’re going to have to learn it. Or, they’re going to hire somebody who already knows it. (Field Note 141111)

In many ways, this shows us how builders who saw the market changes coming to AEC practice found ways to complement their construction skills with those of design—suggesting how they deal with the shifts of institutional logics. The implication is that they are able to contribute more fully and operate with more authority and value in contemporary integrated project environments. Looking more closely at these evolving institutional logics may illuminate how it is accomplished and what new work practices it entails.

4.3 Evolving institutional logic of builders

We have interviewed a number of AEC practitioners who have exhibited integrated practice logic that is emerging as characteristics of a new kind of builder: the synthesizer. This kind of builder sees the role of a builder as a synthesizer of building elements and systems, acting as a translator between the design issues of form/systems and constructability. Synthesizers advocate for building performance with cross-disciplinary domain knowledge and an interdisciplinary knowledge management style. Among our study participants, one builder in particular stands out as an exemplification of this logic. His responses to our interview offer some substantive issues that could be thought of as potential foundations for the evolving institutional logic of contemporary builders in integrated project practice. Our synthesizer-builder used this kind of holistic thinking to explain, in his experience, that co-location works because it is

... a back and forth conversation. That smooths the process out a ton, because we don’t need a lot of specifications because everyone involved understands the design intent. And the design intent is developed collaboratively. The subcontractors said “Well, what about this? Does this meet your budget?” Eh, it doesn’t quite meet our efficiency. What about this?” It’s like, “well, yeah, it’s close to your budget, but it doesn’t meet your schedule” right?... It’s like, it’s almost a real-time conversation... that’s really developed early on. (Field Note 141111)

Our synthesizer-builder was encouraged by his leadership team to offer environmental design services more typically provided by design professionals such as sustainable design, storm water and habitat restoration. His firm saw this as a good business practice in their market: “[My firm] wanted my expertise to be on the table, whether that was related to schedule or cost or constructability or not. ...we want to get that information in front of the client” (Field Note 141111).

At some point, integrated design practices may push more construction firms to accommodate other holistic thinking that synthesizes construction and design domain knowledge. Ultimately, this evolution of the institutional logic of this particular construction firm recognized the strong value proposition in being a company with a proven integrated project track record and a demonstrated capability to realize sustainable building performance: “Of course we can meet the budget, of course we can meet the schedule, of course we can get this thing built for you. But, you know, the way in which we’re going to do that is slightly different; we’re going to participate in the conversation rather than do what you otherwise normally would...” (Field Note 14111).
All of these challenges to the existing institutional logics of construction as they move more toward design were wrapped up in our synthesizer-builder’s imagined future for integrated AEC teams:

If I could walk into a room in an integrated design project meeting and not know anybody, I shouldn’t be able to tell the difference between the contractor and the architect. . . . And, that is okay, or it needs to be okay in an integrated design process in order for that process to work smoothly. (Field Note 141111)

5 DISCUSSION AND CONCLUSION

There are parallels in how architects, engineers, and builders in integrated AEC projects attempt to incorporate their disciplinary realms and work toward problem solutions. This occurs when designers and builders encounter gaps in their knowledge that require different domain knowledge, synthesize design and construction issues holistically, and link construction and design work practices. We see incremental shifts of institutional logics when people connect their domain of expertise with that of other team members. This occurs when collaborative communication processes bridge different disciplinary expertise.

We saw this in case of the synthesizer-builder where cross-disciplinary knowledge allowed him to translate between design and constructability issues. The synthesizer-builder allowed shifts from construction to design logics whenever it seemed to be efficient, effective, or brought capabilities necessary to solve the problem at hand. He could engage in a productive and authoritative interdisciplinary knowledge management style that took advantage of the ability to synthesize qualitative and quantitative forms of domain knowledge. When our synthesizer-builder reported how his firm’s management encouraged him to offer design strategies to clients “whether that was related to schedule or cost or constructability or not,” we see a change to the firm’s construction logics by an inclusion of new domain knowledge and ambiguous design problem solving—a direct move toward an incorporation of some of the institutional logics of design.

Our study shows how these design and construction logics can impact builder and designer roles, knowledge management, and domain knowledge. Institutional logics shape the context of professional norms and values in which builders and designers act, and they guide how people perceive project problems and solutions through the lens of their disciplinary domains. However, integrated AEC work practices are creating new professional and social contexts where institutional logics can be challenged, shifted, and adapted. In these contexts, communication processes centered in collaboration are the means by which domain knowledge and expertise are shared. These changes might suggest that builders working in integrated AEC projects pay attention to and test the institutional logics of designers while at the same time become aware of the constructs pushing builders to adopt new institutional logics of design. Conversely, designers in integrated projects might be encouraged to engage in more of the institutional logics of construction through more rigorous attention to constructability and cost issues in the earliest phases of project design.

This study uses a small interview sample of builders and designers from the Pacific Northwest, a region where there is an increasing market in integrated design. To draw more generalizable conclusions, we will need to conduct more interviews with AEC professionals working in other parts of the U.S. and North America. This study also draws from observation data within firms that regularly use integrated design and construction project delivery. Future research could involve observations in firms that are less involved in integrated project delivery allowing for greater comparison between the institutional logic shifts of builders and designers. Still, there is much to be learned from studying leading-edge work practices in a rapidly changing industry. In larger scale studies, we expect to see evidence that evolving dimensions of AEC domain knowledge between builders and designers will be associated with attention to and the testing of institutional logics.
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References


METHODOLOGY FOR AUTOMATED GENERATION OF 4D BIM

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Abstract: Lack of adequate visualization of project construction operations often causes project parties to struggle with large amount of data. 3D Building Information Modeling (BIM) is a static model, built for representing the geometry of a constructed building and its respective information. However, construction processes are dynamic and require dynamic representation. 4D BIM is gaining more momentum in construction research and in industry. There are commercial packages that can generate 4D BIM and numerous researchers have used 4D BIM in their research. However, related literature does not disclose the methodology used or the know-how of creating 4D BIM. This paper presents an automated methodology and describes how to construct a 4D BIM. The automated methodology maps the 3D BIM objects to project schedule activities through a newly added attribute to each 3D BIM object. As such, different groups of objects within the 3D BIM are assigned to different activities. For each group, a series of decisions are made to classify whether it belongs to completed activity, activity in progress or activity to be executed in the future. The developed methodology was implemented in prototype software. Autodesk Revit has been customized so that the integration between 3D BIM and project schedule be applied using Revit Application Programming Interface (API). The developed automated methodology and software were applied to a construction project in Montreal area to demonstrate its use. The developed methodology is straightforward and easy to use. It is expected to facilitate the utilization of 4D BIM in research and in practice.

Keywords: Automation, Project Visualization, Building Information Modeling & 4D BIM

1. INTRODUCTION

Construction Industry Institute (CII) studies showed that the cost of rework could range from zero to 25% of the installed cost of construction. However, the use of visualization representations such as 3D models by management team can reduce that amount of rework by 65% on average. The efficient use of space on a construction site is a site-specific, difficult task and is often left to the intuition of construction managers. Poor spatial planning has been deemed one of the major sources of productivity loss (Thabet and Beliveau 1997). On large construction projects, project management teams often suffer from not being able to mentally visualize a project complexity. Thus, they are frequently not able to make the best decisions to mitigate risks. Visual representation is one way to overcome this problem. Visual models represent the spatial aspects of schedules and communicate schedules more effectively than traditional methods such as bar charts (Kang et al., 2007). Building information modeling (BIM) is gaining momentum in the architecture/engineering/construction (AEC) industry, especially since owners such as the US Army Corps of Engineers (USACE) implemented initiatives requiring future projects involving the design and construction of facilities include BIM. In 2005, the United States General Services
Administration (GSA) announced that starting 2006, AEC firms would be required to provide a building information model with their designs (McCuen, 2008).

By themselves, 3D models do not have the ability to show the exact status of a project at a specific point in time, and so are of little help in progress control. In order to create a construction schedule from 2D drawings, planners have to visualize the sequence of construction in their minds. This is an extremely difficult task since workspace logistics and resource utilization are highly dynamic by nature. Most site organizations plan their works based on conceptual site layout and drawings, which are rarely updated during the project execution. Thus, site managers have not fully benefited from recent advancements in visualization-information technologies (Chau et al., 2005). 3D models have some basic knowledge that results from shapes, sizes and locations. This is the geometric database, where each element has geometric attributes. In addition to the geometric attributes, which describe the physical 3D model, each element in the model can have any number of non-geometric attributes associated with it. One non-geometric attribute might be the construction method or specifications (Aslani et al., 2009).

The goal of adopting a BIM is to provide a comprehensive view of the building by including (drawings, specification, details, etc.) in a single-source model (Krygiel et al., 2008). BIM databases contain physical and functional characteristics of a structure since a BIM model is composed of smart objects rather than lines, arcs, and text. All of these characteristics are mainly due to BIM’s capability to realize the building through all of the stages in the form of a database (Fu et al., 2006). BIM users can obtain information about any single element, or for all elements in a project, to inform decisions about the project. Examples of data included with an element are material quantities, costs of elements, time considerations related to the element, building performance, operations and maintenance, and several other items essential in the lifecycle of a constructed facility (McCuen, 2009 and Motamedi and Hammad, 2009). Montaser and Moselhi (2012) developed an automated methodology utilizing BIM and tablet PC for progress reporting in construction jobsites. They added the data taken from BIM database to RFID tags attached to the components. The idea of making components data readily available on the tags provides easy access for project and construction managers through real-time connection to a central database or a portable device.

With its potential to assemble the whole project virtually before any actual construction begins, BIM adds a level of accuracy to both quantity and quality issues. Building materials can be demonstrated in real time scenarios rather than requiring manual analysis. By drawing building elements only once for a project in a plan view, the projections of all elevations and sections are generated automatically. One of the direct benefits is the reduction in drawing time; therefore, designers can mainly focus on other design issues (Krygiel et al., 2008). 3D BIM model is a static model, built to represent a building. This could be seen as a shortcoming for the construction process/operation since it is a dynamic process and merits a dynamic presentation. 4D BIM is a visual representation that combines an object oriented 3D BIM model with time. 4D BIM is information visualization that is easier to understand than traditional methods. Traditionally, project managers use 2D drawings, bar charts, and sketches to clarify the construction design, but these visualization methods do not integrate the temporal or spatial dimensions. 4D BIM models are a form of visual representation of a project that also takes into consideration the temporal aspect of how project teams plan to actually build a project, according to construction schedules. 4D BIM could be used strategically by on-site management for visualization (Hartmann et al., 2008).

Moreover, 4D BIM can assist site personnel in brainstorming sessions and discussions about access, storage and sequencing of works. Better visualization facilitates team collaboration in removing illogical relationships among activities in construction operations. Owners of the constructed facilities may have little experience in construction, and are often unable to truly participate in the development of construction plans unless a simple method of visualization and communication is made available to them. 4D BIM visualization seems to be an effective way of enhancing the many different types of human perception and it can help anticipate potential construction conflicts during the operational stages (Chan et al., 2004, and Staub-French et al., 2008). However, related literature does not disclose the methodology used or the know-how of creating 4D BIM. This paper presents an automated methodology and describes how to construct a 4D BIM.
2. DEVELOPED METHODOLOGY

4D BIM integrates the building project 3D model and its construction schedule. A realistic project baseline schedule should be developed, including project activities and their early start (ES) and early finish (EF) dates. The 3D BIM model, first, imports the planned data directly from scheduling software, in database format. Figure 1 depicts the flowchart of the procedure used to link the 3D BIM model to project schedule. It then maps the 3D BIM model objects to project schedule baseline activities. As such, different groups of these 3D BIM objects are assigned to its respective activities. Figure 2 shows the flow chart for manipulating 4D BIM for visualization purposes and the template creation process. For each group and according to current date, a series of decisions are made to classify whether it belongs to a finished activity, an activity in progress or an activity to be executed in the future. The automated procedure compares the current date to the ES and EF dates of each group, and controls each group’s visibility accordingly. Future activities, those that have not yet started, are hidden from the developed 4D BIM. For finished activities, the 4D BIM checks if each group has been inspected and checked as being finished, or if according to the as-planned schedule it is finished but not yet checked or inspected. The 4D BIM makes the finished and checked activities visible in their final forms, and displays unchecked finished activities in a red highlighted form. The activities currently in progress are displayed in yellow. The activities displayed in red and yellow are divided spatially among identified zones. To facilitate data storage, fusion and processing a relational database was developed. The database has six entities; interconnected with one-to-many, many-to-one and many-to-many relationships. Due to space limitation, the Entity Relationship (ER) diagram is not included. For more details about the developed database, please refer to Montaser (2013).

![Figure 1: Linking the 3D BIM model to project schedule](image)
Figure 2: The process of 4D BIM model visualization
3. DEVELOPED SOFTWARE

The developed methodology was implemented in prototype software. BIM models are capable of recognizing building objects in its fixed asset hierarchy (Family - Type - Object) while being user-friendly for creating a building's indoor and outdoor zones. It links those objects to the zone that hosts them by relating an object's ID to a zone's ID. Different software developers such as Autodesk, Bentley and CATIA have applied the BIM concept. None of these systems' providers, however, describe any BIM web application. All of them are standalone applications installed on the user computer that could be connected to internet. Each has its pros and cons; however, Autodesk Revit customization capabilities have been significantly extended over the past few years. Revit Application Programming Interface (API) allows users to program with any .NET compliant language such as VB .NET and C# .NET. Revit has thus been selected here to be customized so that the integrated tablet PC data acquisition system be applied in its API and utilized as add-In.

This section presents the developed automated tool, which was developed using the "Visual C# .NET" in Revit's API. Revit was selected to be customized and the developed software was implemented to the Center for Structural and Functional Genomics (CSFG) at Concordia University in Montreal as a proof of concept and for testing the developed software. The building consists of basement floor, ground floor, first floor, second floor, mechanical floor and roof. The total built up are is 6000 m². The building is a reinforced concrete structure, except the mechanical and fire escape stairs, which are of steel structures. The contractual budget was $20 million with contractual duration of 12 months. The Architectural and Structural plans provided by Concordia University were in the form of 2D CAD drawings, and there was no BIM model for the building. A 3D BIM model was created as a part of the developed methodology. The BIM model was developed using the project 2D drawings. Revit Autodesk software was used to develop the 3D BIM model. The 3D BIM model has all of the parameters and attributes for building zones and objects. Each parameter and attribute is associated with a unique ID to avoid conflicts when dealing with data exchange and scheduling software, which is Microsoft Project 2013. The generated 3D BIM model feeds the developed software with data, such as the number of spaces, the area of each space, the object families and family types, in order to identify objects inside each space, and later facilitate integration of the 3D model with the construction schedule.

In addition to the unique ID that each object has, BIM objects also have two important characteristics that are family and type. Family represents the main description of objects such as wall, door, window, etc. While, type represents specific kind of a family object such as internal wall 1 hour fire rated or wooden door single flush panel. The developed software utilizes these two aspects of BIM objects to categorize the whole building. The software should be utilized by users, who are familiar with the project 3D BIM model and the construction schedule of the building being modeled such as project managers or project schedulers. The user is responsible for linking the Microsoft Project file to the 3D BIM model of the project and maps the 3D BIM objects to project activities through utilizing the control visibility options. Visibility options have three different use-cases that are show by activity, show and hid activities manually and show activities by date. “Show activities by date” use-case is considered the 4D BIM model that was customized in Revit. The visibility options given to the user facilitate the process of modifying or changing activities objects in case of any design modification or introduced change orders.

The user first activates the developed add-in menu in the Revit screen and subsequently selects from a pull-down menu “Set MS Project File” and completes the process depicted in Figure 3. The software closes the file explorer dialog and inserts the selected file path into displayed writable textbox. The user presses the “Done” button so, the developed tool checks if the file exists, which is part of the verification process. Then, it saves the new MS project path into the system configuration file to use it as default MS Project path and closes the change MS Project form. The second step, performed by the user, is to map 3D BIM objects to its respective activity. In creating group of elements, the user can link one object or a set of objects to one activity as diagrammatically shown in Figure 4. Prior to that linkage, MS Project schedule must be activated and verification is performed to make sure that the schedule has more than one activity. If the MS project file have list of activities, it displays two buttons “Finish” and “Close”. Then, the system allows the user to select multiple objects from the 3D Revit model and link them to one of the activities being displayed. After selecting multiple objects, the user selects the MS Project activity from a
pull-down menu “Choose Group Name” and completes the process depicted in Figure 4. Upon completion of the linking process, the object(s) inherits the attributes of the associated activity such as activity name, early start and early finish, which are then used for generating the 4D BIM model. This process is repeated until all 3D Revit objects are mapped to associated MS Project activities.

Each object in Revit, referred to here as element, has a set of attributes such as ID, family, type. These attributes vary from object to another and they are either generic or specific. A new attribute was added to all Revit objects to facilitate the linking process, as shown in Figure 5. It is referred to it as “Group”, which represents one object or a set of objects. The user selects a set of objects such as supported deep excavation piles, as shown in Figure 4, then; the name of “Group” is made identical to the activity name. The sequence of this process was designed and implemented to be from outside to inside and from top to bottom. Upon finishing one group, objects of that group will be hidden to provide access to the other objects. The mechanics of linking identified objects to relevant scheduled activities are performed interactively as shown in Figure 6.
Figure 4: Mapping 3D Revit objects to project activities (part 2)

Figure 5: The added attribute “Group” to Revit object
Figure 6: Assigning MS Project activity to Group name

Controlling visibility of activities is crucial in the developed automated tool. Therefore, three different options were developed to identify which activities are visible and which are hidden. To activate the visibility controls, the user activates the add-in menu and selects “Show/Hide Groups”. Then, the automated tool checks that at least one activity is linked to the 3D Revit objects. Otherwise, the system pops up an error message instructing the user to map the 3D Revit objects to the MS Project activities first. If this check is false then the system displays “Group Visibility Control” form. The form contains three different options, as shown in Figure 7. The user has to select one of the three options. If the user selects “Show/Hide Based on Activity” then it shows under that option a drop down list with all activities that were linked to 3D Revit objects. The user selects one activity that required to be displayed. It displays the selected activity on the current view and hides all other activities.

If the user selects “Show/Hide Based Manual” then the automated tool displays a form containing all displayed activities under the visible list and all hidden activities in other list. The user selects the needed activity to be displayed and press move or select the needed activity to be hidden and press move. In addition, the user could select to move all activities from one list to the other and vice versa. The user presses done button to apply the above actions to Revit current view. Showing specific activity or activities become very handy to the experienced user specially, in the cases of design modification or change orders. Therefore, the user can isolate the activity objects, modify it, and link it again to the MS Project activity. The third option is to show/hide activities by date, as shown in Figure 7. This option represents the methodology for applying the 4D BIM concept inside Revit without the need for third party software. When the user selects s the option of “Show/Hide Based on date”, two calendars appear. The first calendar to specify the start date and the second calendar for the end date. The automated tool applies the algorithm explained earlier for showing and hiding activities on specific date range. Figure 8 shows pictures from the generated 4D Revit visualization.

4. CONCLUSION

Lack of adequate visual representation often causes construction managers to struggle with large, amounts of data. Such limitations of traditional tools on one side and the advances in visualization-information technologies on the other have stimulated various research and development efforts to advance new innovative construction visualization techniques that depict sequence of construction operations. Traditionally, project teams use 2D drawings, Gantt-charts, and sketches to provide the necessary details of construction sequence simulation. However, these tools do not provide the
information required to generate 4D visualization of project progress. 4D BIM is the solution for this problem, which is generated by integrating the 3D BIM with project schedule. It allows a three dimension (3D) simulation of a building and its components that is called 4D BIM. This simulation goes beyond demonstrating how different building assemblies can be put together in the project. It can assist in predicting problems, show the construction variables associated with different building designs, and calculate material quantities. However the literature and current practice do not reveal a clear methodology or procedure to create a 4D BIM. Additionally, most of the work done in this area is through integrating 3BIM and schedule using third party software. This paper presents an automated methodology to create 4D BIM models. The methodology is generic, straightforward and easy to use. It is expected to facilitate the use of 4D BIM in research and in practice. The methodology has been implemented in a prototype software and was applied to a case study to demonstrate its use.
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Montaser, A. 2013. Automated Site Data Acquisition for Effective Project Control. Ph.D. Thesis presented to the Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada.


OUTDOOR AUTOMATED DATA ACQUISITION FOR PROGRESS REPORTING

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Abstract: Tracking and control of construction projects depend primarily on the accuracy, frequency and time required to collect actual onsite data of construction operations. Automated site data acquisition has received considerable attention in recent years to circumvent the limitations of manual data collection. Outdoor operations represent significant portion of construction operations, particularly in heavy civil engineering projects. This paper presents an automated methodology to track outdoor activities in near real time through 4D Building Information Modeling (BIM), Global Positioning System (GPS) and Tablet PC. The integration of 4D BIM, GPS and tablet PC provides platform for automated progress reporting that supports visualization, localization and automated data acquisition, respectively. The developed methodology was applied to a construction project in Montreal area to demonstrate its use. NavisWorks Autodesk was used to generate 4D BIM model through linking project schedule with the objects of the 3D BIM model. The tablet PC has barcode reader, Radio Frequency Identification (RFID) reader, Wi-Fi, Bluetooth, camera for images and videos and a speaker microphone for voice recording, which add more automated data acquisition capabilities. The used tablet did not have GPS. So, mobile GPS was acquired for outdoor localization. The tablet PC and the mobile GPS communicate and exchange data via Bluetooth standard communication protocol. Near-real-time automated data acquisition of onsite operations facilitates early detection of discrepancies between actual and planned performances and supports project managers in taking timely corrective measures. This methodology is expected to enhance traditional tracking and progress reporting procedures.

Keywords: Automated Data Acquisition, Progress Reporting, 4D BIM, GPS, Tablet PC

1. INTRODUCTION

Accurate and timely collection of information on the status of project resources and activities is necessary to support managers in effective assessment of project progress and in making timely decisions during the execution of work onsite (Abdelrehim, 2013). Effective tracking and control system requires collecting accurate data form construction site in timely manner with cost efficient methods. Ineffective tracking and control system can result in costly delays, rework and additional costs (Jang and Skibniewski, 2008). Tracking and control process is a challenging task in view of the dynamic change of onsite operations including material delivery and utilization (El-Omari, 2008). Traditionally, project teams use 2D drawings, Gantt-charts, and sketches to provide the needed information of measuring project progress. These tools, however, do not provide the information required to generate 3D visualization of project progress (Chan et al., 2004). Building Information Modeling (BIM) is gaining momentum in the architecture/engineering/
construction (AEC) industry by owners such as the GSA (General Services Administration) and the USACE (US Army Corps of Engineers) embraced its use on their constructed facilities (McCuen, 2008). 3D BIM model is a static model, built for representing the physical building geometry and its related information. However, construction process is a dynamic process and needs a dynamic presentation (Staub-French et al., 2008). 4D visualization requires integration of project schedule and the spatial data of the project utilizing BIM. 4D BIM is a concept, which combines an object oriented 3D model with project schedule. It is a kind of information visualization that is easier to understand than traditional methods. The literature reveals that project managers have already applied 4D models on a number of projects (Hartmann et al., 2008).

Current approaches for capturing, storing and managing construction jobsites data are mostly manual and labour-intensive methods. Data collected using manual methods are not reliable or complete, as they are dependent on the motivation, judgment and skills of the site personnel for data collection. Furthermore, data collected through these methods are typically transferred and stored in paper-based format, which is difficult to search and access, and which makes processing them into useful information expensive and unreliable (Montaser et al., 2012). Tablet PC capabilities have been enhanced considerably in recent years, in addition to its traditional advantages which, is durability mobility, expressivity of display and ease of use. Currently, it integrates various automated data acquisition technologies such as, barcode readers, RFID readers, wireless communication (Wi-Fi and Bluetooth), GPS and camera for video clips and digital images (Montaser, 2013). Recent technological advancement in data acquisition systems has made the consistent management of construction projects and their information more feasible. Bar coding and RFID are used to automatically identify, track and facilitates generating status reports (Cheng and Chen, 2002, Shehab et al., 2009, Razavi et al., 2012 and Montaser and Moselhi, 2012). Using cameras for data collection can enables the user to capture a broader perspective of construction activities and operations. The camera captured images can reduce the time needed for inspection by allowing this task to be done remotely. The captured information can be transferred to project management team via internet connection (Brilakis, 2007).

GPS has proven to be a suitable technology to locate the assets position for the outdoor operations with accuracy of centimeters (Navon and Goldschmidt, 2002). GPS is at present fully Global Navigation Satellite System (GNSS). However, GPS signals can be affected by several sources of error during transmission. Therefore, a real time data correction is performed to eliminate or minimize those errors. Differential GPS (DGPS) correction should be applied to the captured GPS data. DGPS requires one or more additional receivers, called base stations or reference stations, which are located at known points. Data collected at base stations is used to determine GPS measurement errors and compute corrections to these errors. Errors are corrected with DGPS either in real time or during post-processing (Blewitt, 1997). GPS data at a point is in the form of latitude (Φ), longitude (λ) and height (h), which is mainly a form of astronomical observations (Satellite reference coordinate system). Hence, this data needs to be converted into the Universal Transverse Mercator (UTM) coordinate system, which is a geodetic coordinate system (X, Y, Z). It comprises a standard coordinate frame for the Earth (the datum or reference ellipsoid). Further transformation is performed to transform the captured data into the 3D local coordinates system. This is done through calculating the vector 3D transformation matrix, refer to the procedure described in Leick (1995).

GPS technology has attracted researchers looking for effective ways to track the outdoor location of construction labor and equipment on jobsites (Navon et al., 2002). The construction industry has already embraced the use of GPS in control of site surveying and earthmoving operations. GPS can be used to track the location of equipment over a wide range of geographic and geometric scales. The use of GPS for earthmoving operations has reported to lead an increase of 22% in productivity and 13% in cost savings for short haul distance projects. Also for long haul distance, the advantages were less, a productivity increase of 5.57% and cost savings of 4.79% (Han et al., 2006). Caldas et al. (2006) developed a system integrating GPS and Geographical Information System (GIS), in which GPS was used to track the position of pipe spools on a construction project. Montaser and Moselhi (2014b) developed a new web-based model for the tracking and control of earth moving operations. Their model uses spatial technologies, including GPS and GIS, to facilitate automated data acquisition. This paper presents the proposed methodology that integrates 4D BIM, GPS and tablet PC automated site data.
acquisition capabilities to support tracking and progress reporting of outdoor construction operations. A recently constructed building is utilized as a case study to demonstrate the application of the developed method and to illustrate its capabilities.

2. PROPOSED METHODOLOGY

The proposed methodology integrates 4D BIM visualization, GPS localization and tablet PC automated data acquisition technologies to improve progress reporting procedures. Tablet PC is used as integration media in the developed methodology for 4D BIM model for the project being considered, GPS data and automated site data acquisition technologies. Outdoor construction areas are divided into exclusive zones which stored in the project 3D BIM model. The user has the tablet PC that incorporates the 4D BIM model and adjusts the model to the current date to have a planned visualization that represents current project status. The GPS identifies the location of the site personnel who is collecting onsite data. Based on the location identified, the zone can be retrieved from the 4D BIM. The user while, walking outdoor, collects the as built progress data utilizing the automated data technologies capabilities of the tablet PC to capture ongoing progress data in various formats such as RFID data and barcode data. The user can take snapshots with the tablet PC’s camera and write comments and notes about the onsite activities being monitored. These comments and notes are entered directly on the tablet PC screen and stored in the database. In addition, the user fills progress templates related to his current zone. The user utilizes the templates for data input for some activities in cases where the use of the above mentioned technologies is deemed costly and/or technically impossible. For example, if the bar code is not accessible or taking a picture in a dark zone is not useful.

After finishing the first zone, the user move to the next zone for data collection. The data collected in each zone is attached to the developed database with new attributes of time stamp and zone. This procedure is designed to facilitate data storage and retrieval. Project managers can analyze these data for different purpose such as safety or taking corrective actions. These steps are repeated until all zones are covered, as shown in the procedure outlined in Figure 1. This data collected is used to represent actual progress, which is then compared as planned baseline progress using earned value analysis (EVA) to measure the project performance. The analysis and processing of the captured data is depends mainly on the data source and its type. For example, RFID can be utilized for material localization and tracking, for more details please refer to (Montaser and Moselhi, 2014a). Regarding images and videos, image processing can be used to capture colors, edges and texture for finishing activities. The results of the reported progress are used afterwards to update the project schedule, which will detect any experienced delay. It will also facilitate early detection of discrepancies between actual and planned performances and, accordingly, support project managers in taking timely corrective measures. Organizing collected data is very important as it facilitates future retrieval of this data, which can help not only in progress reporting but also in management of claims and in the production of as-built 3D BIM. To facilitate data storage, fusion and processing a relational database was developed. The database has ten entities; interconnected with one-to-many, many-to-one and many-to-many relationships. Due to space limitation, the Entity Relationship (ER) diagram is not included. More details about the developed database can be found in Montaser (2013).

3. CASE STUDY

Field studies were conducted during the construction of the Center for Structural and Functional Genomics (CSFG) at Concordia University, as shown in Figure 2. The project is located at the corner of Sherbrook St. West and West Broadway St. in Montreal. It forms an expansion to the existing Science Complex. The building consists of basement floor, ground floor, first floor, second floor, mechanical floor and roof. The total built area is 6000 m². The building is of reinforced concrete framing, except for the mechanical and fire escape stairs, which are of structural steel. The contractual budget was $20 million with contractual duration of 12 months. Initial visits to the jobsite of the project were made and the blue prints released for construction as well as the construction schedule in MS project were reviewed to get familiar with the various aspects of the project. More than forty (40) jobsite visits were made. The Architectural and Structural plans provided by Concordia University were in the form of 2D CAD drawings,
and there was no BIM model for the building. A 3D BIM model was created as a part of the developed model. The BIM model was developed using the project 2D drawings. Revit Autodesk software was used to develop the 3D BIM model.

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**Figure 1: Proposed methodology**
All construction data, such as objects' materials as well as their specifications were extracted either from available related documents or directly from observations during site visits. Since, the developed objects have parametric relationship with each other, then the sections, elevations, and perspectives were generated automatically. The model consists of 7450 parametric object. NavisWorks Autodesk was used to link the project schedule with the objects of the project 3D BIM model. The 3D Revit model objects were exported to Navisworks along with the construction schedule. Once the Microsoft Project schedule and 3D model were imported into Navisworks detailed relationships were developed to link each scheduled activity to its corresponding objects of the model. The software automatically simulates the construction sequence as per the project schedule, as shown in Figure 3. Different colors were assigned to objects in the developed 4D BIM model to express their respective status of progress. At any given time, the 4D model can reflect the time schedule in a visual manner. Objects with user selected colors indicate that they are already executed, while those highlighted in green indicate that the activities they belong them are in progress. At the top left of the simulation screen the date and the name of the activities being executed along with their exact durations.

Tablet PC is considered one of the most important components in the developed methodology. This is because it houses the captured data and the generated 4D BIM. The tablet PC used in this research is a rugged Panasonic Toughbook®H2 handheld tablet PC, as shown in Figure 4. It has 10.1" sunlight-viewable LED screen, fast Intel® Core™i5 vPro™ processor and 1.7GHz with Turbo Boost up to 2.7GHz Intel®. In addition, it has 40 GB hard drive, Smart Cache 3MB, 4GB SDRAM (DDR3-1333MHz), twin batteries (6.5 hours with both batteries), ports such as USB, serial and Ethernet and IP65 sealed all-weather design (Panasonic, 2015). GPS could be embedded in the tablet PC. However, the tablet used in this research did not have GPS. So, Trimble GeoXT mobile GPS was acquired for outdoor localization. The tablet PC, mobile RFID reader and mobile GPS communicate and exchange data via Bluetooth standard communication protocol. It was used to identify site personnel location in outdoor zones. It is a high performance GPS receiver combined with a rugged handheld computer with a powerful 520 MHz processor, 128 MB RAM, and 1 GB of onboard storage, as shown in Figure (5-a). TerraSync software was installed on the handheld GPS. It collects and updates geographical data, as shown in Figure (5-b). Differential GPS (DGPS) correction should be applied to the captured GPS data. DGPS requires one or more additional receivers, called base stations or reference stations, which are located at known points. Data collected at base stations is used to determine GPS measurement errors and compute corrections to these errors. Errors are corrected with DGPS either in real time or during post-processing (Trimble, 2015). Both methods were performed in this paper.
Figure 3: 4D BIM NavisWorks© mode

Virtual Construction @ Different time

Figure 4: The used tablet PC
For real-time DGPS correction, the base station calculates and broadcasts the error for each satellite as each measurement is received, which enables corrections while the user is in the field collecting data. Real time DGPS corrections are generated and broadcasted in real-time by privately or self-owned GPS base stations, or by a wide range of government agencies. Real-time DGPS sources include external beacon and radio sources, as well as Satellite Based Augmentation Systems (SBAS) such as VRS networks in Canada. VRS networks use multiple base stations to calculate the DGPS corrections that are then delivered to the user from a Geostationary satellite (SBAS) or from a radio or cellular phone. For example, corrections generated by a VRS network are commonly broadcasted over an internet server. A VRS network uses data from several base stations to provide corrections that are generally more accurate than corrections based on a single station. Factors that affect real time DGPS accuracy include how often the corrections are updated, how far the user is from the base station, and whether the coordinate system used by the correction source matches the coordinate system used by the GPS receiver (Can-Net, 2015). VRS base station was 50 Km far from Genomics building jobsite. Therefore, cellular connectivity was added to the Trimble GeoXT GPS handheld via the TDL 3G cellular modem, which was acquired with the GPS, as shown in Figure (5-c). It was connected to the GPS via wireless Bluetooth (Trimble, 2015). TDL 3G provides continuous network/internet access to real time VRS corrections. The authors acquired the VRS corrections license service for one-month to experiment with it through TDL 3G cellular modem.

For post-processed DGPS correction, the collected GPS data is transferred to the tablet PC via wireless Bluetooth. Since, the construction jobsite was in Concordia University Loyola campus, wireless Wi-Fi connection was available. Measurements from the base station were downloaded and GPS data processed through GPS Pathfinder Office software version 4.10 that was earlier installed on the tablet PC, as shown in Figure 6. Typically, post-processed DGPS uses only one base station (Trimble, 2015). The GPS Pathfinder software provides the functionality needed to manage and process data collected using GPS. It provides the tools needed to correct, view, and edit GPS data collected in the field, and to export it in a format suitable for GIS, CAD, or database. Both the wireless Wi-Fi and GPS PathFinder software were available on the tablet and the GPS PathFinder converted the data into Microsoft Access database format, as shown in Table 1. Therefore, the data is first transferred wirelessly from the GPS to the tablet PC and then processed through GPS PathFinder software installed on the tablet PC. Accordingly, this method was integrated with the developed 4D BIM model using NavisWorks Autodesk Application Programming Interface (API). Then, the user’s outdoor location is visualized on the 4D BIM model, as shown in Figure 7. The user in the same location can capture many data such as sound, video, image, hand written note, barcode and RFID scan. The data collected, in different formats, have two new
main attributes, time and location. This procedure facilitates data analysis and retrieval for progress reporting as well as for the remote monitoring of the project status.

![Post-processed GPS data using GPS PathFinder software](image)

**Figure 6:** Post-processed GPS data using GPS PathFinder software

**Table 1:** Sample of GPS corrected data

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4. CONCLUSION

This paper presents an automated methodology for data acquisition and progress reporting to support time and cost tracking of construction projects. The developed methodology integrates project visualization, localization and tablet PC automated site data acquisition. Project visualization is achieved by utilization of 4D BIM that integrates 3D BIM model and project schedule. Localization was done through GPS. Automated site data acquisition technologies were utilized through tablet PC enhanced capabilities that integrates RFID, barcode, wireless communication and camera technologies. It also utilizes 4D BIM to provide visualization capabilities to the process of data acquisition. Data is collected on site and stored in a database for processing to generate progress reports. With the continual development of automated data acquisition sensors and its integration, a significant amount of data can be collected on site. Near real time control of on-site operations, facilitates early detection of discrepancies between actual and planned performances and supports project managers in taking timely corrective measures. A case study of a construction project was utilized to illustrate the features of the developed methodology in collecting data required for tracking and control.

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The authors would like to thank Mr. Peter Bolla, Associate Vice-President and director of Concordia University’s Facilities Management Department and Ms. Marie Claude Poitras of Genivar for providing the data used in the case study.

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DEVELOPING A SYSTEM OF SYSTEMS FRAMEWORK FOR AN INTEGRATED TRANSPORTATION SYSTEM USING SYSTEM DYNAMICS

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Abstract: Demand forecasting plays an integral role both in planning and managing urban transportation infrastructure. Analyzing travel demand is an integral part of any transportation system. Different types of demand forecasting models are being used by transportation industries not only to plan for renovation and expansion but also to evaluate several policy scenarios associated with the particular infrastructure system. The traditional demand forecasting models that exist mostly focus on individual transportation sectors such as air-transportation, highways, etc. and not much attention is given to consider the interdependencies and complexities among the various components and thus many-a-times ignore the emergent behaviors. To overcome this deficiency, the research study applied a system-of-systems approach to forecast the overall public transport demand considering all the different sectors of the transportation network of an integrated public transport system. However, forecasting the public demand for each transportation mode is a major challenge as it depends on several uncertain factors such as population growth, GDP growth of the country, traffic congestion on roads, average annual income of population, ticket prices, travel types and others. System dynamics modeling approach was adopted to represent the information and physical flows among the different components / entities within a system at an aggregate level with high degree of accuracy. These types of models would help the decision makers in evaluating several policy scenarios by altering the model variables and developing investment strategies for future transportation infrastructure planning. This research paper developed a conceptual framework to assess the public demand for individual transportation modes in an integrated transportation network using Abu Dhabi’s surface transport expansion and integration project as a case study.

1 INTRODUCTION

Abu Dhabi is undergoing a rapid and visionary transformation to get established as a world-leading city and the Abu Dhabi Surface Transport expansion and integration project is the core for such an infrastructure expansion involving multimillion dollars of investments. The “Plan Abu Dhabi 2030” Urban Structure Framework Plan attempts to envisage the year 2030 and provide the basis for future growth accordingly. The Surface Transport Master Plan (STMP) commissioned in February 2008 developed the conceptual transportation strategy into a detailed Master Plan and an implementation program based on the outline provided in Plan Abu Dhabi 2030. The plan addresses the regional transport needs of the Emirate as a whole, while focusing particularly on metropolitan Abu Dhabi. The challenges in this plan are the current congestions, which are swiftly approaching to full capacity, as well as the drastic increase in demand owing to increasing population. The population increase is mostly due to an estimated 400% increase in gross area of the city, six million additional office space leading to huge economic growth, and
a four-fold increase in the number of regional and international visitors (Abu Dhabi DoT 2009). Currently, private passenger car mode of transport is involved in around half of all daily person-trips while public bus transportation is approximately one percent. Reliance on private cars and taxis is the main reason for congestion. As growth continues, a multi-faceted, multi-modal transport system will be vital to creating a vibrant, sustainable world-class city (Abu Dhabi DoT 2009). By 2030 the integrated public transport network is expected to comprise of a high-speed rail service to Dubai; some 130 km of metro railway, regional rail connections; over 340 km of tram lines served by bus feeder services and a passenger water transport network. The system will also include all of the supporting Intelligent Transport Systems (ITS) and unified automatic fare collection systems (Abu Dhabi DoT 2009). Forecasting the demand on the overall network as well as its components is an essential task to facilitate proper design and management of the transportation system in order to meet its objectives.

The major objective of this paper is to develop a framework that would eventually foster the analysis of how the interdependencies between components of an integrated public transport can affect the overall demand based on the demand fluctuations of the individual modes of transport. The demand for individual modes of transport is extremely uncertain as it depends on GDP, population, roads congestion, price, level of service of each mode, and congestion of each transportation mode all play an important role in determining the overall demand on the public transport network as well as the demand on the individual modes. The System Dynamics model framework developed based on a SoS approach would allow to forecast the passenger demand for an integrated transport network based on the demand on individual modes once the real data is available. This would also provide a platform to the decision maker to test a combination of policy scenarios designed to suffice the overall objectives of a Transport Integration Project. The following sections of the paper provide a description of the research objectives, a brief summary of the reviewed literature, model development methodology, model framework and finally a discussion on the framework developed and conclusion.

2 BACKGROUND: SYSTEM OF SYSTEMS & SYSTEM DYNAMICS IN TRANSPORTATION DEMAND

A system-of-systems (SoS) is defined as a “set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities” (Office of the Deputy Under Secretary of Defense for Acquisition and Technology 2008). A SoS can be differentiated from a monolithic system based on several aspects such as autonomy, belongingness, connectivity, diversity, and emergence (Boardman and Sauser 2006; Liu 2011). Other advantages as offered by SOS approach include operational and managerial independence of the components, geographic distribution, evolutionary behavior, emergent behavior and consideration of heterogeneity of the system components (Maier 1998; Delaurentis 2005). However, the two most important advantages as mentioned above are “operational independence” and “managerial independence” of the components. These aspects specify that in a SoS the sub-systems are “useful in their own right and generally operate independent of other systems”.

System Dynamics (SD) modeling is one of the tools used for studying dynamic problems arising in complex systems, such as social, managerial, economic, or ecological systems. As defined by Richardson (2011), SD is the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behavior“. Like some other modeling approaches, most notably Agent-Based Modeling, SD is also a bottom up system modeling approach that aggregates representations of component processes and their relationships that helps to understand the underlying structure of the system (North and Macal 2007). SD can be further used to trace this behavior over time at discrete points and to analyze how a change in a specific part of the system can affect that behavior (Martin & Forrester 2001). According to Richardson (2011), the SD approach involves defining problems dynamically, in terms of graphs over time; focusing inward on the characteristics of a system; considering dynamic behavior of a real system and formation of loops, feedbacks and circular causality; identifying independent stocks or accumulations (levels) in the system and their inflows and outflows (rates); formulating a behavioral model using a computer simulation model expressed in nonlinear
equations; getting the outputs, deriving understandings and applicable policy insights from the resulting model; and finally implementing changes.

System Dynamics (SD) has been used repeatedly in modeling surface or air transportation networks for studying, inter alia, the effect of a set of identified factors on the demand on the said networks and others. Selected examples from the literature include the works of Wang, Lu, and Peng (2008), Haghani, Lee, and Byun (2010), Suryani, Chou, and Chen (2010), Yevdokimov (2002), Wang et al., (2005), and Stave (2002). All the aforementioned research studies have treated the transportation network from a single mode perspective without recognizing that it is in fact composed of a group of interconnected systems. This research builds on the aforementioned studies by viewing the surface transportation network from a system-of-systems approach through recognizing the managerial and operational interdependence of each transport mode whilst considering the interconnections and interdependencies between the SoS components. It is worth mentioning that Agusdinata, Fry, and DeLaurentis (2011) in their work followed a SoS approach to take into account the complexity of a multimodal transportation system in assessing the carbon emission impact of on-demand air service and automobiles.

3 MODEL FRAMEWORK DEVELOPMENT PHASES

The System Dynamics model framework based on System-of-Systems (SoS) approach was developed in two phases namely definition phase and abstraction phase. A description of each of these phases are provided below:

3.1 Definition Phase

The definition phase encompasses identifying constituents of the SoS, mapping traits of the SoS and categorize the network levels by utilizing the established SoS lexicon.

3.1.1 Constituents of the Systems of Systems

The integrated multimodal surface transport system of Abu Dhabi is solely targeted to provide an efficient and pleasant mode of transportation to the public that might include a number of modes of transport in a single journey. The total demand on the integrated transportation system would be thus dependent entirely on the availability and convenience of the individual modes of transport. In order to suffice this motivation, the two major criteria that should be taken into account are a comprehensive planning from macro level ensuring that all the individual modes of transport are effectively coordinated with each other and incorporation of Intelligent Transport Systems (ITS) such as automatic ticketing, travel planning, updates of departure and arrival times, etc. The individual modes of transport, referred here as components of the transportation systems-of system (SOS) include roadways, high-speed regional train, metro network, tram network, bus service, ferry and water taxi service.

3.1.2 SOS Traits Mapping and Design Principles

The SOS traits and design principles needed to establish the Integrated Public Transportation System of Abu-Dhabi as a system of systems comprising of different individual modes are identified in Table 1 (Maier 1999 and DeLaurentis 2005).

<table>
<thead>
<tr>
<th>Trait/Design Principle</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Managerial Independence of the components</td>
<td>The component systems are acquired by separate program management offices and run by separate operational units.</td>
</tr>
<tr>
<td>Operational Independence of the</td>
<td>Operation would be mostly through the government action and would be run by different public agencies at different levels independently, but with a common mission to provide optimized service to the public and also improving the</td>
</tr>
</tbody>
</table>

Table 1: SoS Traits Mapping and Design Principles
<table>
<thead>
<tr>
<th>Trait/Design Principle</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>components</td>
<td>economic, environmental, social, and cultural scenarios for the Abu Dhabi city.</td>
</tr>
<tr>
<td>Geographically distributed</td>
<td>The individual system components are not collocated and are distributed according to their needs and accessibility.</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>The constituent system components are significantly different from each other and they operate on different elementary dynamics</td>
</tr>
<tr>
<td>Stable Intermediate Forms</td>
<td>A variety of stable intermediate forms, both in time and space, are evident in the design of the component systems.</td>
</tr>
<tr>
<td>Policy Triage</td>
<td>Individual system components are directed and controlled by the individual service providers maintaining a communication and a level of collaboration with the other system components.</td>
</tr>
<tr>
<td>Leverage at the interfaces</td>
<td>Multiservice system of integrated public transport system concentrate on information transfer</td>
</tr>
<tr>
<td>Emergent behavior</td>
<td>Demand forecast of the entire system is not evident from demand of the individual system components as they operate on different elementary dynamics</td>
</tr>
<tr>
<td>Networks</td>
<td>Networks define the rules of connectivity between the different semiautonomous system components</td>
</tr>
<tr>
<td>Ensuring Collaboration</td>
<td>All the systems should work collaboratively in order to provide both optimized service to the public and the expected profit to the government.</td>
</tr>
<tr>
<td>Directed SoS</td>
<td>The integrated public transportation system will be developed and operated to fulfill a particular purpose of reducing congestion and provide best services to the public through formal organizations, policies, etc.</td>
</tr>
</tbody>
</table>

### 3.1.3 SOS Lexicon and ROPE Table

The following ROPE (Resource, Operations, Policy, and Economics) table (Table 2) shows the Abu Dhabi Integrated Public Transport Network in SoS lexicon and taxonomy terms. This is considered to be an important initial step in development of our model framework. Based on nature of the research problem described hereunder, the scope of the proposed model will tentatively be restricted to the Resources, Operations, and Policy elements of the β and the γ levels. As highlighted in the ROPE table, our focus is mainly to study the interaction between the different modes of the transport system and how their interaction affect the overall transportation system of Abu Dhabi. Each mode is an independent system and thus their interaction is expected to reveal some of the interesting emergent behaviors for the overall system, i.e. from a systems-of-systems perspective. This research covers both the vertical and horizontal interactions within the boundary specified in the above ROPE table.

<table>
<thead>
<tr>
<th>Level</th>
<th>Resources</th>
<th>Operations</th>
<th>Policy</th>
<th>Economics</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Vehicles and Infrastructure (buses, ferries, metros, railways, trams, etc.)</td>
<td>Operating an individual resource (e.g. a bus, a ferry, a metro)</td>
<td>Policies relating to single resource use</td>
<td>Economics of building/operating/buying/selling/leasing a single resource</td>
</tr>
<tr>
<td>β</td>
<td>Set of resources performing a common function (e.g. buses, ferries, metros)</td>
<td>Operating resource networks for common function (e.g. Abu Dhabi bus network, ferries network, metro network)</td>
<td>Policies relating to multiple resource use</td>
<td>Economics of operating/buying/leasing resource networks</td>
</tr>
</tbody>
</table>
3.2 Abstraction Phase

Abstraction is the most important step in developing a framework for a model. Its main purpose is to identify the key entities of actors, effectors, disturbances, and interdependency networks. Lewe and DeLaurentis (2004) identified four categories of entities such as explicit, implicit, exogenous, and endogenous. Entities are further classified as Endogenous-Explicit (Resource Network), Endogenous-Implicit (Stakeholder Network), Exogenous-Explicit (Disruptors), and Exogenous-Implicit (Drivers). Using the same approach, the following sections provide a description of the entities identified for our integrated public transport network model.

3.2.1 Resource Network

At the beta (β) and the gamma (γ) levels of the transportation system, the resource network can be viewed as a set of interconnected entities, each represented by a transportation mode, all having the common goal of reducing congestion and providing quality and convenient services to the public. The major modes considered in modeling Abu Dhabi’s surface transport network include highways, private transport (private vehicles and taxis) and public transport (rail, metro, bus, tram, and water ferries) systems. The attributes of these modes are assumed to be (1) average speed of the mode; (2) accessibility and range; (3) operation cost; (4) fare; (5) capacity; (6) delay time; (7) intermodal capability and (8) connection time. It is noteworthy that each transportation mode has its own unique set of attributes that differentiates it from the other modes and makes it a more favorable to a certain group of users (i.e. passengers). Figure 1 shows various transportation modes that are interconnected at the beta (β) level forming the gamma (γ) level that comprises Abu Dhabi’s integrated public transport network. The transportation network of Abu Dhabi is further connected to that of other states within the United Arab Emirates forming the UAE’s national surface transportation system but it is not in the scope of this research. Interactions and communications between the resource-network entities are expected to occur both horizontally (between the different modes as well as between the UAE states) and vertically (in a hierarchical sense) for management and coordination between the system components on technical,
economic, policy, and administrative aspects. Such interactions and communications take place through the various federal and governmental bodies as described below in the “Stakeholders” section.

3.2.2 Stakeholders

Similar to any public transportation system, there is a wide range of stakeholders in Abu Dhabi integrated public transport network. As the project is in planning stage, several entities are being acknowledged as stakeholders of the transport network but not yet fully established. Users can be considered as primary stakeholders in the transportation network. They are the ones who create the demand on the transport modes and their attributes would determine the most preferred mode of transportation on the beta (β) level. Each user has his/her special travel pattern, car availability, trip purposes, and personal preferences; however, only the aggregation of these alpha (α) level attributes will show on our model as an aggregation. At the country level, federal institutions such as National Transport Authority (NTA) in United Arab Emirates are responsible for development and implementation of transport policy of the entire country. At the state level, Department of Transport (DoT) is the main institution with responsibilities of developing general transport strategy, implementing the emirate’s air, land and sea transport policy, making recommendations to the government on setting up corporations in the related sectors, legislation, privatisation and tariffs. Now, modeling the attributes and behaviors of such stakeholders through a System Dynamics approach can prove to be a challenging task due to the limitations of such modeling technique. However, the directed nature of this System-of-Systems, as mentioned above, and by assuming that all stakeholders of relevance to our research problem, described herein, work together to achieve one single goal—rather than competing goals—made such modeling task feasible.

3.2.3 Drivers

Driver entities affect the behavior of the stakeholders and these can be categorized as economic, societal, and psychological (Lewe, DeLaurentis, & Mavris 2004). These drivers play an instrumental role in creating the demand on one or more of the transportation modes as well as in determining several transportation policies such as the tariff structure. Examples of drivers in our model include the following: (i) Population growth is deemed to be one of the core indicators of total demand on surface transportation network; (ii) GDP growth is of pivotal importance because population and demographics are directly affected by a change of GDP in Abu Dhabi which subsequently impacts demand on the network and its components; (iii) Passengers’ behavior: Abu Dhabi government has declared its ambitions of convincing residents to change their behavioral patterns and choose public transport for many of their daily trips in an attempt to reduce congestion and gas emissions from vehicles.

3.2.4 Disruptors

Disruptors are entities that are unfavorable and can affect the efficiency of the system. In the surface transport network, disruptors can directly result in the decrease of demand on the entire network or on one of the modes, each with a unique degree of effect. Examples of disruptors include (i) natural disruptors such as inclement weather. Abu Dhabi is known to have a hot arid climate throughout the summer and during the hot season the demand on transportation modes that may require short walks between nodes (between metro stations) or waiting time in an open space (bus station) will decrease causing a mode shift by users and (ii) artificial disruptors such as financial crisis. A financial crisis will directly result in a decreased number of expatriate workers and tourists, which will eventually decrease the total demand on the transportation network as the workers and tourists are believed to be the main potential users of the transportation network upon its completion.

4 MODEL FRAMEWORK

As highlighted earlier, total demand on the transportation network as well as individual demands on various transportation modes is believed to be influenced by several factors such as population, demographics and economy. To that end, the framework of our System Dynamics model is in form of a causal loop diagram that is composed of multiple interconnected sub-models. The sub-models as shown in Figure 2 are: (1) population sub-model; (2) migration sub-model; (3) GDP sub-model; (4) car ownership
The sub-models are connected by means of feedback loops. Each feedback loop has either a reinforcing or a balancing effect. For example, a population growth (out of the population sub-model) increases the congestion; on the other hand an increased fare for a transport mode will most likely result in decreasing the congestion in that mode. The relationships are based on information from existing literature, basic concepts and assumptions. The different types of sub-models considered to be the building blocks for developing the framework of the requisite model are as follows:

- **Population Growth & Migration Sub-models**
  Typically, the population growth will directly lead to more travel demand. Demand on the individual modes will also change, thus affecting the total demand on the integrated transportation system. Total population on the other hand is affected by the birth and death rates.

- **GDP Sub-model**
  As discussed before, increase in GDP of a country affects the travel demand by attracting more people to settle in that area. A decrease in GDP on the other hand might lead to emigration and thus decrease the overall travel demand and change demand on the individual travel modes.

- **Car Ownership Sub-model**
  Car Ownership, also considered as a level variable, plays an integral role in determining the demand on the private transportation network. Higher number of car ownership might lead to higher road congestion level and render the other modes of travel such as metro, rail and water ferry to be more convenient. However, the emergent behavior of the system cannot be predicted and it is unique for each individual scenarios.

- **Demand Sub-models**
  The demand sub-models include multiple auxiliary variables such as private and public transport attractiveness, people availing private transport, bus demand, HSR demand, metro demand, tram demand, and water ferry demand (shown in Figure 3). The attractiveness of each mode is assumed to be affected by road traffic congestion, fare, and level of service.
5 RESULT DISCUSSION

The framework developed in this paper would provide an essential tool for analyzing how a demand change for a particular mode would affect the total demand on the integrated transportation system. This would serve as an important decision making tool for the policy makers and investors to plan for the integrated transportation system. A major limitation of system dynamics model is that it requires mathematical relationships to run the simulation and study several scenarios and policies. Lack of data is a major problem in developing such types of system of system models. However, as a proof of concept we developed a hypothetical situation and run the model with synthesized data. The outputs of the simulation with respect to different time periods is given in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Model (at t=360 months)</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>6.5575 million capita</td>
<td>8.84527 million capita</td>
<td>3.93426 million capita</td>
</tr>
<tr>
<td>GDP</td>
<td>$231,945 million/capita</td>
<td>$398,875 million/capita</td>
<td>$312,742 million/capita</td>
</tr>
<tr>
<td>Migration</td>
<td>902,057 persons</td>
<td>2,191,580 persons</td>
<td>206,826 persons</td>
</tr>
<tr>
<td>Private Transport Demand</td>
<td>256,733 (active) cars</td>
<td>367,571 (active) cars</td>
<td>214,193 (active) cars</td>
</tr>
<tr>
<td>Metro Demand</td>
<td>476,922 passengers</td>
<td>644,543 passengers</td>
<td>294,486 passengers</td>
</tr>
<tr>
<td>Tram Demand</td>
<td>527,064 passengers</td>
<td>709,869 passengers</td>
<td>323,352 passengers</td>
</tr>
<tr>
<td>Bus Demand</td>
<td>554,948 passengers</td>
<td>736,404 passengers</td>
<td>244,551 passengers</td>
</tr>
<tr>
<td>HSR Demand</td>
<td>373,289 passengers</td>
<td>502,995 passengers</td>
<td>229,214 passengers</td>
</tr>
</tbody>
</table>
6 CONCLUSIONS AND LIMITATIONS

This paper presented a system dynamics model framework for an integrated public transport network based on a system-of-systems approach. The model can be used to forecast passengers demand on a public transport network as well as on individual modes such as bus, metro, tram, HSR, and water ferries. The model can be further used to evaluate multiple scenarios by changing the values of variables and
rates incorporated in the model to show how the demand will change if GDP, migration rate, fare, crowdness, and level of service are changed for example. Several constraints and assumptions were made in developing and implementing the model. These include limiting the model to cover only passengers with no allowance for freight transportation, which resulted in omitting trucks and rail freight transport from the network. In addition, the model assumes that all stakeholders have the same objective of providing quality transportation services to the residents of Abu Dhabi. Profit making by the operators of each transport mode is not recognized as an objective of the stakeholders. In other words, the different transportation modes do not compete with each other but rather collaborate. Since the actual project is still in an early design phase, the capacity of each transportation mode as well as the fare are not yet determined.

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MANAGEMENT OF CONSTRUCTION RISK THROUGH CONTRACTOR’S ALL RISK INSURANCE POLICY – A SOUTH AFRICA CASE STUDY

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Abstract: Contractors’ All Risks (CAR) is a special insurance cover, which insurances those losses not covered by an ‘excluded peril’ in a construction contract. The benefit to the insured under this type of policy is that the burden is shifted to the insurer who, to resist the claim, is required to show that the cause of the loss falls within an exclusion. The objective of the current research is to study the efficiency of CAR in mitigating construction risk and to determine the factors which affect the use of CAR insurance policy in South Africa. The data for the study were derived from both primary and secondary sources. The primary data was obtained through the survey method, while the secondary data was derived from the review of literature. The primary data for the study was collected through a structured questionnaire survey distributed to a sample of 67 contracting firms who had taken CAR insurance and are currently using CAR in mitigating construction risk and 6 insurance companies who insure contractors under this policy. Findings from the study revealed that CAR Effectively covers work in progress, CAR protects the contractor’s interest effectively, CAR policy also protect the client’s interests effectively and that CAR assist the contractor in risk management by recognising potential risks and reducing the probability of such risks. Whilst the factors which affect the use of CAR insurance policy in the South Africa construction industry include: stipulation of the adopted conditions of standard construction contract, client’s requirement, cost and contractor’s own interest. The study adds to the body of knowledge on the use of CAR in the management of construction risk in the South Africa construction industry.

1 INTRODUCTION

Risk is inherent in any business venture, much more to the construction industry. Vital organizational resources are invested in business opportunities in the hope of obtaining a favourable financial return (Liu, Li & Lin, 2007). Risk lies in the possibility that such a return might not be realized; hence, risk management is crucial in a project. The rapid growth of the construction sector in South Africa since the end of the apartheid era and with the hosting of the 2010 FIFA world cup, brought new challenges due to the risks involved in design and production. South Africa construction enterprises are experiencing significant developments and structural reforms. South Africa construction companies are mostly privately and publicly owned whose risks, losses and profits are undertaken by the individuals and the enterprise managing directors. The changing business environment in the South Africa construction industry requires all contractors to manage risks adequately thus protecting the client’s from any form of loss.
According to Hertz and Thomas (1983), construction risk refers to a variety of situations involving many unknown, unexpected, frequently undesirable and often unpredictable factors. While, Perry and Hayes (1985) also referred to risk as an uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective. Likewise, Jaffari (2001), asserted that risk is the exposure to loss, gain, or the probability of occurrence of loss/gain multiplied by its respective magnitude, whilst Abbasi et al. (2005) considered risk by the possibility of loss, injury, disadvantage or destruction from a given task. On the other hand, Berk and Kartal (2012) described risk as the potential for unexpected consequences of an activity. Construction risk management is widely recognized as one of the most important procedures and capability areas in the field of project management according to Tadayon et al (2012). Because construction projects are unique and dynamic, the construction operation involves numerous uncertainties, multiple intricacies, varies techniques, and divergent environments with uncertainties. Hence, recognising and managing the potential risk factors, which can considerably differ from project to project depending on several conditions, plays a crucial role in enhancing the performance and accomplishing the successful delivery of the enterprise.

Construction risk management has been the subject of numerous research studies. One of the earliest attempts to study construction risks and systematically identify their sources can be credited to the work of Chapman and Cooper (1983), whose study presented the “risk engineering” approach, which incorporated different techniques and tools, such as PERT, decision trees, and probability distributions. Liu et al. (2003) inform that managing risk involves creating awareness of uncertainty, qualifying the risks, managing the controllable risks, and minimizing the impact of uncontrollable risks by risk allocation. The ineffective implementations of risk management are often caused by (Liu et al., 2007):

- a lack of formalized risk management procedures, including risk identification,
- analysis and control (Tah and Carr, 2001);
- a lack of continuity of risk management in the different stages in the project life cycle, including conceive, design, plan, allocate, execute, deliver, review and support;
- poor integration between risk management and other key processes, including design, estimating, planning, production, logistics, cost analysis, manufacturing, quality assurance, reliability, schedule analysis, support (e.g. maintainability), and test and evaluation; and
- a lack of interaction among different parties, including clients, contractors, Insurers, and suppliers.

Construction risk management mechanism and procedures are not new to the South Africa construction industry. One of the major methods of mitigating against construction risk in South Africa, include risk transfer. Transferring risk is normally through subcontracting, insurance and modifying contract conditions. Out of these, insurance is one of the commonly used risk transferring methods in the construction industry. Hence, the contractor’s all risk insurance policy is a major risk mitigating tool in the South Africa construction industry. Hence, Odenyika (1999) observed that the insurance is one of the main methods of construction risk transfer in the construction industry. Also, Perera et al. (2008) scholar work also revealed that in the Sri Lankan construction industry risk is managed through insurance. Risk if, not managed properly, impacts negatively on the construction industry, hence the need to assess the efficiency of the generic solutions for risk management such as insurance. Therefore, the objective of this study is to assess the efficiency of CAR in mitigating construction risk and to determine the factors which affect the use of CAR insurance policy in the South Africa construction industry. The next section of the study discusses the subject matter of the research and thereafter, the methodology used for the study is presented before the presentation of the research findings, and thereafter, some conclusion and recommendation are made.
2   CONTRACTOR’S ALL RISK INSURANCE

Contractors’ All Risks (CAR) insurance is an all-inclusive insurance cover used in construction contracts. CAR is a short term insurance policy, which insures “the works” in a construction contract. The first CAR policy is said to have been issued in 1929 to cover the construction of the Lambeth Bridge across the Thames in London. Further to that, a special policy was created in Germany in 1934, but the real development of the policy took place with economic recovery and the construction boom after the Second World War (Wassmer, 1998). In South Africa, the Contractors’ All Risk policy is also often referred to as the ‘Builder’s risk’ or the ‘Course of construction policy’.

There are broadly two types of construction risks insurance. The first covers damage to property, such as damage to buildings and other structures being constructed or to the existing building in which the construction is being carried out (Dunning, 2009). The second type of CAR covers liability for third party claims for injury and death or damage to third party property. Modern forms of contractors’ all risks policies in the South Africa construction industry covers both. CAR’s basic principle is that the insurance covers those losses not covered by an “excluded peril”. The Contractor’s All Risks Insurance is specially designed to cover engineering projects involving both constructions of the building and other civil engineering works that are being carried out. CAR insurance provides coverage against any unforeseen and sudden physical loss or damage from any cause, other than those specifically excluded. Newman (2010) explains that the main characteristic of the CAR policy is that unlike other insurance policies, the CAR clause is not limited by reference to specified perils; in other words, everything is covered unless it is excluded, expressly or by implication. CAR policy is usually combined with (but must be distinguished from) Public liabilities or Third party liabilities policies in the South African setting. CAR is designed to provide cover for all the parties involved in a construction project, hence, the policy is usually acquired in the joint names of the Client or the Principal agent and the Contractor. Other interested parties, such as funders, often ask to be added as a joint name. According to Dunning (2009), the theory is that if damage occurs to the insured property then, regardless of fault, insurance funds will be available to allow for reinstatement. The effect of joint names insurance is that each party has its own rights under the policy and can therefore claim against the insurer. Each insured should comply with the duties of disclosure and notification. However, insurer has no right of subrogation against the other insured party, which means that the insurer is not able to recover sums paid to one co-insured under the policy by pursuing a subrogated action in the name of the other insured (Bunni, 1986; Flanagan & Norman, 1993; Dunning, 2009). The CAR insurance has a standard format regarding cover although different insurance companies may have different special wordings to suit their clients. Some significant features and benefits of the Policy include:

- Covers permanent and temporary works being carried out.
- Covers contractors’ tools, plant, equipment (including spare parts), site huts and scaffolding.
- Covers cost of recovery of property that is immobilised or embedded in soft ground providing it is not due to mechanical or electrical failure of the property.
- Covers materials in transit to or from or, held in storage at contract site.
- Policy provides cover as standard in Great Britain. Republic of Ireland, Northern Ireland, Isle of Man, and the Channel Islands.
- Covers the cost of professional fees incurred during the reinstatement of property.
- Unlimited cover for the cost of debris removal.
- Cover applies during any maintenance periods specified in contract.
- Cover for the cost of rewriting plans and specifications (this is project specific).
- Provides cover (to a specified limit per employee) for the loss of employees’ tools and effects.
- Contents cover (to a specified limit) for loss and damage to contents of show houses.
- Optional extension to cover continual hiring in fees.

The CAR insurance not only transfer risks, it is also assist the contractor in risk management by recognizing potential risks and assist in the reduction of the probability of such risks. Hence, Flanagan and Norman (1993) state that the readiness of the insurer to write an insurance coverage reflects favorably on the insured’s efforts at risk prevention. According to McNameee, (1999) risk management
practice of the past largely focused on hazard insurance and probable loss. But today it focuses on the broad issues of general management. Among the insurance covers used in construction, Contractors’ All Risk (CAR) policy has been accepted worldwide as a comprehensive cover by which all the material damages and third party damages are covered (Perera et al., 2008). The CAR policy used in South Africa is almost the same as that of other countries. The next section of the research discusses the methodology used in conducting the research.

3 METHODOLOGY

The data used in this study were derived from both primary and secondary sources. The primary data was obtained through the questionnaire survey method, while the secondary data was derived from the review of literature and archival records. The primary data was obtained through the use of a structured questionnaire aimed at 67 contractors, construction professional and insurance companies in Johannesburg to meet the research objectives. The construction professionals and contractors were randomly selected amongst their peers. Whilst the insurance companies that are known for undertaking CAR were surveyed. Survey participants included contractors, architects, quantity surveyors, civil engineers, construction and project managers who have experience in the use of CAR policy. A list of construction professional who works within the greater Johannesburg Metropolitan Municipality was obtained from the respective professional council and the Council for the Built Environment- the watchdog of professionals in the country via the various professional councils; whilst the list of contractors was obtained from the Construction Industry Development Board, the entity responsible for the registering of contractors in the country. This approach concurs with the work of Swan & Khalfan (2007) who advise that the inclusion of all construction professionals and contractors, is essential for successful project delivery- which applies to the current study. Random sampling was used to select the professionals and the contractors from the obtained list. According to Kombo and Tromp (2006) random sampling is the probability whereby people, place or things are randomly selected. From the list of construction professionals and contractors, 60 were randomly selected. This yardstick was considered vital for the survey in order to have a true assessment of the efficiency of CAR in mitigating construction risk and likewise to determine the factors which affect the use of CAR insurance policy in the South Africa construction industry.

Because all professionals as contained on the list had an equal chance to be drawn and participate in the survey. Out of the 60 questionnaires sent out, 51 were received back representing 85.0% response rate. This was considered satisfactory for the analysis based on the assertion by Moser and Kalton (1971), that the result of a survey could be considered as biased and of little value if the return rate was lower than 30% to 40%. Because the sample size for this study was relatively small, all groups of respondents were combined together in the analysis in order to obtain significant results. The data were analysed by calculating frequencies and the mean item score (MIS) of the rated factors. Although the empirical study is based on a relatively small sample of 51 construction professionals and contractors, the findings provide an insight into the general perception of the efficiency of CAR in mitigating construction risk and likewise the factors which affect the use of CAR insurance policy in the South Africa construction industry. The calculation of the MIS is explained in the next section. The research was conducted between the months of July to October, 2014. The questionnaire was designed based on the information gathered during the literature review and does not form part of an existing survey instrument.

3.1 Mean Item Score (MIS)

A five point Likert scale was used to determine the efficiency of CAR in mitigating construction risk and likewise the factors which affect the use of CAR insurance policy in the South Africa construction industry with regards to the identified factors from the extant review of literature. The adopted scale was as follows: (1) = Strongly disagree; (2) = Disagree; (3) = Neutral; (4) = Agree; and (5) = Strongly agree. The five-point Likert scale scores were transformed to an MIS for each of the identified factors as scored by the respondents. The indices were then used to determine the rank of each item. These rankings made it possible to cross compare the relative importance of the items as perceived by the respondents. The computation of the MIS was calculated from the total of all weighted responses and then relating it to the
total responses on a particular aspect. This was based on the principle that respondents’ scores on all the selected criteria, considered together, are the empirically determined indices of relative importance. The index of MIS of a particular factor is the sum of the respondents’ actual scores (on the 5-point scale) given by all the respondents’ as a proportion of the sum of all maximum possible scores on the 5-point scale that all the respondents could give to that criterion. Weighting were assigned to each responses ranging from one to five for the responses of ‘strongly disagree’ to ‘strongly agree’. This is expressed mathematically in Equation 1.0. The relative index for each item was calculated for each item as follows, after Lim and Alum (1995):

\[
MIS = \frac{1n_1 + 2n_2 + 3n_3 + 4n_4 + 5n_5}{\sum N}
\]

Where; \( n_1 \) = Number of respondents for strongly disagree; \( n_2 \) = Number of respondents for disagree; \( n_3 \) = Number of respondents for neutral; \( n_4 \) = Number of respondents for agree; \( n_5 \) = Number of respondents for strongly agree; \( N \) = Total number of respondents. Following the mathematical computations, the criteria were then ranked in descending order of their relative importance index (from the highest to the lowest). The next section of the article presents the findings of the survey and some discussion.

4 FINDINGS AND DISCUSSION

4.1 Efficiency of the CAR policy- The Insured’s perspective

Based on the ranking (R) of the weighted averages, the mean item scores (MIS) for the listed perception of the efficiency of CAR in mitigating construction risk in the South Africa construction industry were identified (Table 1). The survey findings revealed the six list factors were all significant. The most important efficiency of the use of CAR in the industry were that: CAR policy protect the client’s interests effectively (MIS=3.80; SD=0.71; R=1); CAR policy protect the contractor’s interest effectively (MIS=3.71; SD=0.90; R=2); and that CAR assist the contractor in risk management by recognising potential risks and reducing the probability of such risks (MIS=3.68; SD=0.91; R=3) as shown in Table 1.

<table>
<thead>
<tr>
<th>USE OF CAR</th>
<th>RANK</th>
<th>MIS</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractor’s all risk policy protect the client’s interests effectively</td>
<td>1</td>
<td>3.80</td>
<td>0.74</td>
</tr>
<tr>
<td>Contractor’s all risk policy protect the contractor’s interests effectively</td>
<td>2</td>
<td>3.71</td>
<td>0.90</td>
</tr>
<tr>
<td>CAR assist the contractor in risk management by recognising potential risks and reducing the probability of such risks</td>
<td>3</td>
<td>3.68</td>
<td>0.91</td>
</tr>
<tr>
<td>CAR covers liability for the third parties</td>
<td>4</td>
<td>3.60</td>
<td>1.04</td>
</tr>
<tr>
<td>CAR effectively covers work in progress</td>
<td>5</td>
<td>3.46</td>
<td>1.04</td>
</tr>
<tr>
<td>CAR serves the procurement needs by covering material related risks</td>
<td>6</td>
<td>3.20</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Whilst the two least rated usage of CAR as shown in Table 1 are that CAR effectively covers work in progress (MIS=3.46; SD=1.04; R=5) and that CAR serves the procurement needs by covering material related risks (MIS=3.20; SD=1.13; R=6).

4.2 Factor affecting the use of the CAR policy

Furthermore, when the perspective of the Insurer’s was solicited on the factors which affect the efficiency of CAR, result emanating from the questionnaire analysis revealed that the most significant factors were
Table 2: Factors affecting efficiency of CAR - insurer’s perspective

<table>
<thead>
<tr>
<th>Factors influencing the use of CAR</th>
<th>Rank</th>
<th>MIS</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of background understanding of construction works</td>
<td>1</td>
<td>4.33</td>
<td>0.78</td>
</tr>
<tr>
<td>Lack of risk management knowledge and expertise in managing or administering CAR</td>
<td>2</td>
<td>4.25</td>
<td>0.87</td>
</tr>
<tr>
<td>Lack of understanding of contractor’s/ construction risk</td>
<td>3</td>
<td>4.17</td>
<td>1.11</td>
</tr>
<tr>
<td>Lack of risk assessment (extend to known)</td>
<td>4</td>
<td>4.08</td>
<td>0.74</td>
</tr>
<tr>
<td>Construction projects are too vulnerable to loss.</td>
<td>5</td>
<td>3.33</td>
<td>1.07</td>
</tr>
<tr>
<td>Lack of qualification to undertake construction project risks</td>
<td>5</td>
<td>3.33</td>
<td>0.98</td>
</tr>
<tr>
<td>It is a one chance business since construction insurance is a once off policy with no renewal applicable like property which is issued every year.</td>
<td>7</td>
<td>3.08</td>
<td>1.16</td>
</tr>
<tr>
<td>Complex risks which are often inter-related</td>
<td>8</td>
<td>3.0</td>
<td>1.13</td>
</tr>
<tr>
<td>Too many insured parties, (client, principal, main contractor, third party although for the project only)</td>
<td>9</td>
<td>2.83</td>
<td>1.03</td>
</tr>
<tr>
<td>Difficulty for the insurer to design an insurance policy</td>
<td>10</td>
<td>2.45</td>
<td>1.03</td>
</tr>
</tbody>
</table>

The least rated factors related to: too many insured parties, (client, principal, main contractor, third party although for the project only) – (MIS=2.83; SD=1.03; R=9) and difficulty for the insurer to design an insurance policy (MIS=2.45; SD=1.03; R=10).

Table 3: Contractors / construction professional perspective of factors affecting the use of CAR policy

<table>
<thead>
<tr>
<th>Factors influencing the use of CAR</th>
<th>Rank</th>
<th>MIS</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client’s requirement</td>
<td>1</td>
<td>4.07</td>
<td>0.96</td>
</tr>
<tr>
<td>Construction industry environment</td>
<td>2</td>
<td>4.00</td>
<td>0.88</td>
</tr>
<tr>
<td>Conditions of standard construction contract</td>
<td>3</td>
<td>3.87</td>
<td>0.92</td>
</tr>
<tr>
<td>Knowledge and experience</td>
<td>4</td>
<td>3.77</td>
<td>0.80</td>
</tr>
<tr>
<td>Government policy</td>
<td>5</td>
<td>3.57</td>
<td>1.18</td>
</tr>
<tr>
<td>Contractor’s own interest</td>
<td>6</td>
<td>3.45</td>
<td>1.15</td>
</tr>
<tr>
<td>Cost</td>
<td>7</td>
<td>3.21</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Also, when the factors which affect the use of the CAR policy was assessed from the contractors’ and design professional perspectives, it was found that the following statements as shown in Table 3 were scored higher: client’s requirement (MIS=4.07; SD=0.96; R=1); construction industry environment (MIS=4.00; SD=0.88; R=2); conditions of standard construction contract in use for the project (MIS=3.87; SD=0.92; R=3) and knowledge and experience of the contractors / professionals (MIS=3.77; SD=0.80; R=4). However, the findings further revealed that the contractor’s own interest and cost were not factors that affect the usage of CAR in the construction industry.

Findings from the study concurs with the work of Perera et al. (2008) which was based on the Sri Lanka construction industry; which revealed that the client’s requirement is the most significant motivation for the
use of the CAR policy as opposed to the contractor's own interest. Also, the contractor's own interest was rated low which may have a bearing to the fact that contractors are not paying attention to the two concepts as theorised Flanagan and Norman (1993) which informed that contractors should not have a mentality of “All Goes According to plan” but must consider “What happens IF” in order to trigger their personal interest in obtaining the CAR insurance. The findings for the study was further supported by Liu et al. (2007) who inform that Chinese contractors do not use insurance because of the high influence of the environment which the Chinese government has caused contractors not to have a realistic attitude towards risk.

5 CONCLUSION

The study investigated the efficiency of CAR in mitigating construction risk and likewise the factors which affect the use of CAR insurance policy in the South Africa construction. This study identified the efficiency of the use of CAR and likewise the factors which affects it usage in the industry. The most critical efficiency of CAR's were identified to be that CAR policy protect the client’s interests effectively; CAR policy protect the contractor’s interest effectively; and that CAR assist the contractor in risk management by recognising potential risks and reducing the probability of such risks. Furthermore, the study found that the insurer’s factors which affect CAR's usage in the industry as: lack of background of construction; lack of risk management knowledge and expertise in managing or administering CAR; lack of understanding of contractor’s/ construction risk and lack of risk assessment (extend to known). The study also identified the contractor’s and design professionals’ factors which affect the use of CAR as: adherence to client’s requirement; construction industry environment; conditions of standard construction contract in use for the project and knowledge and experience of the contractors / professionals. The study concludes that there are a number of usefulness in the use of the CAR insurance in mitigating against construction risk in the South Africa construction industry. These usage have the potentials to greatly reduce risk to all parties to the construction projects in South Africa; and when properly implemented, it will give the industry an advantage to meaningful enhance profitability, productivity, compatibility and delivery of construction jobs which will boost the South Africa national economic growth and strength and performance of the construction industry. Hence, it is therefore recommended in order to increase the efficiency of use of CAR insurance, insurance companies should investigate the site in order to assess the risk and before computing the premium. Also, the contractors need to maintain a good records of accidents throughout the project to enable me see the need to protect their own interest. Also, insurance companies and contractors should maintain a cordial relationship by means of active communication especially with underwriters, loss adjusters, which will assist in knowledge sharing that will be mutually exclusive in the formation of the policy and that contractors should implement maximum safety measures as a priority especially if it can be foreseen as a potential risk of damage.

References


AN IMAGE-BASED FRAMEWORK FOR AUTOMATED DISCREPANCY QUANTIFICATION AND REALIGNMENT OF INDUSTRIAL ASSEMBLIES

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Abstract: Image-based frameworks for automated as-built modeling and infrastructure 3D reconstruction are increasingly being used in the construction industry. The increasing use of image-based technologies in the construction processes is due to the ease of application, cheap cost of enhancement, time effectiveness and high level of accuracy and automation. Automating the tasks involved in the inspection, quality control and quality assurance (QA/QC) processes are the potential avenues for utilizing such frameworks. This paper presents an image-based approach for acquiring the built status of fabricated assemblies and describes a framework for realigning the defective segments by borrowing concepts from robotics and forward kinematics. A laboratory set of experiments is then conducted to measure the accuracy and performance of the proposed framework for realignment of industrial facilities, in general, and pipe spools, in particular. Results demonstrate that it can be utilized in real cases providing the required level of accuracy as well.

1 INTRODUCTION

Inspecting and monitoring of civil infrastructure is a critical challenge that has to be performed in various construction and maintenance phases. Inspection processes guarantee that construction segments and components are reliably fabricated, transported, and erected. They also provide the determination of as-built status and dimensions required for potential considerations needed to be given to defective segments. These tasks are difficult to perform on construction sites. Inspection processes to perform quality control and quality assurance (QA/QC) processes become more critical in staged fabrication that requires sequential fabrication and installation. In the construction industry, in particular, staged fabrication includes but is not limited to prefabricated steel columns, concrete segments and huge pipe spools/modules. Although construction segments are typically correctly fabricated considering recent advances in the fabrication industry, they still require continuous inspection as dimensional errors are introduced during transportation and shipment. As-built status acquisition is therefore necessary to assess the current state of construction elements and determine the potential considerations for repair and realignment.

Manual and conventional approaches to acquire the as-built status are inherently prone to error and therefore often ineffective and inaccurate. Craft workers use tape measuring and paper-based methods to inspect and control the fabrication quality. The as-built status acquired is therefore often unreliable and may cause profound unfavorable effects on construction sites such as schedule delays and rework. For example, in the case a defective segment is erected on site and discrepancies are not detected in a
timely and accurate manner, the segment is going to be either repaired or replaced whereby both cases are associated with rework. Therefore, as-built status of construction elements must be acquired in a timely manner and electronically transferred to various interfaces involved in order to provide managers and decision makers with an effective framework. In the last couple of decades, adequate accuracy and speed for as-built status acquisition and assessment has become possible utilizing various sensing technologies including Ultra Wide Band (UWB) tags, Global Positioning System (GPS), Radio Frequency Identification (RFID), and 3D imaging techniques. Among these sensing technologies, 3D imaging that provides spatial and detailed geometric information of objects is a reliable method for detailed and geometric as-built status acquisition. 3D imaging is the general name for the process used to generate three dimensional images, also called point clouds, that includes LADAR (Laser and Distance Ranging), range imaging, videogrammetry, traditional photogrammetry, and modern photogrammetry which is also known as image-based sensing technology. Among these technologies, laser scanning is the most common technique in the related industry because of the ease of use and the level of accuracy provided. However, there are major limitations involved with laser-based methods that make it less applicable under some conditions. These conditions may include the time required for setting up, data preprocessing, and occlusion occurrences in busy construction environments. Cost of purchasing is an additional barrier for laser scanners that makes them less accessible by all contractors and project managers. Developing a cheaper framework, commonly affordable, with a high rate of accuracy that can address the mentioned deficiencies of laser scanners is therefore necessary.

In recent years, some research efforts have attempted to address these limitations of laser scanners. Image and video based techniques that have been developed during the past several years are the emerging solutions that are significantly less expensive than laser scanning. It has been stated that image-based methods can provide the desirable level of accuracy and automation if well applied. According to (Dai et al. 2013; Golparvar-Fard et al. 2011; Zhu and Brilakis 2009) image-based 3D reconstruction has provided a comparable level of accuracy to laser-based methods without the previously discussed limitations of laser scanners.

One of the key advantages of utilizing the image-based techniques to assess the as-built status of construction elements is that it does not require any further consideration or procedure on construction sites as images are taken on a regular basis by inspectors (Golparvar-Fard et al. 2011). Such random and unordered images can be imported to a cloud server on a daily or weekly basis for further processing in order to generate 3D images for assessing the as-built status. This paper presents an image-based framework in order to accurately detect, characterize, and identify the discrepancies between the as-built status and as-designed data (Figure 1). Most research to date is relatively limited in its approach to the automated detection of visible damage and defects. There is still a significant lack of knowledge in civil infrastructure aimed at effectively and efficiently assessing the construction processes in different phases in order to realign defective assemblies in a timely manner.

![Figure 1: Proposed framework for image-based 3D model generation and realignment strategy](image)

This research is directed toward damage prevention by localizing and quantifying fabrication errors and generating a potential solution for repair and rehabilitation in a systematic way. In order to comprehensively determine the knowledge gap and the need in the construction industry, the related background is extensively investigated. The research methodology to develop the proposed framework is then presented, and required functions and metrics are formed. A set of experiments are then designed in
order to validate the proposed framework and evaluate its accuracy by comparing the results with previously acquired laser-based data.

2 RESEARCH BACKGROUND

The key contribution of the framework presented in this work is an image-based reconstruction technique for the as-built status assessment of industrial facilities compared with laser-based status acquisition. Recent studies attempted for inspecting, monitoring, and assessing the built status of civil infrastructure, in general, are also briefly reviewed. The related background is extensively investigated in order to determine the current state of these methods, and the knowledge gap is therefore comprehensively identified.

2.1 Monitoring and Inspecting Civil Infrastructure for the Built Status Assessment

Using automated tools for monitoring and inspection purposes in construction provides a superior level of accuracy. The automated tools and techniques for reliable and accurate 3D measurement are also being increasingly used because of electronic communication and integration with other interfaces in the construction management system. 3D spatial locating devices such as ultra-wide band (UWB) and radio frequency identification (RFID) tags have been used for automated material location on heavy industrial construction facilities (Razavi and Haas 2010). They have been found to improve productivity and to reduce risk substantially.

Additionally, 3D sensing and imaging technologies such as laser scanning, image/video-based reconstruction methods, and range imaging are used for a wide range of applications in construction. Laser scanning was first introduced as a tool for structural health monitoring (Park et al. 2007). Automating the tasks involved in the processing step to use the point clouds generated by laser scanners improved the applicability of laser-based techniques in real-sized and complex construction sites. Bosche et al. (2009) developed a method for automated recognition of CAD objects in cluttered point clouds that was later employed for automated progress tracking of construction components (Turkan et al. 2012). Laser scanning can be employed for compliance control used for QA/QC purposes. An automated framework was used for compliance control of industrial assemblies using laser-scanned point clouds (Nahangi and Haas 2014). A video-based 3D point cloud generation technique (videogrammetry), was also employed to acquire the as-built status (Brilakis et al. 2011; Koch et al. 2013), to be used for various purposes such as progress tracking and status assessment discussed earlier. Recently, 3D sensing technologies have been actively employed for tracking the progress of the industrial construction or Mechanical Electrical and Piping (MEP) components (Ahmed et al. 2012; Dimitrov and Golparvar-Fard 2015; Lee et al. 2013; Son et al. 2014). The use of image-based techniques and their application in the construction industry are discussed in the following section.

2.2 Image-Based 3D Reconstruction State-Of-The-Art in the Construction Industry

Photogrammetry is well known as a 3D reconstruction technique. It was originally developed for generating the stereo elevation from aerial photos (Mikhail et al. 2001). In recent decades, advances in the camera production industry have provided the required accuracy for close-range applications such as industrial inspection and architectural documentation. The challenge associated with traditional photogrammetry techniques is the manual labour and computationally intensive processing involved. When high accuracy is desired for further investigations, computational cost and time also increased. This drawback of traditional photogrammetry has been a challenging factor over the years that makes it limited and currently not applicable for near-real-time modeling. Later advancements in the processing unit and related industry significantly improved the preprocessing time involved for common feature detection; however, it was still time consuming to achieve the required accuracy (Mikhail et al. 2001).

With the rise of digital images and digital photos, traditional techniques were replaced with modern and digital photogrammetry, which resulted in profound improvements in accuracy considering the required processing time (Brilakis et al. 2012; Jahanshahi et al. 2009; Liu et al. 2014). In the construction industry, the use of modern photogrammetry thus became more significant as it was much less expensive than
laser scanning, the most common technique in AEC industry for as-built status acquisition, mentioned earlier. A study by (El-Omari and Moselhi 2008) showed the enhancement of integrating photogrammetry and laser scanning for progress tracking, which was proven to be more time effective. Researchers enhanced the use of close range photogrammetry for pavement pothole localization and progress tracking in pipe-works construction (Ahmed et al. 2011; Ahmed et al. 2012). Most of this research showed the time effectiveness of the application of photogrammetry in the related industry, however, some major limitations such as the desired accuracy and required intensive preprocessing, such as camera calibration, severely diminished the method’s practical utility compared to its competitor, laser scanning.

New and innovative techniques have emerged, however for the detection of common features of the desired accuracy without requiring camera calibration. Such automated feature detection techniques include scale the invariant feature transform (SIFT) and speeded up robust features (SURF). (Golparvar-Fard et al. 2009) introduced as automated reconstruction techniques that use time-lapsed photographs to generate the as-built status of construction projects in order to measure the progress on construction sites. (Zhu and Brilakis 2009) investigated the accuracy of the optical-based methods compared to laser-based techniques for the reconstruction of the built status of civil infrastructure. They concluded that laser scanning has larger range for data collection with a higher level of accuracy that makes it more reliable though also more costly. They have suggested the efficient optical-based technique for different applications in the construction industry under various circumstances. These methods include videogrammetry and 3D range imaging that can be employed based on the level of accuracy required and the application used.

The construction industry, several research efforts have been attempted to evaluate the accuracy and investigate time and cost effectiveness of the image-based methods compared to laser scanning. Golparvar-Fard et al. (2011) evaluated the accuracy of an image-based 3D point cloud for determining the as-built status of construction elements compared to a laser-based 3D point cloud. They concluded that the accuracy provided by laser scanning is slightly higher than image-based techniques, however, image-based reconstruction is quicker and less costly.

Bhatla et al. (2012) evaluated the accuracy of an image-based reconstruction framework for assessing the built status of bridge girders. According to this study, image-based 3D reconstruction using free, promising commercial software packages provided the desired level of accuracy; however, their study also revealed that for highly accurate modeling purposes, laser scanning is more appropriate. (Dai et al. 2013) comprehensively compared the image-based techniques with time-of-flight in various civil infrastructure. Such a comparison includes the accuracy of reconstruction, density of the point cloud generated, cost of purchasing and utilizing, and the required time for setting up and processing. Their study revealed that both photogrammetry and videogrammetry can provide sufficiently dense and accurate point clouds to be employed for different applications such as visualization. It was stated that photogrammetry is sufficiently accurate to be used for as-built quality control on construction sites. In summary, image-based 3D reconstruction, which is originally known as photogrammetry, has provided the desired accuracy within a reasonable processing time due to the recent advances in the related industry that are previously discussed. Such improvements in image-based reconstruction provide the opportunity to employ related techniques in different inspection phases of civil infrastructure.

Despite the significant impact of automated tools, in general, and image-based techniques, in particular, in the construction industry, their uses are mostly directed toward object recognition for status assessment. A preventive approach to measure the discrepancies in a time effective way that can avoid rework is needed. Nahangi et al. (2015a) showed the effectiveness of laser-based point clouds for discrepancy detection and a realignment strategy. This paper is aimed to generalize the previous developments by employing an image-based framework for the as-built status acquisition and to measure the performances of the resulted realignment strategies. The detailed methodology along with the required functions and metrics are explained in the following section.
3 PROPOSED METHODOLOGY

For generating the 3D model required for performing the as-built status identification and discrepancy quantification, an image-based framework is used. As shown in Figure 2, the image-based algorithm for automated discrepancy detection and quantification has two primary steps: (1) Image-based 3D point cloud generation that provides the as-built status with a reasonable level of accuracy, and (2) processing that enables detection, localization, and quantification of incurred discrepancies based on the original drawings. The primary steps and the required components are extensively explained in the following section.

![Image-based framework](image.png)

**Figure 2: Algorithm for automated discrepancy quantification using an image-based framework**

3.1 Image-Based 3D Point Cloud Generation

Inspectors and QA/QC managers use off-the-shelf digital cameras. Cellphone and tablet cameras can also be used to acquire the required images. Once sufficient numbers of images with sufficient overlap are captured, they are imported to a cloud server/database for point cloud generation. The image processing toolboxes for image stitching and 3D point cloud generation can be employed. These toolboxes include MATLAB Image Processing Toolbox and open source databases such as Open CV (Open source computer vision library at the University of Washington) and PCL (Point Cloud Library). In this study, Autodesk 123D Catch (www.123dapp.com/catch) is employed. The 3D reconstruction of construction assemblies using images is composed of a set of steps:

- Finding common features in the images taken,
- Matching the common features detected,
- Transforming the images into a global coordinate space based on the common features.

Based on the required processing steps mentioned above, more images taken improves the applicability and performance of the algorithm. Furthermore, a sufficient level of overlapping between images must exist in order to find a reliable set of matching features. Once a 3D model of the construction environment is roughly generated, unwanted objects and the existing noise are filtered. Noise removal is performed manually by removing the objects outside the region of interest. This can be automated in the future.
3.2 Processing

Once appropriate 3D model is generated using the proposed image-based framework, a set of processes is required to quantify the incurred discrepancies based on the framework developed by Nahangi et al. (2015b). Such processes include:

- **Registration**: the filtered 3D model can now be used for registration with CAD drawings converted to an appropriate format (i.e. point cloud format such as STL), in order to enhance a comparison. A modified iterative closes point (ICP) is used for registration in this study.
- **Kinematics chain development**: the geometric relationship is established using an analogy of robotics. The kinematics chain development results in a set of transformations required to identify the geometry of assemblies.
- **Local registration**: a sliding cube moves along the assembly and quantifies the discrepancies where it is occurred. A local registration is performed on the contained points in the cube at each location that the discrepancy is being investigated. The resulted discrepancy is then transformed to the local coordinate system defined by the previously developed kinematics chain.

The quantified discrepancy can be fed into a realignment planning framework for potential realignment strategies (Nahangi et al. 2015a).

4 EXPERIMENTAL VERIFICATION

A set of experiments is designed to verify and validate the performance of the explained image-based algorithm for discrepancy quantification.

4.1 Design of Experiments

The experiments are validated on a small-scale set of pipe spools existing in Civil Infrastructure Sensing Laboratory at University of Waterloo. The pipe spool is designed so that the connections and joints allow reconfigurability. In other words, the pipe spool can be reconfigured by introducing any alteration; so that the algorithm for discrepancy quantification can be tested. The reconfigurable pipe spool used for the experimental tests is shown in Figure 3.

![Adjustable connections](image)

Figure 3: The experimental specimen (reconfigurable set of pipe spool) and the investigated branch.

An off-the-shelf digital camera is used for this experimental study. An SX40-HS Canon camera was used at 12.2 megapixel resolution. Technical details of the camera can be found in Table 1.
Table 1: Technical details for Canon SX 40-HS used in the experiments

<table>
<thead>
<tr>
<th>Camera type</th>
<th>Digital camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>(size)</td>
<td></td>
</tr>
<tr>
<td>Shutter speed</td>
<td>1/3200 sec (min) - 15 sec (max)</td>
</tr>
<tr>
<td>Focal length</td>
<td>24-840 mm</td>
</tr>
</tbody>
</table>

* [L]: Large, [M]: Medium, [S]: Small.

In order to compare the accuracy of the proposed image-based framework with laser-based point clouds, a similar set of alterations to the previous experimental study by (Nahangi et al. 2015b) is applied. The alteration is applied in the form of rotational, translational, and combined discrepancies on the investigated branch shown in Figure 3.

4.2 Results

After uploading the taken images they are uploaded to the server for generating the 3D point cloud of the tested assemblies and spool branches. Typical photogrammetry data and results of the generated point cloud for the original state of the investigated branch are shown in Table 2 and Figure 4.

Table 2: Typical photogrammetry data and results for the pipe spool original state

<table>
<thead>
<tr>
<th>Size of images taken</th>
<th>[L]: 4000×3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of images processed</td>
<td>59</td>
</tr>
<tr>
<td>Total number of points retrieved</td>
<td>134,742</td>
</tr>
<tr>
<td>Number of points retrieved from the pipe spool</td>
<td>15,152</td>
</tr>
<tr>
<td>Total processing time</td>
<td>26 min</td>
</tr>
</tbody>
</table>

Figure 4: Photogrammetry results. 123D Catch software output (a); the mesh is converted to point cloud (b); the noise is manually removed and the branch is properly retrieved (c)

Experimental results (Figure 5) show that the quantified discrepancies provided by photogrammetry are less accurate comparing to the similar tests performed on laser-based technologies. Maximum error for the image-based framework developed in this work is 0.369° and 0.184 cm for rotational and translational discrepancies, respectively; while, maximum error for the laser-based technique used in the previous study by Nahangi et al. (2015b) is reported as 0.237° and 0.02 cm. However, the image-based 3D point cloud is still reliable for discrepancy quantification based on the required level of accuracy in some
applications. Moreover, using a finer mesh for 3D reconstruction will provide a more accurate point cloud although it is computationally more intensive.

5 CONCLUSIONS AND RECOMMENDATIONS

An image-based framework was presented for automated discrepancy detection and realignment planning. The scope of this study was industrial assemblies, in general, and pipe spool assemblies, in particular. Typical users who are QA/QC managers or inspectors use cellphones, tablets or digital cameras to take unordered photos and upload to a cloud server for processing. The processing step results in a 3D point cloud representing the built status that will be compared with the original CAD drawings. For the comparison purpose, 3D image registration is employed. Once the two representing states are appropriately registered, an analogy of robotics results in the development of geometries of the assemblies. Such an approach provides localized discrepancy feedback to be used for realignment strategies. Some remarks on the experimental verification follow:

- The enhanced image-based framework is significantly cheaper than laser-based techniques. This makes it more applicable, particularly for the cases where a lower level of accuracy is required.
- The data acquisition step for the proposed image-based framework requires minimal prior knowledge and training.
- Image-based discrepancies are reasonably reliable and accurate; however, laser-based point clouds are more precise, which concurs with the previous evaluation studies (Bhatla et al. 2012; Dai et al. 2013; Golparvar-Fard et al. 2011)

A limitation of the proposed methodology is that it requires more processing time for the images to be retrieved and generate the 3D point cloud.

Acknowledgements

The authors would like to thank Ian Bowes for assisting in the development of the framework during his coop term at the University of Waterloo. This research is funded by National Science and Engineering Research Council (NSERC) of Canada (partially funded by NSERC CRD with Aecon and SNC-Lavalin and NSERC Discovery Grant).
References


A SMART MOBILE APP FOR SITE INSPECTION AND DOCUMENTATION

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Abstract: Extensive time and effort are spent on inspecting and documenting construction defects for facilities under construction or in use. The goal of this study is to provide construction engineers and experts with a smart mobile application to efficiently record and document construction defects. This study first investigated typical inspection processes, data, and reports which were used in site inspections in practice. An Android-based mobile application called InSite Inspector (Intelligent Site Inspector) was then developed to facilitate site inspection and documentation. This smart app is able to: (i) take images and catalog details of construction defects such as defect types, construction trades, building components, and date and time; (ii) automatically locate defects using the global positioning system (GPS); and (iii) produce various types of reports for different inspection purposes such as punch lists and defect reports. The inspectors are allowed to customize the app features such as text entries, type of data to be recorded and/or reported to meet their specific inspection requirements. Additionally, the InSite Inspector allows engineers and experts to manage different construction sites, inspections, and to keep track of past and ongoing inspections. Finally, the app can be used to save, email, or upload the resulting reports to cloud-based repositories. An inspection case study was used to demonstrate the application and utilities of this development. The InSite Inspector is expected to significantly streamline site inspection and documentation processes.

1 INTRODUCTION

In the construction industry, extensive time and effort are spent on inspecting and documenting construction defects for buildings under construction or in use. When a building project is almost completed, project parties conduct site inspections to prepare punch lists and repair defects before the building is handed over to its owner. For an occupied building, the owner, designer, contractor, and other parties may conduct site inspections when substantial defects are identified. Construction defects are therefore a major concern for all stakeholders, including owners, designers, builders, and insurance companies. Literature indicates the ratification cost of defects in between 2% and 12.4% of the construction cost (Lundkvist et al., 2014). With the construction value of $975 billion in 2014 (Census Bureau, 2015), the ratification of defects could cost the U.S. taxpayers in a range of $20 – $120 billion last year. In addition to the cost of repairs, defects are one of the major sources of costly and lengthy construction dispute and litigation in the U.S. In a construction defect dispute or litigation, both claimant and defendant inspect the property and report their findings and results of the inspection. Unfortunately, the current inspection, defect classification, and documentation process is time-consuming and expensive.
This paper presents a smart application called InSite Inspector (Intelligent Site Inspector) that efficiently records and documents construction defects. The InSite Inspector is able to (i) take images and catalog details of construction defects such as defect types, construction trades, building components, and date and time; (ii) automatically locate defects using the global positioning system (GPS); and (iii) produce various types of reports for different inspection purposes such as punch lists and defect reports.

2 BACKGROUND

Site inspections regularly take place during the course of construction to discover non-conformities for timely rectification. A study of 20,000-square meter conference center in Sweden showed that a combined total of 41 pre-inspections over the course of just over a year were conducted for the construction of roof, facades, balconies and glasswork alone prior to the final inspection (Lundkvist et al., 2014). In the inspection process, site engineers and managers typically record information about defects on documents, such as drawings and checklists, while walking around the site (Cox et al., 2002; Kwon et al., 2014). As such, Gordon et al. (2007) stated that the present defect management techniques require a lot of manual labor.

Site inspection may also be required in the operation phase of a facility if defects are recognized or potentially occur. Many defects were latent and only appeared a few years after commissioning (Park et al., 2013). In fact, construction defects are a major cause of dispute and litigation in all types of construction, from residential, institutional, and commercial to industrial and infrastructure. Figure 1 showed the typical current construction defect inspection and documentation. The parties in dispute are required to investigate and classify defects for allocating liabilities of the alleged defects (Figure 1, Step 1). When a construction defect dispute or litigation arises, both parties have to hire construction experts for numerous hours for site inspection, defect classification, and documentation (Figure 1, Step 2). In addition they must spend time to describe and classify defects, and document their findings (Figure 1, Steps 3, 4, and 5). Step 6 can be applicable to site inspection for disputes involving construction defects. Therefore, reducing the time and cost of the defect inspection, classification, and documentation is imperative. Fortunately, the current information and communication technologies (ICTs) can be employed to improve the defect management systems (Park et al., 2013).

Figure 1: Current construction defect inspection and documentation

Previous studies have proposed various ICT tools to improve defect management. The development of these tools helps not only improve the defect management but also reduce its costs (Lundkvist et al., 2014). Cox et al. (2002) investigated the use of Pocket Personal Computers (Pocket PCs) to automate the field data collection process. Dong et al. (2009) presented a synchronous collaboration between a
construction site and an off-site office using telematics digital workbench that incorporated mobile computing, wireless communications, and a horizontal tabletop interface. Kim et al. (2008) and Wang (2008) developed a computerized quality inspection and defect management system that can collect real-time data in construction sites using Personal Digital Assistant (PDA) and wireless Internet. A major drawback of the above approaches is that their technology platforms are obsolete or even no longer exist.

Recent studies attempted to improve defect management using Building Information Modeling (BIM), augmented reality, and ontology-based data collection template (Park et al., 2013; Kwon et al., 2014). These improvements may be useful for construction projects in which BIM are employed for collaboration. Thus, the improvements may not be widely used in a foreseeable future as BIM models are still not adopted in many construction projects in the present time. This is particularly the case for defect inspection and management for facilities under occupancy. This current research has attempted to develop a stand-alone application, InSite Inspector, which can be used specifically for site inspection and documentation for facilities either under construction or in use. Figure 2 demonstrates our proposed construction defect inspection and documentation.

![Diagram of construction defect inspection and documentation]

Figure 2: Proposed construction defect inspection and documentation

Step 2 (Figure 2) is focused at the current stage of our study and is the scope of this paper. Engineers and managers can use InSite Inspector for collecting defect information (images, location, defect type, partied involved, etc.) InSite Inspector allows users to customize and produce different types of inspection reports. Engineers and managers will then spend minimal time to finalize report of their site inspection (Figure 2, Step 3). The ultimate goal of the InSite Inspector is to support site inspection, automatically classify defects, extract defect records, and generate inspection reports. However, the automatic classification of defects using image processing and machine learning (Figure 2, Step 2') is currently under investigation and thus not presented in this paper.

3 METHODOLOGY

This study started with literature review regarding the state of practice in site inspection. Current relevant ICT tools published in previous studies and related applications available in iTunes, Google Play, etc. were also reviewed. Different types of inspection documents (e.g., issue reports, defect lists, punch lists) from the industry were collected for understanding the formats of the inspection reports. Because one of the authors worked in construction in various capacities and was involved in site inspections of constructed facilities under construction and under occupancy, real-world inspection documents were readily collected for this study.
The Android-based platform and JAVA/XML technology were adopted for developing the first and current version of InSite Inspector. As there are various platform versions of Android available (Figure 3), the evaluation and selection of the right platform was conducted in this study because choosing the right version target is critical. Choosing too high versions would result in more phones being incompatible, isolate more potential users, and hence decrease the user base, while choosing too low versions would result in the app missing important built-in features of the newer versions. In other words, choosing the right platform version is the trade-off of increasing the user base and utilizing newer and better features.

![Figure 3: Distribution of the Android platform versions in early January 2015](image)

Figure 3 displays the percentage of devices running different versions of the Android platform in early January 2015 (Android, 2015). The shares of these versions were 0.4% (2.2, API level 8), 7.8% (2.3.x, API level 10), 6.7% (4.0.x, API level 15), 19.2% (4.1.x, API level 16), 20.3% (4.2.x, API level 17), 6.5% (4.3, API level 18), and 39.1% (4.4, API level 19) (Figure 3). The current InSite Inspector employs Android 4.1.x version with application programming interface (API) level 16 that was released in July 2012. It should be noted that Android versions are backwards compatible. That is, Android version 4.1.x with API level 16 is compatible with its own version and newer versions (4.2.x, API level 17; 4.3, API level 18; and 4.4, API level 19). The Android version 4.1.x with API level 16 was selected for InSite Inspector because it is relatively new while it supports 85.1% of current devices (Figure 3).

Creating InSite Inspector involved designing and developing the user interface, with capability of taking and storing photos, as well as text entry in form-type fields. Multiple site inspection tests were conducted to evaluate and improve InSite Inspector. Finally, the current version was used and tested in inspecting the envelope of an academic building on the authors’ campus.

4 DEVELOPMENT OF THE INSITE INSPECTOR

4.1 Overview of the InSite Inspector

A few site inspection applications are available in different platforms. Perhaps the most related app was Defects app. The Defects app required iOS 6.0 or later (Contractors Apps, 2015). While this app can generate reports in PDF format, it seemed not able to generate a more flexible and customizable format, such as csv (comma-separated values) files. The Defects app also seemed not to allow to associate the responsible parties with defects. InSite Inspector includes those features not available in the current apps.
and other features that assist efficient site inspection. Figure 4 displays a simplified Unified Modeling Language (UML) class diagram of InSite Inspector.

![Figure 4: Simplified UML class diagram of InSite Inspector](image)

Within Android activities, there are six classes, including Main Menu, Inspection, Location, Concerned Party, Defect, and Report (Figure 4). These Android activities interact with the built-in global positioning system (GPS) package to locate site location and defects. They interact with the Image Handling package when a defect image is taken by the camera. The Image Handling is used for subsampling. That is, InSite Inspector will automatically estimate the memory usage of loading a defect and resize the image file and/or change resolution if necessary. Finally, the Android Activities interact with Data, Database and File Management packages for restoring and reporting inspection data and information. A SQLite database was developed to store the inspection data. It stores these data as "db" files hidden on the system. The File Management package is used to write the inspection data (e.g., defect images, locations) to or read them from internal/external device storage. The next two sections describe the two major modules, namely Site Inspection and Documentation and Reporting in detail through a case study. The case study was an inspection of the envelope of an academic building on the authors’ campus in January, 2015.

### 4.2 Site Inspection Module

The site inspection module includes processes used by the site engineer or manager in InSite Inspector in order to collect and store inspection data. Figure 5 demonstrates four screenshots of the major processes for site inspection with InSite Inspector. An inspector may create a new inspection, continue previous inspection, or generate reports from previous inspections. These are features in the Main Menu class (not shown in Figure 5). If an inspector starts a new inspection, he/she may first assign his/her inspection name, location, inspector profile.

![Figure 5: Site inspection module](image)
The inspection can proceed by adding a new defect (Figure 5a). The defect recording process allows an inspector to take multiple images of a defect and to choose up to two images representing the defect (Figure 5b). An inspector may provide entries such as type and location of defect (Figure 5b) and additional defect information (not shown). These entries can be recorded either by text or voice to text with the Google Voice typing feature. InSite Inspector will automatically capture the inspection time and date of the defect and locate the defect location using GPS. It utilizes the built-in GPS for Android in two different ways for two scenarios. If the device and hence InSite Inspector search and find at least four GPS satellites of the available 24, a defect can be located by all three: latitude, longitude, and altitude. The “Window sill crack” defect in Figure 5b was located by these three coordinates. If not, InSite Inspector can determine a defect location through a network provider based on availability of cell towers or WiFi access points. In this case, only latitude and longitude of the defect will be determined. As the current defect management systems tended to error (Park et al., 2013, Lundkvist et al., 2014), the proposed automatic positioning of defects will eliminate this drawback.

InSite Inspector allows site engineers and managers to associate a defect with concerned and/or responsible parties. Defects occurred due to many reasons such as design, specification, materials, workmanship, and managerial errors and malpractice. The reasons are all related to human errors and more specially, parties involved throughout the project life cycle, including owners, designers, general contractors, subcontractors, suppliers, and users. During or after an inspection, site inspectors can add parties involved (Figure 5c) and relate them with any defect already investigated (Figure 5d). For example, D&W Sub C installed windows for the building investigated and thus might be associated with the “window sill crack” defect (Figure 5d). The association of defects and concerned parties facilitates engineers and managers in customizing inspection reports as discussed in the next section.

4.3 Documentation and Reporting Module

Figure 6 presents the selected snapshots of the inspection documentation and reporting module. An inspector can customize inspection reports in different ways. All or a subset of defects can be easily chosen before generating reports (Figure 6a). For example, an inspector may only select defects related to stucco work (Figure 6a) for a report and send it to Stucco Sub B (Figure 5c). For a certain defect, an inspector may also choose information to include or not in an inspection report, such as defect type, location, associated parties (Figure 6b).

![Figure 6: Documentation and reporting module](image)

After customizing information for the report, a few export options are available for the report (Figures 6c and 6d). The output types include the portable document format (pdf) files or csv files where inspectors
can further edit and format the report (Figure 6c). Finally, inspectors have different options to export their report. They can save it in their current device, email to related parties, or upload to clouded-based repositories such as Dropbox (Figure 6d).

Figure 7 presents portions of two reports, one created with a specialized software on a PC by a professional inspector for an actual project in California (Figure 7a) and one created by InSite Inspector in the inspection case study in Florida (Figure 7b). A professional inspection report such as one shown in Figure 7a may take hours or days to be prepared. InSite Inspector efficiently creates professional-like reports (Figure 7b) with more details, especially those automatically captured on site in a few seconds or a few minutes depending on the magnitude of the inspection and the capacity of the mobile device. Substantial time savings and more accurate defect information can be achieved with InSite Inspector.

![Figure 7: Real-world vs. InSite Inspector generated reports](image)

5 LIMITATIONS AND FUTURE WORK

There are a few limitations of the present version of InSite Inspector. First, it is currently available only on Android although the share of Android was 84% as of the third quarter of 2014 (Barrie, 2014). Second, to position accurately the location and including all latitude, longitude, and altitude of a defect, an inspection device has to detect at least four GPS satellites. From our case study, this could only work for locating defects outside of the building (e.g., exterior walls, roofs, windows). For defects inside the building, the approximation of the defect location was retrieved from the cellphone or WiFi network provider and only included latitude and longitude.

Future work will include employing techniques to overcome the above limitations and, especially in the longer term, utilize image processing and machine learning techniques for automatic defect classification (Step 2, Figure 2). The ultimate goal of this ongoing research is to develop InSite Inspector that allows engineers and managers to take pictures of defects and automatically classify the types of defects. Image processing and machine learning algorithms and techniques (e.g., Fast Fourier Transforms (FFT), Butterworth filters, Artificial Neural Networks (ANN)) may make the automatic classification of construction defects possible. Future research will also utilize the defect classifications available for different types of construction such as industrial construction (Fayek et al., 2003), timber construction (Johnson and Meiling, 2009) and bridge construction (Cheng and Leu, 2011).

6 CONCLUSIONS

An Android-based smart mobile app named InSite Inspector was developed for site inspection and documentation. It is designed to be effectively used for site inspection in both construction and operation phases. A case study involving the inspection of the envelope of a building was conducted with InSite Inspector. This inspection demonstrated that InSite Inspector facilitates engineers and managers to record defect information, parties involved, and automatically locates defects using GPS. Inspectors can
customize report information and formats and generate reports and documents for different purposes. The documentation and reporting process with InSite Inspector can significantly save site engineers’ and managers’ time and eliminate errors that potentially occur in current site inspection practices. Future work will include improving the accurate positioning of the defects and utilizing image processing and machine learning techniques to automatically classify defects captured on site.

References


EXPLORING KNOWLEDGE AREAS OFFERED IN PROJECT MANAGEMENT PROGRAMS IN CONSTRUCTION

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Abstract: Construction project management requires various knowledge, skills, techniques, and applications. Therefore, project management (PM) degree programs have to equip future project engineers and managers accordingly. However, literature has provided limited understanding about how extensive these knowledge areas (KAs) have been offered in these degree programs. The goal of this paper is to explore to what extent different KAs are taught in PM Master’s degree programs with emphasis in the construction industry. A survey was conducted with respondents who were academic staff responsible for these programs. Most of these programs under the current study were at institutions located in the U.K. and the U.S.A. Six KAs that had high percentage (50% or more) of construction programs offering more than ten teaching hours were time management and risk management (65%), procurement management, sustainability, and legal and ethical aspects (55%), and cost management (50%). In terms of relative teaching priority within a program, time management, risk management, sustainability, and cost management were frequently the top focus in these programs. Project scope, quality, and stakeholder management had the least teaching priorities among the PM KAs. While relative teaching priorities of many KAs were anticipated, the lowest teaching hours and priorities of project scope and quality management, and occupational safety and health were not expected as they were identified as major competencies for construction graduates.

1 INTRODUCTION

Project management in construction requires a variety of knowledge, skills, techniques, and applications. Project management (PM) degree programs have therefore to account for those when preparing the next generation of project engineers and managers. Because construction project management has taken place in an ever-changing environment, the required knowledge has also evolved over time. Accordingly, PM educators have to constantly update curricula and knowledge areas (KAs) offered in their PM degree programs to respond to such change. The dynamic nature of the construction industry requires constant curriculum updates to meet the workforce demands (Ahmed et al., 2014; Azhar et al., 2014). Russell et al. (2007) urged that educators and those involved must integrate key concepts to improve students’ critical thinking, understanding globalization, social awareness, and the use of information technology for future construction professionals to meet the needs of society.

The need for investigating how various KAs have been delivered in PM degree programs in construction is essential. However, literature has provided limited understanding how extensive these KAs were offered in these degree programs. The goal of this study is to explore to what extent different KAs were
taught in PM Master’s degree programs with emphasis in construction. Consequently, this paper aims at (i) identifying the distribution of teaching hours for KAs in PM Master’s programs in construction and (ii) comparing the relative teaching priority of these KAs within a program. It should be noted that different degree names of these Master’s programs have been used by different institutions around the world. Examples include Master of Construction Management (CM), Master of Science in Construction PM, Master of Science in CM, and Master of Science in Civil Engineering with a major in PM. This study called these programs as PM Master’s degree programs with emphasis in construction or Construction PM Program.

2 BACKGROUND

As more than one-fifth of the global economic activities have taken place as projects (Bredillet et al., 2013), PM skills are generally needed in all industries, including construction. To respond to this demand, educators have launched new PM programs (Berggren and Soderlund, 2008) and increased enrollments. The number of accredited PM degree programs have also increased worldwide. For instance, as of 2014, more than 90 PM and related degree programs have been accredited by the Project Management Institute (PMI)’s Global Accreditation Center for Project Management Education Programs (GAC) (GAC, 2014).

The evolution of PM education is a point of concern as the PM body of knowledge (PMBoK) has been evolving from research and practice (Bredillet et al., 2013). In construction PM education Becker et al. (2011) urged that programs had a responsibility of anticipating the skills and competencies for effective future professionals and refining curriculums to best prepare students for the future work. Ahmed et al. (2014) identified desirable skills from today’s CM graduates. The top five skills were knowledge of health and safety regulations, interpreting contract documents, listening ability / giving attention to details, knowledge of building codes and regulations, and time management. Therefore, construction PM programs have to deliver KAs that provide the necessary skills to their graduates.

Previous studies investigated what construction graduate programs offered to their students. Arditi (1984) found that in 1982, the most three popular subjects in 24 graduate programs in construction in the U.S.A. were (1) laws, contracts, and specifications, (2) planning and scheduling, and (3) operations research methods. Later, Arditi and Polat (2010) observed that the trends in course offerings in 1982, 1996, and 2008 seemed to have minimal change except for the number of courses in PM going up significantly while the number of courses in cost estimating going down. A study in 23 PM Master’s degree programs with a construction emphasis worldwide showed that the average percentages of courses related PM, business management, leadership and human resources (HRS), and stakeholders’ relationships and a developed environmental framework were 45%, 32%, 13%, and 11%, respectively (Yepes et al., 2012). In addition, the top three common subjects in these 23 programs were PM (14.4%), followed by contract management (10.8%), and project scheduling (10.5%) (Pellicer et al., 2013).

Table 1: PM and related knowledge areas investigated

<table>
<thead>
<tr>
<th>PM knowledge areas</th>
<th>Related knowledge areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project integration management</td>
<td>Program / portfolio management</td>
</tr>
<tr>
<td>Project scope management</td>
<td>Legal and ethical aspects</td>
</tr>
<tr>
<td>Project cost management</td>
<td>Leadership</td>
</tr>
<tr>
<td>Project time management</td>
<td>Entrepreneurship</td>
</tr>
<tr>
<td>Project quality management</td>
<td>Intellectual property</td>
</tr>
<tr>
<td>Project human resource management</td>
<td>Occupational safety and health</td>
</tr>
<tr>
<td>Project communications management</td>
<td>Sustainability</td>
</tr>
<tr>
<td>Project procurement management</td>
<td>Computational tools / techniques</td>
</tr>
<tr>
<td>Project risk management</td>
<td>Decision sciences</td>
</tr>
<tr>
<td>Project stakeholder management</td>
<td>Others (specified by the respondent)</td>
</tr>
</tbody>
</table>

Although these studies identified courses and/or subjects taught in PM degree programs there is still a need to investigate to what extent different KAs have been delivered in these programs. The reason is
that there are potential overlaps if course or subject level is investigated. Arditi and Polat (2010) reported PM and cost estimating as two courses. However, cost estimating is an aspect within project cost management of the PMBoK. Similarly, PM and project scheduling were considered two separate subjects in Pellicer et al. (2013) while project scheduling is a subset of PM. This current study explored the PM degree programs at the KA level. Nineteen specific KAs and one "others" were investigated in this study (Table 1). The 19 KAs consisted of 10 from the PMBoK (PMI, 2013) and nine related KAs.

3 METHODOLOGY

This study used a questionnaire survey as a primary tool of data collection. Potential population were academic institutions worldwide that offered PM degree programs. The population was first stratified into regions, e.g., Africa and Middle East, America, Asia, Europe, and Oceania. Internet search engines and available publications (e.g., World University Rankings, PMI GAC) helped identify institutions and their websites. The authors accessed the websites and identified if a PM degree program(s) was offered in these institutions. If there was a PM degree program, one academic staff (typically program leader unless not specified in the websites) and his/her contact were identified and added to the list of potential respondents. Finally, the authors compiled 256 respondents in 256 PM degree programs from 233 institutions. These 256 programs consisted of Africa and Middle East (8), America (91), Asia (20), Europe (109), and Oceania (28). A questionnaire were developed and pilot-tested with a group of five respondents. Their comments and feedback helped refine KAs, redesign the questions and improve the questionnaire. The final version was significantly shorter than the questionnaire used for pilot testing. An online survey was then created based on the final questionnaire (in an electronic form). The online survey was emailed to these 256 potential respondents. The data collection took place in October 2014.

The survey had a question: "In which industry (or sector) has the PM degree program you have selected mostly focused? (select all that apply)." The possible responses consisted of: (1) none in particular; (2) business; (3) production; (4) engineering; (5) IS/IT, software, and communications; (6) construction; (7) government; and (8) other, please specify. For the theme of this conference, this paper presents our analysis from programs which focused on construction. That is, this paper focuses on responses that selected either "construction" (6) or both "engineering" (4) and "construction" (6) for the above question. Due to the nature of the data and a limited number of responses, this study mainly used descriptive statistics for data analysis.

4 ANALYSIS AND FINDINGS

4.1 Characteristics of Respondents and Surveyed Programs

The online questionnaire was emailed to 256 potential respondents working at institutions offering degree programs in PM or with emphasis in PM all over the world. These respondents were holding academic and/or administration positions in PM degree programs. The survey was opened on October 1 and closed on October 17, 2014. Sixty respondents from 60 institutions attempted to complete the survey. Fifty four (out of 60) fully responded to all questions in the survey and were valid for analysis. The valid response rate was 21%. Among these 54 programs, twenty were Master’s programs that focused on construction. This paper presents our analysis and findings of these twenty Master’s degree programs. Table 2 summarizes the characteristics of these twenty programs. Seven and six programs were from the U.S.A. and U.K., respectively. The other seven programs were from seven different countries or territories (Australia, China, Hong Kong, Spain, Switzerland, Trinidad, and Vietnam). Eleven programs (55%) were accredited by at least one third-party entity. Four programs (20%) were accredited by two or more agencies (e.g., RICS, CIOB, PMI GAC). Nine programs (45%) were not accredited or accredited internally (Table 2).

Seventy five percent (15 out of 20) of the respondents had at least ten years of experience in PM education. Thirty five percent (7 out of 20) of the respondents had more than 20 years of experience. Only one respondent (5%) had less than five years of experience in PM education. The respondents
holding program director, chair, leader, or coordinator were 55% (11 out of 20). The other 45% were holding a professorship or lectureship position.

Table 2: Characteristics of the PM Master’s program with construction emphasis

<table>
<thead>
<tr>
<th>Description</th>
<th>Frequency (Percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program Delivery Method:</td>
<td></td>
</tr>
<tr>
<td>On campus only</td>
<td>14 (70%)</td>
</tr>
<tr>
<td>Both on campus and online</td>
<td>6 (30%)</td>
</tr>
<tr>
<td>Accreditation*:</td>
<td></td>
</tr>
<tr>
<td>American Council of Construction Education (ACCE)</td>
<td>2</td>
</tr>
<tr>
<td>Association for Project Management (APM)</td>
<td>1</td>
</tr>
<tr>
<td>Chartered Institute of Building (CIOB)</td>
<td>3</td>
</tr>
<tr>
<td>PMI Global Accreditation Center (GAC)</td>
<td>3</td>
</tr>
<tr>
<td>Royal Institution of Chartered Surveyors (RICS)</td>
<td>5</td>
</tr>
<tr>
<td>Internal or none</td>
<td>9</td>
</tr>
<tr>
<td>Number of Students Enrolled:</td>
<td></td>
</tr>
<tr>
<td>Less than 50</td>
<td>11 (55%)</td>
</tr>
<tr>
<td>Between 50 - 100</td>
<td>5 (25%)</td>
</tr>
<tr>
<td>More than 100</td>
<td>4 (20%)</td>
</tr>
</tbody>
</table>

*A degree program could be accredited by more than one third-party entity.

4.2 Teaching Hours for PM and Other Knowledge Areas

A PM degree program in construction provided not only PM KAs but other KAs. Among the ten PM KAs, cost, time, and risk management tended to be taught the most. All of the surveyed programs taught these three KAs (Figure 1). Figure 1 shows that 65% of programs offered more than 10 teaching hours (11-20 hours to over 50 hours) for time management and risk management. Fifty percent of the programs delivered more than 10 hours for cost management. Time, cost, and risk management were taught more than 30 hours (31-40 hours to over 50 hours) in 45%, 30%, and 30% of programs, respectively.

![Figure 1: PM knowledge areas with high teaching hours](image)

After risk, time, and cost management, four PM KAs, namely, integration, HR, communications, and procurement management, were taught in a considerable number of hours (Figure 2). Procurement management tended to be delivered between 6 hours and 30 hours (70% of programs). While 55% of
programs offered at least 11 hours for procurement management, only 10% offered 31 contact hours or more for this knowledge area. Communications management was prone to be offered in a range of one to 20 hours (70% of programs). Sixty percent taught HR and integration management in ten hours or less.

![Figure 2: PM knowledge areas with medium teaching hours](image)

PM degree programs in construction tended to offer least hours for scope, quality, and stakeholder management as the teaching-hour distributions skewed to the right (Figure 3). Project quality management and stakeholder management were taught less than 10 hours in 75% of the construction PM Master’s degree programs. Only 25% of programs taught quality and stakeholder management more than 10 hours. Scope management was taught less than 10 hours in 60% of these programs. No program taught scope and stakeholder management more than 40 hours.

![Figure 3: PM knowledge areas with low teaching hours](image)

In addition to PM KAs, these programs also delivered other KAs. Figure 4 presents other KAs that had significant teaching hours. Sustainability and legal/ethical aspects each had more than 10 teaching hours...
in 55% of programs. Computation tools/techniques had more than 10 teaching hours in 40% of programs. Sustainability were taught more than 30 hours in 30% of programs. The teaching hours of sustainability and legal/ethical aspects were comparable with such PM KAs with high teaching hours as project time, cost, and risk management.

![Figure 4: Other knowledge areas with significant teaching hours](image)

### 4.3 Teaching Priority within a Construction PM Program

Teaching hours for each KA within a degree program depend on the length of this program. Therefore, the extent of the KAs taught should be analyzed not only between programs but also within programs. In other words, for a knowledge area, five teaching hours in this program and 10 teaching hours in another program should not only be compared each other but also be compared with the numbers of teaching hours for other KAs taught in that program. This study assigned a relative teaching priority for each knowledge area to compare its level of effort (in terms of teaching hours) to those of the other KAs within a degree program. Table 3 exemplifies the proposed teaching priority for analysis within a program. The highest priority (i.e., 1) was assigned to KAs that had the most teaching hours within that program. Because program A had 41-50 teaching hours for KA2 and KA6, both KA2 and KA6 had number one priority. Similarly, KA1 in program B also had number one relative priority. KA4 in program A had the next highest teaching hours and hence had priority 3 (after KA2 and KA6). If a program did not teach a certain KA, this KA had zero priority (e.g., KA3 in program A).

<table>
<thead>
<tr>
<th>KA1</th>
<th>KA2</th>
<th>KA3</th>
<th>KA4</th>
<th>KA5</th>
<th>KA6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Program A</td>
<td>11-20 hrs</td>
<td>41-50 hrs</td>
<td>0 hr</td>
<td>21-30 hrs</td>
<td>1-5 hrs</td>
</tr>
<tr>
<td>Assigned priority</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Program B</td>
<td>Over 50 hrs</td>
<td>1-5 hrs</td>
<td>31-40 hrs</td>
<td>21-30 hrs</td>
<td>6-10 hrs</td>
</tr>
<tr>
<td>Assigned priority</td>
<td>1</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Within a program and among PM KAs, project time, risk, and cost management tended to be allocated more teaching hours while project quality, scope, and stakeholder management tended to be allocated less teaching hours (Figure 5). Fifty percent of programs had time management as the first teaching priority. Time and risk management was on the top five priority among nineteen KAs in 70% of programs while cost management and procurement management was on the top five priority in 55% and 50% of
programs, respectively. Project HR, integration, and communications management tended to have similar priority. They were in the top five priority between 35% (communications) and 40% (HR and integration) of programs. Surprisingly, quality management was never the first priority in these programs. Project scope, quality, and stakeholder management was in the top five priority in terms of teaching hours in only 25% of programs.

![Figure 5: PM knowledge areas with teaching priority within a construction PM program](image)

For other nine KAs, sustainability and legal/ethical aspects were on the top five priority among PM and non-PM KAs in 50% of programs (Figure 6). Similar to project risk management, sustainability had the first teaching priority in 30% of programs, only after project time management. Although computational tools/techniques was usually not the first priority (only 10% of programs), it was in the first five priorities in 45% of programs. Leadership and decision sciences was on the top five priorities in 35% and 30%, respectively, of programs. It was not surprising that entrepreneurship and intellectual property did not have high teaching priority in construction PM Master’s programs. Program/portfolio management was still not focused in these programs. Occupational safety and health had also low priority when it was on the top five priority in 15% of programs.

### 4.4 Discussion

The analyses showed that project time, risk, and cost management, sustainability, and legal and ethical aspects were the five KAs usually having highest teaching hours in PM Master’s degree program with construction emphasis. They also tended to have the highest teaching priority within a program. Time, cost, and risk management were undoubtedly the essential PM KAs. Legal / ethical aspects having high teaching hours and priority within a program was not a surprise. Many previous studies emphasized the need of legal aspects in construction programs (Householder, 1987; Shahbodaghliou and Rebholz, 1990; Mead and Gehrig, 1995). In fact, contract administration/legal issues was consistently ranked first in terms of percent of programs offered this course category over the past 30 years in the U.S.A. (Arditi, 1984; Arditi and Polat, 2010). In the U.K construction law was also considered as an important subject in construction programs. (Mihara et al., 2014).
The PM degree programs in construction increasingly focused on offering sustainability to their potential students. The sustainability knowledge area seemed not to appear in the 1982, 1996, and 2008 surveys of graduate programs in construction management (Arditi and Polat, 2010). A decade ago, only a few number of programs (members of the Associated School of Construction) offered sustainability-related courses (Tinker and Burt, 2004). However, the integration of the sustainability body of knowledge in construction curricula has been observed in recent years (Wang, 2009; Sullivan and Walters, 2013). Iyer-Raniga et al. (2010) stated that future construction graduates would be in a working environment where sustainability would be incorporated at the core level of their practice. Therefore, programs in CM progressively concentrated on environmental responsibility because of increased regulations and increasing opportunities for practicing sustainability knowledge upon graduation (Celik et al., 2014).

The fact that project scope and quality management, and occupational safety and health had the lowest teaching hours and lowest teaching priorities was a surprise. Scope management and quality management have been considered as critical KAs in construction project management. In fact, they are considered as primary project and project management objectives. Considering scope as important as budget and schedule, Oberlender (2000) observed that “the source of many problems associated with a project is failure to properly define the project scope.” Mincks (2008) argued that quality management was an essential knowledge for individuals involved in CM and had to be addressed in construction education. Finally, knowledge of health and safety regulations was the top skill desired by the industry from graduating CM students (Ahmed et al., 2014).

### 4.5 Limitations

This study has a few limitations. The findings were drawn from a small number of programs and responses. The small number of responses also limited the use of statistical analysis, i.e., inferential statistics. Although the authors endeavored to identify as many PM degree programs as possible, the research samples (256 PM degree programs) were programs that had information on the Internet (e.g., program websites), especially information provided in English.
5 CONCLUSIONS

This paper investigated KAs taught in 20 Master’s PM degree programs around the world (U.S.A. [7], U.K. [6], Australia [1], China [1], Hong Kong [1], Spain [1], Switzerland [1], Trinidad [1], and Vietnam [1]) with emphasis in construction. Nineteen specific KAs, including 10 PM and nine related KAs, were explored in these programs. Six KAs that had high percentage (50% or more) of the programs offering more than ten teaching hours were time management, risk management, procurement management, sustainability, legal and ethical aspects, and cost management. The four PM KAs including project integration, human resource, communications, and procurement management followed these six KAs in teaching hours. In terms of relative teaching priority within a program, time management, risk management, sustainability, and cost management were frequently the top focus in these programs. Project scope, quality, and stakeholder management had the least teaching priorities among the PM KAs. While relative teaching priorities of many KAs were anticipated, the lowest teaching hours and priorities of project scope and quality management, and occupational safety and health were a surprise because they were identified as major competencies for construction graduates. Construction educators may use these findings when reviewing, refining, and updating their PM degree programs.

Acknowledgements

The authors sincerely thank the construction and project management educators who participated in this study.

References


TOPIC MODELING FOR INFRASTRUCTURE-RELATED DISCUSSIONS IN ONLINE SOCIAL MEDIA

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Abstract: Decision making for construction of modern civil infrastructure not only involves internal stakeholders, but also aims to include interests of as many external stakeholders as possible. In mega-projects, complexity and diversity of stakeholders call for more advanced communication tools and channels. Extensive prevalence of social web as a two-way communication channel during the last decade has caused a paradigm shift in communication among the e-society, and this has attracted the attention of decision makers in the domain of urban infrastructure among other domains. Although having a wide public outreach, the open and unstructured nature of inputs from the e-society results in chaos and makes it difficult to distil knowledge from the contents communicated by the public. This paper presents tools from topic modeling to process such an unstructured data collected from online social media into information which can be plugged into the process of decision making. We use k-means clustering to cluster followers of an infrastructure project on micro-blogging website Twitter based on semantic similarity among their user profile descriptions. This helps profiling the main groups of followers of the infrastructure project and can provide decision makers with valuable hints regarding typology of external stakeholders. We also extend our analysis to project-related tweets through Latent Semantic Indexing, and find the main topics discussed. The latter guide help decision makers understand the public’s major vested interests in the project. We have applied the proposed method to a Light Rail Transit (LRT) mega-project in Toronto, Ontario and have discussed the results.

1 INTRODUCTION – INFRASTRUCTURE DISCUSSION NETWORKS (IDN)

Decision making for construction and development of civil infrastructure in the modern society is involved in a networked procedure. This is not only related to the network of interdependent sub-decisions, random variables involved, and the governing criteria; but also requires interactions among a multitude of decision makers (internal stakeholders), each having their own beliefs, goals, and interests in the project. On the other hand, the external stakeholders (those affected by the decisions) and their vested interests must be considered in decision making, and it adds even more to the complexity of the decision network. The final decision in such a networked scenario will be in form of a 'package-deal' (Bruijn and Heuvelhof 2000); a sub-optimal solution which accommodates major interests of different internal and external stakeholders of the project.

One major goal of community engagement practices in the domain of urban infrastructure is to detect the main groups of external stakeholders along with their interests and to involve them in the network of decision making. Public engagement in infrastructure projects has traditionally been carried out through off-line tools such as community meetings, public hearings, questionnaires, etc. or online tools such as
Web 1.0 portals and project websites which are considered as one-way communication channels to educate the society about the project and its related decisions. On the other hand, as a social-network-related issue, this procedure is influenced, if not re-shaped, by the wind of Web 2.0 (social web). Many public engagement agencies have recently started trying tools such as weblogs and micro-blogging websites (such as Blogger and Twitter), multimedia sharing websites (including YouTube and Instagram), and other tools for a bi-directional communication with the public about infrastructure projects (Bregman and Watkins 2013), (Azhar and Ablen 2014). Social web is not only a portal used to comment on design and planning; rather it is a platform for bringing community members along with their ideas together. Web 2.0–based engagement will hence create a ‘network of people’ together with a ‘network of ideas’. Such networks formed around infrastructure projects are called Infrastructure Discussion Networks – IDNs (Nik Bakht and El-diraby, 2013a & b & 2014).

The formation and evolution of these two interdependent networks (network of people and network of ideas), around the physical network of the infrastructure should be closely and precisely monitored and different trends in them must be followed in order to make the best out of users’ ideas and innovations in design and construction of a sustainable infrastructure. This requires employing tools and methods from network science, information retrieval, and computational linguistics to link people to their ideas and understand their patterns of connectivity over IDNs. One important outcome of monitoring such patterns is to detect cores of interest in a project, in conjunction with the people who support them. Some potential applications of making such a connection between users and ideas over the IDN can be listed as:

- Classifying typology of stakeholders, particularly the end users of the infrastructure system;
- Profiling core interests to be involved in package deal solutions offered for infrastructure project;
- Detecting relations and interactions among different community groups;
- Finding possible communication bottlenecks in the process of public consultation;
- Demand detection in a more direct, and pro-active manner;
- Activating ‘user innovation’ by understanding and ranking community generated inputs.

Achieving such goals requires detection and analysis of interests for nodes and communities of the IDN. Steinhaeuser & Chawla (2008) suggested assigning interest as node attribute to the social network and then clustering the network based on the similarity of attribute. In a similar study, Kalafatis (2009) harvested Twitter users based on their similar interests through occurrence of some pre-defined keywords in their Twitter biography. To include the degree of importance for nodes, Nik Bakht & El-Diraby (2013a) proposed community detection through analysis of the network topology, and then extracting shared interests within each community through computational linguistics. While segmenting users through the similarity among their attributes is a ‘top-down’ approach, finding communities and then interpreting similarities among them can be considered as a ‘bottom-up’ method. Applications such as topic detection in collaborative tagging systems, reviewed by Papadopoulos et al. (2012), and social trust evaluation for recommender systems, addressed by Pitsilis et al. (2011) are among other examples which combine the two approaches to create tools for profiling and labeling groups of followers.

Although the bottom-up approach is helpful for understanding the social construct of e-society around the infrastructure project; it does not necessarily result in cores of interest in the project. In order to detect the major lines of interest to be included in the package-deal solution, the main clusters of ideas discussed by project followers must be detected and highlighted. This paper presents a top-down approach to reach this goal. We start by clustering users and ideas based on their semantic similarity (rather than social connectivity). We use data collected from Micro-blogging website Twitter as the most popular social media used in the domain (Bregman, 2012), (Azhar & Ablen, 2014). By focusing an LRT mega-project in Toronto, Ontario, Canada we use semantic analysis combined with clustering algorithms to detect the main lines of interest in following this project on Twitter. We apply our method to the IDN of the project and cluster its nodes based on the semantic similarity among their profiles. Then we focus on tweets about the project over a certain period of time and use our proposed method to detect the core themes discussed. We will finally show how the results can be a representative of the public community’s vested interests in practice.
2 METHODOLOGY– CLUSTERING BASED ON SEMANTIC SIMILARITY OF USER PROFILES

Users in online social network websites normally address their interests through their online activities including contents they share, and comments they leave. However, in many cases they also state their interests directly in user profile descriptions (also known as biography or ‘bio’ for short). Twitter users can indicate their location, professional affiliations, and interests in a short bio in fewer than 160 characters. Such descriptions are accessible through Twitter API (Application Programming Interface). Also, one can use Twitter API to retrieve most recent tweets of a user\(^1\). Such tweets can also indirectly reflect users’ interests. The aim of this paper is to partition the IDN into groups of nodes with similar interests.

We collect descriptions/tweets of all nodes of an IDN as a set of ‘pseudo-documents’, and form an analysis corpus. Data clustering techniques combined with semantic approaches are then employed to cluster the corpus based upon the similarity between those pseudo-documents. The method can therefore be simplified as: clustering nodes of an IDN based on semantic similarity among their descriptions collected from their user profiles. This requires cleaning and pre-processing the collected data; modeling it and evaluating the semantic similarity among each pair of data points, and finally clustering nodes to the most similar groups.

2.1 Pre-processing and modeling users as vectors

In order to analyze documents they must be first modeled as data-points (vectors) with specific attributes (dimensions) and attribute values (entries). In text mining and natural language processing (NLP), dimensions of analysis vector space (called features in NLP and attributes in data mining) are associated with terms of the corpus. Texts collected via Twitter API, are normally not in a uniform encoding format and also include some ‘noise’. Therefore, the first step in modeling documents is to tokenize, unify, and clean up the collected data. These tasks are called pre-processing and include the following steps:

Cleaning:
- Removing html tags and attributes which are not visible in a browser;
- Replacing all html character codes (such as &amp, &quot, etc.) with their ASCII equivalents;
- Removing all URLs (as most of them are associated with advertisements and commercials);
- Removing Twitter specific characters such as hash-tags (#) and mentioning handles (@);
- Replacing monetary values and percentages with a trackable variable (for this purpose we transformed all numbers followed or preceded by dollar sign to XXX and all numbers followed or preceded by percentage sign to XX);
- Removing all other numbers (as they are less probable to contribute to semantics).

Tokenizing:
- Splitting texts at white spaces;
- Decomposing clitics and punctuations from their hosts;
- Saving ellipsis and other forms of multiple punctuations as separate tokens.

All these activities were performed using RegEx (regular expression). Stemming may also be a part of pre-processing; i.e. all words with the same root could be transformed into their roots. However, this was not done in the present paper due to aggressive nature of most stemmers available and confusions caused by stemming. Apart from the noise, common words with no specific semantics (such as conjunctions, articles, the gibberish, punctuations, etc.) should be filtered out from the corpus. This is normally done by introducing a ‘stop list’ (a complete list of such words). We started by a compilation of some standard stop lists and added new terms to it as the analyses progressed. As the text processing is involved in occurrence and co-occurrence of terms in multiple documents, terms which appear in one document only, were also removed to reduce dimensions of the analysis space.

A dictionary was formed by collecting all tokens of the cleaned corpus. Each term in this dictionary would be one dimension of the analysis space. Project followers were then modeled as vectors in such a vector

\(^1\) Currently, up to 3200 most recent tweets by a user are accessible
space. Assuming the dictionary contains $M$ terms in total ($t_1$ to $t_M$), each user $X$ with description $d(X)$ that is called a pseudo-document here and is specified by a set of attributes (terms) $t_i$, was modeled as an $M$-dimensional vector with non-zero values in its $i$th entries only. In the simplest case, $d(X)_i$ is 1, if term $t_i$ occurs in description of node $X_i$, and is 0, otherwise. A collection of pseudo documents (modeled as column vectors $d(X)$) for all members of an IDN of size $N$ would then form an $M \times N$ matrix which is equivalent to ‘term-document’ matrices in topic modeling, and attribute-relation tables in data analysis. Such a matrix takes the following form:

$$\begin{bmatrix}
\text{Dictionary terms} \\
\text{(size: $M$)}
\end{bmatrix}
\begin{bmatrix}
d(X_1) \\ \vdots \\ d(X_N)
\end{bmatrix}_{M \times N}$$

More advanced versions of such a matrix can also be considered; they include bag of words in which entries are positive integers reflecting occurrence frequency of words in pseudo-documents, or using TF-IDF (Term frequency – Inverse Document Frequency) as attribute values, which is a measure describing the level of representativeness of a term for a specific user.

### 2.2 $k$-means clustering

By considering each node of the IDN as a data-point and each word of the dictionary as an attribute, the abovementioned term-document matrix collects attribute values for all data-points. It can accordingly be used to formulate the top-down clustering as an unsupervised clustering problem. The goal of such a problem is to partition database $D$ into $k$ classes $C$ such that members in each class are the most similar to each other and less similar to members from other classes. Global optimality (exhaustively enumerating all possible partitions), and heuristic methods are the two main options for performing such a task. Heuristic search can be either agglomerative or divisive; while the former starts with individual nodes and looks for the most similar ones to be collected in the same group, the latter starts at the network level and tries to find the best cut-offs. $k$-means clustering and $k$-medoids clustering or PAM (Partition around medoids) are two of the best known heuristic methods for clustering. Many studies in the literature have successfully applied $k$-means to cluster documents or to detect dominant themes in them. Table 1 lists some recent works in clustering short-length texts (such as tweets, URLs, and comments).

Clustering needs a measure of similarity before anything else. Different metrics are used in the literature to measure distance (dissimilarity) among data-points. Minkowski distance (with its two well-known variants: Manhattan distance, and Euclidean distance), cosine distance (calculated based on the angle between two datasets as two vectors), and Jaccard distance can be mentioned among other basic distance metrics. Distance function must be carefully designed associated with the context of use, and by using the domain knowledge. For semantic clustering purposes, two main groups of distances are used: first, calculating distance through corpus statistics; and second, calculating semantic distance of terms though an external ontology or knowledge-base. The latter is calculated based on the distance of two terms in a taxonomy and the former is the vector distance between pseudo-documents calculated either as cosine or as Jaccard distance. In the present problem, these can be calculated as follows:

$$d_{\text{cos}}(X_i, X_j) = 1 - \frac{\sum_{m=1}^{M} d(X_i)_m \cdot d(X_j)_m}{\|d(X_i)\| \cdot \|d(X_j)\|}$$

$$d_{\text{jac}}(X_i, X_j) = 1 - \frac{|d(X_i) \cap d(X_j)|}{|d(X_i) \cup d(X_j)|}$$

In which:
- $d(X_i)_m$ is the value of $m^{th}$ attribute ($m^{th}$ term) for user $i$ in the term-document matrix;
- $\|d(X_i)\|$ is the norm of vector $d(X_i)$;
- $|d(X_i) \cap d(X_j)|$ is the number of terms in common between profiles of users $i$ and $j$; and
- $|d(X_i) \cup d(X_j)|$ is the number of distinct terms in profiles of users $i$ and $j$.

After selecting a distance measure, $k$-means algorithm takes the following steps:

- Randomly selects $k$ nodes and takes them as centroids of the $k$ communities;
• Assigns each node of the IDN to the community of its closest centroid;
• Centroids are re-calculated for each community and the second step is repeated;
• The algorithm stops when, for a specific number of iterations the position of centroids do not change beyond a certain threshold (stopping criteria).

Table 1 – Semantic clustering of short texts in the literature

<table>
<thead>
<tr>
<th>Author</th>
<th>Data-set Domain</th>
<th>Goal</th>
<th>Features</th>
<th>Feature values</th>
<th>Distance measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kennedy et al. (2007)</td>
<td>Flickr</td>
<td>Detection of events and places from clusters of social annotation</td>
<td>Terms</td>
<td>TF-IDF</td>
<td>Geographic distance</td>
</tr>
<tr>
<td>Antai et al. (2011)</td>
<td>Pdf text files</td>
<td>Subject classification and topic detection</td>
<td>Terms</td>
<td>TF-IDF</td>
<td>LSI semantic similarity</td>
</tr>
<tr>
<td>Rangrej et al. (2011)</td>
<td>Twitter</td>
<td>Clustering tweets</td>
<td>Terms</td>
<td>TF-IDF</td>
<td>Cosine similarity and Jaccard coefficient</td>
</tr>
<tr>
<td>Muntean et al. (2012)</td>
<td>Twitter</td>
<td>Semantics behind hashtags</td>
<td>Terms</td>
<td>TF-IDF</td>
<td>Jaccard distance measure</td>
</tr>
<tr>
<td>Kireyev et al. (2009)</td>
<td>Twitter</td>
<td>Crisis and disaster detection</td>
<td>Domain and event-specific terms</td>
<td>Bag of words</td>
<td>Cosine similarity</td>
</tr>
<tr>
<td>Avanija &amp; Ramar (2013)</td>
<td>Usenet group dataset</td>
<td>Web documents clustering</td>
<td>Terms</td>
<td>TF-IDF</td>
<td>Semantic distance over an external ontology</td>
</tr>
<tr>
<td>Suganya &amp; Srinivasan (2013)</td>
<td>Web search queries</td>
<td>To infer query's goal from feedback sessions</td>
<td>Pseudo terms</td>
<td>TF-IDF</td>
<td>Semantic distance over an external knowledge-base (WordNet)</td>
</tr>
</tbody>
</table>

As it is seen in Table 1, in unsupervised clustering of tweets most studies use ‘terms’ (unigrams) rather than features such as grammar or syntax. More sophisticated NLP-type features such as length, n-grams (sequence of n terms), punctuations, and part of speech are mostly common in supervised learning for training classifiers. Also, the table suggests that semantic distance in one of its two forms is commonly used as the measure of similarity.

Having an unsupervised learning problem in hand, an important question to be answered is how to set a value for k. Different measures are offered in the literature to evaluate clustering performance when different values are selected for k. Similarity among objects within each cluster (intra-cluster similarity) and dissimilarity across different clusters (inter-cluster similarity) are the main criteria controlling the performance. Average distances between the centroid of a cluster and nodes in that cluster (centroid distance) can show the level of similarity among cluster members. This is called intra-cluster similarity (or intra-cluster centroid distance). Clusters with lower intra-cluster distance are more uniform and include more similar members. An Average of centroid distances over all nodes of dataset gives a measure of general intra-cluster similarity. However, at the same time with high intra-cluster similarity, a good clustering system must have low inter-cluster similarity. This criterion is measured through Davies-Bouldin (DB) index (Davis & Bouldin, 1979). Without going to calculation details of this index, it returns lower values for algorithms resulting in clusters with high intra-cluster similarity and low inter-cluster similarity. Therefore, the best k will be associated with the lowest DB index.

To summarize, k-means algorithm can cluster nodes of the IDN through their descriptions (pseudo-documents d(X)) into k classes based on the similarity between terms used in pseudo-documents. This is a term-level comparison which can be known as a first order analysis and matching. However, a more
profound matching among nodes should consider the similarity between 'concepts' addressed by users. Many studies have reported higher level of intra-cluster similarity when semantic distance (rather than a plain cosine distance) is used (see Antai et al. 2011 as an example). This requires highlighting hidden patterns of semantic similarity among pseudo-documents which can be handled through semantic transformation.

2.3 Semantic transformation

Transformation from $M$-dimensional lexical space which explained above, into a lower size (let's say $q$-dimensional) semantic space, under some conditions can expose the underlying semantic correlations among terms and pseudo-documents. Dimensions of the new space are *topics* or *common semantic themes* in documents, and such a transformation is referred to as 'topic modeling'. One important advantage of this approach is the fact the corpus statistics are the base of deriving semantic relations. Hidden patterns of semantic similarity are detected from co-occurrence of terms in multiple documents and therefore, the detected similarity will have a *context-sensitive* nature (Landauer et al. 1998). There are different forms of semantic transformation among which Latent Semantic Analysis (LSA), Probabilistic Latent Semantic Analysis (PLSA), and Latent Dirichlet Allocation (LDA) are the most popular ones. In the domain of construction, such techniques have recently found some applications in classification tasks. Classifying general conditions for contractual documents (Zhang & El-gohary, 2013) and classifying environmental regulatory documents (Zhou & El-gohary, 2014) can be mentioned among other limited examples of such applications.

Latent Semantic Analysis–LSA (or latent semantic indexing–LSI) is a powerful technique in vectorial semantics, working based on estimation of a matrix through Singular Value Decomposition (SVD) and inferring semantic relations among terms and documents. In terms of data analysis, SVD is a transformation of a dataset from one space in which the data has high variations, into a new space with lower variations. This transformation decomposes correlated variables and exposes the level of variation along each dimension in the new space. Therefore, by ignoring variations below a certain threshold, one can reach the best estimation of the original data in a lower-dimensional space. Mathematically, this transformation is decomposition of a rectangular matrix $A$ into the product of three matrices:

$$ A = U \times S \times V^T = \hat{A} $$

Where:
- $U$ and $V$ are formed as collections of eigenvectors of matrix $A^T \cdot A$ (called singular vectors);
- $S$ is a diagonal matrix with *singular values* of matrix $A$ (square root of eigenvalues of $A \cdot A^T$) as its diagonal entries; and
- $\hat{A}$ is the least square fit of matrix $A$.

If the full matrix $S$ is used, then, $\hat{A}$ and will be exactly the same. However, selecting a limited number of (say $q$) dimensions in $S$ will make $\hat{A}$ an estimation of $A$ in a lower dimensional space. As singular values of matrix $A$ are sorted in a descending order in the diagonal of matrix $S$, selecting dimensions which are associated with the $q$ largest singular values will be easily possible. The noise will be filtered out in the resulted estimation ($\hat{A}$), hence it will reflect the underlying structure beneath the first order data. Selection of $q$ will influence the results; if it is set too large, then the noise of first order data will not be fully filtered, and if it is set too small, then some latent correlations will be lost. Reaching an optimal dimensionality for SVD is involved in some levels of trial and error (Antai et al. 2011).

LSA is in fact the result of applying SVD to the term-document matrix. As the result, semantic dependencies and similarities will be highlighted at a deeper level and in a low-dimension semantic space. The results will allow investigation in semantic correlation at three levels: term–term, term–document, and document–document. The latter correlation between pseudo-documents of our problem can be taken as a measure of semantic distance to evaluate semantic similarity between profile descriptions for nodes of the IDN.
3 CASE STUDY PROJECT

We aim to apply the methods explained above in an actual infrastructure project to see how the main groups of social interests in the urban infrastructure system can be crystallized through analysis of online public participation contents. The ‘Eglinton Crosstown LRT’ line is an under-construction project to span 19km of Light Rail Transit, out of which 10km is tunnelled, cutting across Toronto in the east-west direction along Eglinton Avenue and connecting to Scarborough Rapid Transit system. The project at a glance can be summarized as:

- Type: Light Rail Transit – New Construction
- Construction start year: 2011 – Estimated completion year: 2020
- Estimated cost: CAD8.4 Billion – Funding: Provincial funds
- Owner: Metrolinx – Ultimate operator: Toronto Transit commission (TTC)

The Crosstown project is one of the largest transit projects currently underway in North America and it has raised several issues that have gained public and media attention. The owner launched a Twitter account for the project on December 2011. At the time data we first collected data (September 2012), it had 521 followers, and now in more than two years, this number has increased into more than 2800 followers\(^2\). We applied \(k\)-means clustering through topic modeling to investigate which commonalities form the main groups of these followers and what topics they mainly discuss.

3.1 Followers Typology

Using semantic distances (calculated through LSI) as a measure of similarity, IDN of the Eglinton Crosstown project on Twitter (September 2012) was clustered by applying LSI to node descriptions and using the outputs as a distance measure for \(k\)-means clustering. \(k\) (the number of clusters) was selected through distance-based performance measures as illustrated by Table 2. As seen, the lowest DB index (the highest inter-clustering similarity) and the lowest inter-cluster distance are resulted for \(k=4\).

Table 2 – Evaluation of clustering with different number of clusters (nodes with blank descriptions are excluded)

<table>
<thead>
<tr>
<th>(k)</th>
<th>Clusters</th>
<th>Clusters sizes</th>
<th>Average centroid distance for each cluster</th>
<th>Average inter-community distance</th>
<th>Performance (Davies-Bouldin Index)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>C1</td>
<td>203</td>
<td>0.008</td>
<td>0.007</td>
<td>1.920</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>204</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C1</td>
<td>174</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>96</td>
<td>0.012</td>
<td>0.006</td>
<td>1.653</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>137</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>C1</td>
<td>53</td>
<td>0.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>78</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>119</td>
<td>0.004</td>
<td>0.005</td>
<td>1.425</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>157</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>C1</td>
<td>110</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>72</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>84</td>
<td>0.004</td>
<td>0.008</td>
<td>1.730</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>97</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>44</td>
<td>0.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C1</td>
<td>73</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>91</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>91</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>45</td>
<td>0.012</td>
<td>0.007</td>
<td>1.579</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>7</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C6</td>
<td>100</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^2\) As of January 2015
The size of the semantic space \((q)\) was also set equal to 4; this was not only the same as number of clusters but also the same as number of communities detected in the same network via community detection (Nik Bakht and El-diraby, 2013b). It must be noted that some Twitter users leave their descriptions blank; these nodes were assigned to a separate cluster.

After clustering an IDN based on semantic similarity of its nodes’ descriptions, semantic analysis helped to detect dominant themes in each cluster. For this purpose, descriptions for all nodes in one cluster were compiled as one document and then through LSI the top terms in each of these documents were detected. Table 3 lists top terms for the four clusters found in Eglinton Crosstown network through \(k\)-means clustering. Results represent outputs of LSA with 95% of total singular values, in conjunction with a ranker system. In this analysis, bi-grams (combinations of two successive words) were also added to features for latent semantic indexing. Some terms which can help to speculate dominant topics within each cluster are highlighted in bold in this table. Although highlighted terms can give an overview of dominating themes in each cluster, high level of mixing among terms does not allow reaching a firm conclusion confidently.

<table>
<thead>
<tr>
<th>Community</th>
<th>Cluster1</th>
<th>Cluster2</th>
<th>Cluster3</th>
<th>Cluster4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>157</td>
<td>119</td>
<td>78</td>
<td>53</td>
</tr>
<tr>
<td>fan</td>
<td>transit</td>
<td>city</td>
<td>culture</td>
<td></td>
</tr>
<tr>
<td>enthusiast</td>
<td>york</td>
<td>news</td>
<td>interested</td>
<td></td>
</tr>
<tr>
<td>junkie</td>
<td>Mo’m</td>
<td>account</td>
<td>cities</td>
<td></td>
</tr>
<tr>
<td>coffee</td>
<td>work</td>
<td>world</td>
<td>housing</td>
<td></td>
</tr>
<tr>
<td>nerd</td>
<td>political</td>
<td>ttc</td>
<td>awesome</td>
<td></td>
</tr>
<tr>
<td></td>
<td>beer</td>
<td>metrolinx</td>
<td>business</td>
<td></td>
</tr>
<tr>
<td></td>
<td>father</td>
<td>updates</td>
<td>mayor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>music</td>
<td>association</td>
<td>Town_hall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>views</td>
<td>area</td>
<td>ward</td>
<td></td>
</tr>
<tr>
<td></td>
<td>member</td>
<td>village</td>
<td>senior</td>
<td></td>
</tr>
<tr>
<td>cyclist</td>
<td>good</td>
<td>twitter</td>
<td>issues</td>
<td></td>
</tr>
<tr>
<td>news</td>
<td>enjoy</td>
<td>things</td>
<td>economics</td>
<td></td>
</tr>
<tr>
<td>writer</td>
<td>project</td>
<td>active</td>
<td>interests</td>
<td></td>
</tr>
<tr>
<td>avid</td>
<td>theatre</td>
<td>citizen</td>
<td>place</td>
<td></td>
</tr>
<tr>
<td>designer</td>
<td>construction</td>
<td>resident</td>
<td>fan</td>
<td></td>
</tr>
<tr>
<td>design</td>
<td>leaside</td>
<td>affairs</td>
<td>avid</td>
<td></td>
</tr>
<tr>
<td>technology</td>
<td>works</td>
<td>district</td>
<td>baseball</td>
<td></td>
</tr>
<tr>
<td>grad</td>
<td>transport</td>
<td>job</td>
<td>human</td>
<td></td>
</tr>
<tr>
<td>runner</td>
<td>environment</td>
<td>advisory</td>
<td>pop_culture</td>
<td></td>
</tr>
<tr>
<td>resident</td>
<td>chair</td>
<td>progressive</td>
<td>policy</td>
<td></td>
</tr>
</tbody>
</table>

It must be noticed that the authors had formerly shown through social network analysis that this network has four major communities, labeled as: politicians, technical decision makers, city policy makers, and the community of the public (Nik Bakht and El-diraby, 2013a&b). The results of semantic clustering support those findings; dominant terms in cluster2 refer to the owner and operator of the project who are among the main technical actors and decision makers. Also terms such as construction, transport, and project can support this speculation that this cluster is composed of a group of people with interests in technical and engineering aspects of the project. Cluster 3 has top terms which refer to the city councillors and city decision makers. Town hall, mayor, and progressive (referring to the progressive conservative party) are among those terms. As it is seen, here the line to separate ‘politicians’ from ‘city policy makers’ is blurred as many terms describing these groups belong to the same semantic classes. This was not the case when community detection was performed by looking at the social connectivity among followers. Terms in clusters 1 and 4 suggest that they are composed of nodes from the public with two main themes of interest: art/planning, and politics. It may be hard to make a firm claim about these communities due to the diversity of their top terms; but referring back to results of bisection through social connectivity and reviewing the major interests of nodes belonging to the community of the public can explains the source...
of such diversity. Most community leaders in the community of the public were either journalists or planners (Nik Bakht and El-diraby, 2013a).

3.2 Core Interests

Repeating similar analysis on tweets collected through project-related hashtags mentioning the project ID can result in detecting the core themes of interests in online discussions around the project. We repeated the same procedure including cleaning and tokenizing tweets, and then applying k-means clustering based on semantic similarity among the tweets. We applied the analysis to 170 tweets collected between July and September 2013 through mentioning of the project ID (@CrosstownTO) and related hashtags (such as #CrosstownLRT, #Eglinton-Scarborough, etc.). The analysis resulted in five clusters and then we detected top terms in each cluster through LSI. Reviewing the list of these top terms suggests some commonalities in each cluster:

- Economy is the dominant theme of one of the clusters. Terms such as XXX (representing monetary values), Dollars, Dollars_Risk, Investing, Millions, Oaarchitects, Construction_Safety, Mega_Contract are among top terms of this cluster;
- The second cluster is dominated by terms related to technical features of the project: Construction, Safety, Contract, Consultant, Contractor, Procurement, Procurement_Process, LRT_Project, and Tunnel_Boring are among those terms;
- Community related issues, and local/regional aspects are the third group of topics tweeted regarding the project. Terms such as Neighbourhood, Community, Neighbourhood_Revitalization, Eglinton, Yonge_Bus, Finch, and Finch_LRT, Real_estate are some of the key terms representing these topics;
- A smaller group with fewer number of tweets compared to the above three classes use terms which imply Political issues; Councilor, City_Staff, Provincial_Government and Harper are the most outstanding terms of this type;
- Last but not the least, there was a small cluster that we could not realize a specific team among its top terms. When tweets in this cluster were screened, we found that they mostly communicate news and updates about the project, its schedule and improvement, and public meetings.

4 DISCUSSION AND CONCLUDING REMARKS

Titles assigned to the clusters above may be arguable. For example, when focusing on sets of terms detected for different classes of interest, one may argue existence of some anomalies; although terms Construction and Safety are in the class we called ‘Technical issues’, the bigram Construction_Safety is in the cluster of ‘Economy’. The same is true for the term Contract versus the bigram Mega_Contract. Moreover, while Oaarchitects representing Ontario Association of Architects (OOA) is expected to be in the technical cluster, it is among the economy related issues. This made us take a closer look at the project and the associated discussions in this period.

In late July 2013, CDAO (Construction & Design Alliance of Ontario), representing about 200 firms, published an online report, criticizing Infrastructure Ontario and the project owner (Metrolinx) for the procurement contracting process. The report claims that bundling station and maintenance facility construction into one contract does not allow many competitors (particularly the local small or medium sized firms and consortia) to bid and kills the competition. They claimed that as a result, the selected proposal is imposing up to $500million extra cost in design and construction on tax-payers (CDAO, 2013). In a similar report, OAA questioned feasibility of awarding $1.75 billion architectural components in the project worth $4 billion in total in form of a single mega-contract (OAA, 2013). These reports also mention other consequences to the bundled contract including ‘stifling innovation’, accepting bids from a foreign multi-national firm (rather than domestic industries), and concerns regarding the public safety due to contracting the project to the foreigner companies who – according to the reports – lack professional trainings in this regard. Metrolinx responded to such criticism in August of that year, listing Canadian companies having roles in design and construction of the project and providing the hardware. These reports attracted attention in the social media, forming disputes in August 2013. In the data analyzed here a total of 30 tweets were discussing this issue, mainly by emphasizing the economic impacts of such a
decision and that is why the abovementioned terms can be found in the same cluster as terms Dollars, Investing, and Monetary values.

In conclusion, although semantic clustering can successfully detect groups of terms used to discuss the same aspect of a project, making a conclusion on the topic addressed by those terms is a subjective and judgment-based task. Using a taxonomy (when a specific context is scoped) and positioning distribution of detected terms in different branches of the taxonomy may help to automate this phase to some extent. This must be investigated in the future research. Consequently, outputs of the presented method are certainly a good starting point for decision makers to understand the composition of the e-society and the content of discussions around the infrastructure project at stake. This can add meaning to the unstructured and chaotic process of online public engagement by bundling participants and their vested interests. Findings of this paper suggest that it is worthwhile to invest more time and effort in this regard. Expanding domain of the analysis and experimenting with larger datasets can result in more insights.

References


Nik Bakht, Mazdak, and Tamer E. El-Diraby. "What does social media say about the infrastructure construction project?" Beijing, China: CIB W78, 2013b.


OVERVIEW OF CONSTRUCTION SUSTAINABILITY RESEARCH PRODUCTS

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³ woo.jeyoung@utexas.edu

Abstract: Much research has been conducted on capital project sustainability in the last two decades, but most of the findings only provide guidelines for its implementation during facility planning or design. This nearly exclusive focus on early project phases has left the industry with the need for more detailed guidance on implementing construction sustainability practices during jobsite execution. With this need in mind, the Construction Industry Institute (CII) chartered Research Team (RT) 304, "Sustainability Practices and Metrics for the Construction Phase of Capital Projects", to develop this missing practical guidance. This paper overviews the findings and products of the research team. The team developed a catalog of 54 Construction Phase Sustainability Actions (CPSAs) for onsite implementation during the construction phase to increase overall project sustainability. Each CPSA is characterized in terms of corresponding construction functions, potential sustainability impact, influence on project performance (i.e., cost, schedule, quality, and safety), ease of implementation, barriers to implementation, conditions that leverage benefits, and output metrics. The research team also developed two spreadsheet-based tools—the CPSA Screening Tool and the CPSA Implementation Index—to facilitate CPSA implementation during construction. The screening tool enables users to prioritize the 54 CPSAs according to project characteristics, while the index tool assesses CPSA implementation levels. Through its validation efforts, the team determined that the current level of CPSA implementation across the industry is at approximately 60 percent, and that this rate should increase with the regular use of the CPSA catalog, screening tool, and implementation index.

INTRODUCTION

As project teams seek to lessen the environmental impacts of their construction activities—water and electricity consumption, earth work, and wastes generated during demolition and construction, among others—they increasingly recognize the importance of construction sustainability techniques. More and more, owners, contractors, and other capital project stakeholders are looking for guidance and resources for conducting sustainable construction activities to improve their sustainability performance (CII 2014a and CII 2014b).

In recent decades, researchers have developed much practical sustainability-related guidance for construction activities. One of the globally recognized sources of guidance is the Leadership in Energy and Environmental Design (LEED) certification program developed by the United States Green Building Council (USGBC). While this program has been widely implemented, it only offers sustainability objectives and recommendations in the planning and design phases of projects (USGBC 2009). Similar programs were developed by the City of New York Department of Design and Construction and the
Chicago Department of Aviation (City of NY DDC 1999 and CDA 2013). These examples also focused on early project phases.

To provide the industry with practical sustainability guidance for the construction phase, the Construction Industry Institute (CII) organized Research Team (RT) 304, "Sustainability Practices and Metrics for the Construction Phase of Capital Projects." This paper introduces the research products developed by CII RT 304, the Construction Phase Sustainability Action (CPSA) Catalog, the CPSA Screening Tool, and the CPSA Implementation Index. Examples of the construction phase sustainability activities presented in these products are temporary facility design and construction, and construction means and methods.

1 RESEARCH OBJECTIVES

The objectives of the research were (1) to provide practical sustainability guidance for construction field operations, (2) to develop a spreadsheet-based tool to support sustainability implementation during the construction, and (3) to provide sustainability metrics for benchmarking. Since these objectives addressed sustainability implementation during the construction-phase, the scope of the research extended from the contractor's initial set-up to the final commissioning report of a capital project, and sustainability activities during the planning or design phase were excluded.

2 RESEARCH METHODOLOGY

Before proceeding to develop the objectives, the research team defined three key terms, i.e., construction sustainability, construction phase, and conventional project performance criteria. Construction sustainability was defined as "the processes, decisions, and actions during the construction phase of capital projects that enhance current and future environmental, social, and economic needs while considering project safety, quality, cost, and schedule." Construction phase was defined as "all fabrication/jobsite/field activities and decisions starting with construction/fabrication contracting and planning for site mobilization through to initial operations, final performance testing, and handover of the completed facility." Lastly, conventional project performance criteria were defined as "typical criteria for assessing a project's success: safety, quality, cost, and schedule" (CII 2014a and CII 2014b).

As illustrated in Figure 1, the research team reached alignment on the objectives and terms before conducting its literature review. After that the team developed the Construction Phase Sustainability Actions (CPSAs) Catalog and two spreadsheet-based tools—the CPSA Screening Tool and the CPSA Implementation Index. Finally, the team engaged a panel of external sustainability experts to validate these research products (CII 2014a). The following section provides detailed descriptions of each phase of the research.

2.1 Literature Review

The research team examined the relevant literature in the following areas: sustainable development and sustainable construction; common sustainability models; sustainability drivers and barriers; corporate-level and project-level sustainability; advances in project-level sustainability practices; construction and demolition waste management; materials management and selection; construction site energy management and emission reduction; indoor air quality during construction; water consumption/quality during construction; and community and social aspects of sustainability. Due to the page limitations of this article, all detailed findings of the literature review can be found in Implementation Resource 304-2, "A Framework for Sustainability during Construction" (CII 2014a).

While conducting the literature review, the research team was able to study a variety of construction sustainability opportunities and their impacts on construction sustainability performance, i.e., their improvement of economic, social, and environmental aspects of a project. However, most previous research was conducted in early phases of construction projects, such as planning or design. This finding showed the need for more detailed guidance and applicable strategies for construction-phase sustainability practices for owners, contractors, and other stakeholders.
2.2 Development of Construction Phase Sustainability Actions (CPSAs) Catalog

In order to fill the research gap as lacking of guidance on construction-phase sustainability practices, the research team developed the CPSA Catalog with optional 54 actions which enhance project sustainability during the construction phase. The preliminary CPSAs with construction sustainability practices were originated from literature review. Then the research team brainstormed to assemble industry sustainability practices and collected experts opinion on construction sustainability. The team also estimated sustainability impact magnitude of each CPSA implementation with five different levels as significantly positive impact, positive impact, negative impact, significantly negative impact, and minimal/negligible impact. Before finalizing the 54 CPSAs, the draft of CPSAs had been refined with multiple reviews by the research team (CII 2014a).

Each catalog entry follows a template with the following information: CPSA title; primary construction function; secondary construction function; CPSA description; characterization of sustainability impacts; influence on conventional project performance criteria; ease of CPSA accomplishment/implementation; project conditions that leverage benefits from the CPSA; potential sustainability performance output metrics; barriers to successful implementation; and references (CII 2014a and CII 2014b). The team designed and modified the catalog throughout the course of numerous brainstorming sessions and workshops. The team was composed of 15 members, representing owners, contractors, design consultants, and equipment/material suppliers. The team’s cumulative years of relevant industry experience was 316 years, with 21 years as the average amount of experience (CII 2014a).

2.3 Tools Development and Validation

RT 304 developed the CPSA Screening Tool and the CPSA Implementation Index in four different phases: (1) conceptual, (2) detailed planning, (3) tool programming, and (4) testing/modifying. During the conceptual phase, the research team identified inputs, outputs, a logic, and an algorithm for the CPSA Screening Tool. During the detailed planning phase, the team developed the content of the introduction tabs, user guide tabs, input tabs, output tabs, and database tabs for computing, for both tools. Next, the team programmed the content into the tools, using Microsoft Excel software functions. Once the tools had been developed, they were distributed to the panel of external experts to test on specific projects, and the tools were modified according to the panel’s comments and suggestions (CII 2014a).
3 PRODUCT OF THE RESEARCH

This section describes the major characteristics of the research team's three research products: the CPSA Catalog, the CPSA Screening Tool, and the CPSA Implementation Index.

3.1 54 CPSAs Catalog

The research team developed 54 CPSAs for the CPSA Catalog to offer detailed guidance on construction sustainability implementation to owners, contractors, and other capital project stakeholders. Using the information provided in each CPSA, owners or project managers can decide whether to use sustainability activities to affect project performance. Figure 2 presents a sample image of CPSA No. 28. The entire CPSA Catalog can be found in CII Implementation Resource 304-2 (CII 2014a).

![Figure 2. Typical CPSA Catalog Entry (Adapted from CII 2014a and CII 2014b)
3.1.1 CPSA Title and Primary Construction Function

The team identified the following eight construction sustainability-related primary functions for the CPSA Catalog: (1) project management; (2) contracting; (3) field engineering; (4) site facilities and operations; (5) craft labor management; (6) materials management; (7) construction equipment management; and (8) quality management, commissioning, and handover (CII 2014a and CII 2014b).

Table 2 categorizes the 54 CPSAs, first by primary sustainability impact, and then by the most affected project areas and resources. Around 60 percent of CPSAs are relevant to the Site Facilities & Operations, Project management, and Field Engineering. (CII 2014a)

3.1.2 Characterization of Sustainability Impacts

The most affected areas and resources of each CPSA’s sustainability impact was gathered from literature and research team brainstorming. The collected areas and resources were assigned to one sustainability impact area as one aspect among economic, social, and environmental. Table 1 presents the entire list of most affected areas and resources of each sustainable area.

Table 1: Primary Sustainability Impacts of CPSA and the Most Affected Areas and Resources by CPSA (Adapted from CII 2014a)

<table>
<thead>
<tr>
<th>Primary Sustainability Impact</th>
<th>Most Affected Areas and Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Energy consumption; Greenhouse gases; Criteria air pollutants; Indoor air quality; Water consumption; Water quality; Waste generation; Land use; Noise pollution; Odors; Light pollution; or Negligible effect</td>
</tr>
<tr>
<td>Social</td>
<td>Health and safety; Skills development; Community relationships; Local resource depletion; Community infrastructure; Traffic; Job creation; Tax revenue generation; Community service donations; or Negligible effect</td>
</tr>
<tr>
<td>Economic</td>
<td>Project fiscal impacts, or Negligible effect</td>
</tr>
</tbody>
</table>

The tool prompts the user to indicate the most desirable sustainability impacts for a given project on a five-point scale. The research team also designed the tool to measure the positive impact of each CPSA on conventional project performance criteria, i.e., safety, quality, cost, and schedule objectives.

3.1.3 Ease of CPSA Implementation and Leveraging Benefits of CPSA Implementation

The research team assessed the level of difficulty of each CPSA implementation as easy, moderate, or challenging, considering the required resources, expense, skill-sets, and time to implement. In addition to rating the ease of CPSA implementation, the team identified project conditions that leverage benefits from CPSA implementation, grouping them into seventeen categories. These leveraging conditions can be found in CII Implementation Resource 304-2 (CII 2014a).

3.1.4 Sustainability Performance Output Metrics and Barriers to Successful Implementation

The research team identified output metrics for measuring the sustainability performance of each CPSA during its implementation, putting these metrics into nine categories. Moreover, the team examined barriers to each CPSA implementation to prepare project teams for potential challenges. The team grouped these barriers into the following five categories: lack of information; limited project resources; outside owner/contractor control; lack of infrastructure; and unfavorable site or project conditions. The full lists of output metrics and barriers can be found in CII Implementation Resource 304-2 (CII 2014a).
**Table 2: Typical CPSAs according to Primary Construction Functions (Adapted from CII 2014a)**

<table>
<thead>
<tr>
<th>Primary Construction Function</th>
<th>CPSA Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Management</td>
<td>1. Leadership Team Staffing for Sustainable Projects</td>
</tr>
<tr>
<td></td>
<td>2. Community Social Responsibility Program</td>
</tr>
<tr>
<td></td>
<td>3. Contractor Sustainability and Recognition Program</td>
</tr>
<tr>
<td></td>
<td>4. Sustainability Provisions in Construction Execution Plans</td>
</tr>
<tr>
<td></td>
<td>5. Sustainability Risk Management</td>
</tr>
<tr>
<td></td>
<td>6. Stakeholder Engagement Plan</td>
</tr>
<tr>
<td></td>
<td>7. Site Work Hour Schedule to Reduce Traffic Impacts</td>
</tr>
<tr>
<td></td>
<td>8. Work Schedule to Reduce Electricity Impacts</td>
</tr>
<tr>
<td></td>
<td>9. Paperless Communication and Construction Documentation</td>
</tr>
<tr>
<td></td>
<td>10. Construction Team Sustainability Performance Assessment</td>
</tr>
<tr>
<td>Contracting</td>
<td>11. Verification of Sustainability Claims and Ratings</td>
</tr>
<tr>
<td></td>
<td>12. Sustainability-friendly Project Delivery Method</td>
</tr>
<tr>
<td></td>
<td>13. Contractor Prequalification Based on Safety and Sustainability Performance</td>
</tr>
<tr>
<td></td>
<td>14. Promotion of Local Employment and Skills Development</td>
</tr>
<tr>
<td></td>
<td>15. Sustainability Change Proposal Clause</td>
</tr>
<tr>
<td>Field Engineering</td>
<td>16. Labor-intensive versus Equipment-intensive Approaches</td>
</tr>
<tr>
<td></td>
<td>17. Pre-assembly and Pre-fabrication of Construction Elements</td>
</tr>
<tr>
<td></td>
<td>18. Sequence and Route Planning for Project Transport</td>
</tr>
<tr>
<td></td>
<td>19. Minimization of Project's Footprint of Disruption</td>
</tr>
<tr>
<td></td>
<td>20. Sustainable Material Substitutions</td>
</tr>
<tr>
<td></td>
<td>21. Construction Noise/Vibration Abatement and Mitigation</td>
</tr>
<tr>
<td></td>
<td>22. Selective Demolition versus Conventional Demolition</td>
</tr>
<tr>
<td></td>
<td>23. Sustainable Large-scale Earthwork and Grading Operations</td>
</tr>
<tr>
<td></td>
<td>24. Reduction of Dunnage for Equipment Operations</td>
</tr>
<tr>
<td></td>
<td>25. Reusable Shoring, Formwork, and Scaffolding</td>
</tr>
<tr>
<td>Site Facilities &amp; Operations</td>
<td>26. Protection of Cultural Artifacts and Endangered Species</td>
</tr>
<tr>
<td></td>
<td>27. Protection of Trees and Vegetation</td>
</tr>
<tr>
<td></td>
<td>28. Sustainable Temporary Facilities</td>
</tr>
<tr>
<td></td>
<td>29. Sustainable Temporary Worker Camps</td>
</tr>
<tr>
<td></td>
<td>30. Source of Onsite Power</td>
</tr>
<tr>
<td></td>
<td>31. Site Energy Management</td>
</tr>
<tr>
<td></td>
<td>32. Energy-autonomous Pre-manufactured Reusable Facilities</td>
</tr>
<tr>
<td></td>
<td>33. Indoor Air Quality Improvements</td>
</tr>
<tr>
<td></td>
<td>34. Collection, Remediation, and Reuse of Gray water and Storm water</td>
</tr>
<tr>
<td></td>
<td>35. Environmentally-friendly Dust and Erosion Control</td>
</tr>
<tr>
<td></td>
<td>36. Construction and Demolition Waste Management</td>
</tr>
<tr>
<td></td>
<td>37. Collection, Sorting, and Recycling of Construction Wastes</td>
</tr>
<tr>
<td>Craft Labor Management</td>
<td>38. Promotion of Local Workforce Preparedness</td>
</tr>
<tr>
<td></td>
<td>39. Expatriates versus Local Employment for Global Projects</td>
</tr>
<tr>
<td></td>
<td>40. Promote Community Harmony within Diverse Project Workforce</td>
</tr>
<tr>
<td>Materials Management</td>
<td>41. Analysis of Local Materials/Services versus Non-local/Global Alliance</td>
</tr>
<tr>
<td></td>
<td>42. Reduction of Packaging Waste</td>
</tr>
</tbody>
</table>
3.2 CPSA Screening Tool

The research team developed the Excel-based CPSA Screening Tool to help project managers or any capital project stakeholders select the most appropriate and relevant CPSAs. This tool utilizes user input about the project to screen for these relevant CPSAs from the total 54 CPSAs. It then ranks the selected CPSAs according to their likelihood of maximizing project sustainability performance.

The first user inputs for the CPSA Screening Tool are project-specific sustainability objectives; the user determines the relative importance of environmental stewardship, social progress, and direct project economics. Next, the tool prompts the user to provide information about project characteristics. The output is the prioritized list of CPSAs. Figures 3 and 4 show the screenshot of the tool’s Input tab. Figure 5 presents the screenshot of the Output tab. (CII 2014a)

![CPSA Screening Tool - Sustainability Priorities Tab](Adapted from CII 2014)

![CPSA Screening Tool - Sustainability Priorities Tab](Adapted from CII 2014)

Figure 3. CPSA Screening Tool - Sustainability Priorities Tab (Adapted from CII 2014)
Equation 1 presents the Relevance Index (RI), the tool’s prioritizing algorithm. The RI is the Impact Score (IS) times the Conditions Score (CS). The IS is the sum of the Project-specific Sustainability Priorities (PSP) times the Sustainability Impact Rating (SIR); these are shown in Section C of each CPSA sheet. (See the sample sheet in Figure 2.) The percentage of each sustainability priority entered in the Input tab of the tool is its PSP value, and the SIR value is defined as 0 when the SIR is “N,” 0.60 when the SIR is “+,” -0.60 when the SIR is “-,” 1.00 when the SIR is “++,” and, lastly, -1.00 when the SIR is “--.” (CII 2014a)

\[ \text{RI} = \text{IS} \times \text{CS} \]

where \( \text{IS} = \sum \left( \text{Project-specific Sustainability Priorities} \times \text{Sustainability Impact Rating} \right) \)
The CS is determined by the number of leveraging conditions applicable to the project; it is 0.10 when there are zero CPSA leveraging condition, 0.33 when there is one leveraging condition, 0.67 when there are two leveraging conditions, 1.00 when there are three leveraging conditions. (CII 2014a)

3.3 CPSA Implementation Index

To help project teams assess the sustainability performance of their projects, the research team developed CPSA Implementation Index. This tool’s numerical index score (out of 100 possible points) represents the project’s level of CPSA implementation. This score also allows project teams to compare projects for sustainability performance. As discussed above, the input for the CPSA Implementation Index is a rating of the extent of implementation of all 54 CPSAs. Figures 6 and 7 show screenshots of the tool’s Input and Output tabs, respectively. (CII 2014a)

To compute the CPSA Index score, the tool allocates a maximum of 1.85 points for each CPSA implementation, with a total of 100 possible points. That is, the points allocated for each CPSA will be 1.85 when the extent of CPSA implementation is selected as “Full or Almost Full.” Further, when the extent selected is “Substantial,” the points awarded will be 1.23. When the extent selected is “Minimal,” the points will be 0.62. When the extent selected is “None or Almost None,” the points will be 0.00. (CII 2014a)
4 VALIDATION OF THE PRODUCT

4.1 54 CPSAs Catalog

The research team distributed a survey to the review panel, to identify any missing content, to identify any items in need of correction, and to examine their current levels of CPSA application. The 33-member review panel was composed of research team members and external industry practitioners. They had an average of 26 years of industry experience (CII 2014a).

The first section of the survey assessed background, e.g., years of industry experience, project role, primary industry sector, and company size, among other characteristics. The second section asked frequency of CPSA application to the project and likelihood of application of each CPSA to future projects. The respondents indicated that they would either sometimes or frequently apply around 41 CPSAs (75 percent) to their projects; they also said that they were either somewhat or very likely to apply 53 CPSAs (98 percent) to their future projects (CII 2014a).

4.2 CPSA Screening Tool and CPSA Implementation Index

The research team demonstrated the CPSA Screening Tool on a large mining project in Mexico, and demonstrated the CPSA Implementation Index on a large U.S. urban rail transit project. In this validation process, project managers from each project gave constructive and valuable feedback that the team used to modify the tools. The CPSA Implementation Index demonstration showed that the current level of CPSA implementation is 60 percent (CII 2014a).

5 CONCLUSIONS AND RECOMMENDATIONS

The industry’s need for practical guidance on construction-phase sustainability implementation motivated the research team to develop the Construction Phase Sustainability Actions (CPSAs) Catalog, the CPSA Screening Tool to prioritize relevant CPSAs for each project, and the CPSA Implementation Index to measure the level of CPSA implementation efforts. All three outputs were validated by selected experts in construction sustainability. The tool demonstrations showed that the current level of CPSA implementation is 60 percent. (CII 2014a)

Acknowledgements

The authors would like to thank the Construction Industry Institute (CII) for chartering this research project, the members of CII Research Team 304 for their commitment and participation, and the survey participants for their valuable feedback.

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Construction Industry Institute (CII) 2014b. Research Summary 304-1: Sustainability during Construction: Process and Actions, Construction Industry Institute, Austin, TX, USA.
A RAPID LIFT STUDY GENERATION SYSTEM FOR HEAVY INDUSTRIAL PROJECTS

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\textsuperscript{4} bofrim@ualberta.ca

Abstract: The process of creating mobile crane lift studies for heavy industrial projects can be time-consuming and tedious. A large portion of the lift studies required for such projects involve modules that are prefabricated and transported to the site. Composing these lift studies currently requires a considerable amount of time and manual work. Due to the complex nature of these projects the lift studies also often require significant revisions to accommodate changes to the initial plans. This paper introduces a rapid lift study generation program to assist in the planning stage by expediting the drafting process. The program utilizes Autodesk’s AutoCAD, which is one of the most widely used drafting software applications in North America. A custom plug-in to AutoCAD written in the Visual Basic programming language is used to create the graphic portion of the lift study. A separate Windows Form application is used to produce a table of the crane and lift information, such as lifting capacity, ground bearing pressure calculations, and mat design. This application is supported by a database of specifications for various crawler cranes and configurations as well as capacity information. The application allows the user to input information such as the module’s weight, rigging weight, and lift radius in order to obtain a table of relevant information for each lift. This rapid lift study generation program has been tested for validation on a heavy industrial project for which the lift studies had already been prepared by NCSG Crane & Heavy Haul Services using the traditional method.

1 INTRODUCTION

In Alberta, Canada, mobile cranes are frequently used in heavy industrial projects to erect modules that are prefabricated in a controlled environment and then shipped to site. (This offsite construction process is efficient and consumes less waste in general.) In order to achieve a successful lifting process, extensive planning is needed and lift studies are required for each individual lift. Lift studies contain detailed drawings of the crane picking the modules off of the delivery trucks, as well as drawings of the crane placing each module at its final destination. These drawings need to be dimensioned to ensure that the crane and module are placed in their intended locations. Supportive engineering information and calculations are also necessary, such as: (i) the crane configuration; (ii) the length of the boom; (iii) the percent of the crane’s capacity used for the lift; and (iv) the ground bearing pressure (GBP) and mat pressure. However, due to the complicated planning process, lift study requires much preparation time and is error-prone. In addition, any change to the site or project will lead to re-planning and re-design. The objective of the system described in this paper is to accelerate the process of creating these lift
studies by programming the designing algorithms into computer applications. The system involves two main components, one that handles the graphics and one that handles the calculations and table of information. The graphical component is achieved using a plug-in to AutoCAD, which aids with the insertion of transport trucks, modules, rigging, mats, and cranes as well as with dimensioning. The calculations and tables are made by means of a Windows Form application called Smart Lift Planner. This two-program system improves upon the traditional methods of drafting by making it faster and more user-friendly. In previous crane-related research, automation has been the focus in engineering planning and design; this scholarship has included (i) automatic crane selection and positioning (Hanna and Lotfallah 1999; Huang et al. 2011; Safouhi et al. 2011; Wu et al. 2011; Lien et al. 2014); utilizing 3D visualization to simulate crane operations (Al-Hussein et al. 2006; Tantisevi et al. 2009; Lin et al. 2012; Hasan et al. 2013); and lift path planning with the assistance of computer technology (Chang et al. 2012; Zhang and Hammad 2012; Juang et al. 2013; Lei et al. 2013a and 2013b; Olearczyk et al. 2014). However, there are few software applications/systems in the market that can be directly used for heavy lift planning. In Alberta, most large-scale construction companies currently employ drafting personnel that create the graphical portion of lift studies using drafting software such as AutoCAD. Once the site layout has been prepared and the locations of modules, cranes, and transport trucks have been determined, the graphic portion of the lift study must be prepared. To do so the draftsperson must manually insert the transport truck into the drawing, orient it correctly, place the module in the correct position on top of the truck, manually insert the rigging on top of the module, place the crane in its predetermined location, orient the tracks in the right direction, rotate the crane body such that it is facing the module, raise or lower the boom so that the hook block is on top of the pick point, draw a lift line, insert a layout tab, generate the correct view ports, and dimension both the plan and elevation views. Then when it comes time for the set-point drawing to be created, the draftsperson is required to move the module to its set position, rotate it to the correct angle, reposition the rigging in a similar fashion, rotate the crane body, raise or lower the boom, delete the old lift line and draw a new one, delete the old dimensions, and create new dimensions. It is easy to see that this process is tedious and time-consuming. Therefore a level of automation to make the process faster and more efficient would prove to be extremely valuable.

2 AUTOMATED LIFT STUDY GENERATION

The graphical component of the system is handled by an AutoCAD (AutoDesk 2015) plug-in developed in the Visual Basic programming language (Microsoft 2015) at the University of Alberta. The primary use of this plug-in is to aid in the insertion of blocks—objects created from AutoCAD drawings that can be inserted into other drawings. The blocks used by the program have been previously created specifically for the project used to test the program. (These blocks must be saved as individual .dwg files in a specific location so that the program can properly insert them.) Various measurements of the block must be carried out and entered into the spreadsheets from which the program retrieves data. The plug-in is designed to be used after the user has created and inserted the site layout into AutoCAD’s model space.

2.1 Step 1: Crane Matting insertion

The user selects the insert button from a custom toolbar developed for the program. They then specify where they would like to place the mat—either on screen or by entering coordinates into the command line. Options are then given for the insertion angle. For the purpose of selecting the insertion point and angle by moving the cursor and clicking in the 3D environment, the program supports what is known as jigging. In this process, the object being inserted will follow the user’s cursor around the 3D environment and its position will become fixed when the user clicks the mouse. Jigging provides the user with a visualization of the block before its insertion point has been fixed in order to more closely represent how the block will appear in the drawing. This provides an efficient method for determining where to place blocks in relation to existing objects in the drawing. Once a mat has been inserted, if the user requires additional matting they can simply specify a location in relation to the previously placed mat (front, back, left or right). A mat will be automatically inserted in the specified direction and at the same angle as the previous mat.
2.2 Step 2: Transport Truck/Module Insertion

In this step the user first selects the insertion button from the custom toolbar. A prompt will then appear which will allow the user to directly insert a module or to first insert a transport truck into the drawing. Next the option is presented for the user to specify an insertion point either by clicking a point in the model space (jigging supported) or by entering coordinates into the command line. For inserting a module, the insertion point is at ground level directly below the southwest rigging attachment point. For inserting a transport truck the insertion point is located at ground level directly below the trailer hitch. Similar options are then given for the insertion angle. The required module is then selected from a project specific list. This list contains relevant information such as module dimensions and weight, number of cranes necessary for lifting, number of rigging attachment points, rigging height, and locations of pick points in relation to the insertion point. Finally either the user selects where the module is to be placed or it is automatically placed on a previously inserted truck trailer.

2.3 Step 3: Rigging Insertion

After the module has been inserted the user selects the “insert rigging” option, and the rigging (previously designed and saved as a block) necessary to lift the module will be automatically placed on top of it. The automatic rigging placement is performed by inserting the rigging at the same (x,y) coordinates as the module insertion point but at the elevation of the rigging attachment point, which has been measured and entered into a spreadsheet. This displacement is shown in Equation [1] as position vector $\vec{R}_{\text{rig}}$ relative to the origin, where $M_X$, $M_Y$, and $M_Z$ are the insertion points of the module and $H_M$ is the height of the module. The block is then rotated about the z-axis to match the angle of the rigging.

\[ [1] \quad \vec{R}_{\text{rig}} = (M_X, M_Y, M_Z) + H_M \]

2.4 Step 4: Crane Insertion

Now that the module and rigging are in place the user selects a crane to insert. (Cranes available in the current program are the Demag CC2800 and the Manitowoc18000; however, the program could easily be expanded to accommodate other similar cranes.) The user is then prompted to select the desired boom length from a list of crane configurations. Next, the maximum radius must be specified. The program calculates the maximum radius for which the top of the boom will be above the top of the rigging. This value is used as the default maximum radius but can be easily overridden. It is recommended that the second component of the program (Smart Lift Planner) be used when determining this value, as it references the tables supplied by the crane manufacturer in order to determine the maximum radius for a given load. The next prompt provides the user with various options for inserting the crane. These options include:

- Side1/Side: Places the crane perpendicular to the module at a user-defined radius and elevation.
- Specify: Allows the user to either click a point on the screen on which to place the crane or specify the location by entering coordinates. Similar options are given for the crane’s track angle. This method supports jigging.
- Distance Direction: The user enters the location in polar coordinates (radius and angle) relative to the module’s center. Options for track angle are also given.
- Previous Location: This option is available if a crane has previously been inserted and will place the crane in the same location as the previous crane.

While these options are given temporary indicators appearing in the model space that show the locations of sides 1 and 2, as well as circles that show the minimum and maximum allowable radii, these indicators automatically disappear once the crane has been inserted. For all of the options the crane body and boom are automatically configured such that the crane hook will be on the rigging pick point (hook point). The hook point is described using 3D coordinates in Equation [2] by the module’s insertion point $(M_X,M_Y,M_Z)$, the distance in the $x$-$y$ plane from the module’s insertion point to the hook point $(M_{HD})$, the module’s insertion angle ($\theta_M$), the angle in the $x$-$y$ plane from the module’s side to the hook point with the
vertex being the module’s insertion point \( (\theta_{MH}) \), the height of the module \( (H_M) \), and the height of the rigging \( (H_{RIG}) \). Figure 1 provides a labelled plan and dimension views of the module and rigging. The equations the program uses to automate the crane orientation process are outlined below. In all cases the insertion point for a crane is located at ground level directly below the crane’s pivot point \( (\text{Piv}_X, \text{Piv}_Y, \text{Gnd}) \), shown in the position vector relative to the origin in Equation [8]. This is the position at which the crane track is to be inserted. The crane body is then inserted directly over the track at the position described by the position vector in Equation [9], where \( \text{Elev}_{BODY} \) is the elevation of the insertion point of the crane body relative to the ground. Next the crane body is rotated in the \( x-y \) plane by the angle \( \theta_{BODY} \) (Equation [5]) relative to the positive \( x \)-axis. The boom is then inserted at the position described by the position vector in Equation [10], rotated in the \( x-y \) plane by the same angle as the crane body \( (\theta_{BODY}) \), and finally rotated in the \( z \) dimension relative to the \( x-y \) plane by an angle of \( \theta_{BOOM} \) (Equation [7]). In Equation [7] the variable, \( r \), represents the distance from the pivot point to the hook point in the \( x-y \) plane (i.e., the lifting radius), \( L_{BOOM} \) is the length of the boom, and \( O_{BOOM} \) is the boom’s offset from the pivot point in the \( x-y \) plane. With everything in position the program also automatically draws a vertical line from the crane’s boom head to the hook block, representing the load line.

[2] \( \text{Hp} = (M_X + MH_d \cdot \cos(\theta_M + \theta_{MH}), M_Y + MH_d \cdot \sin(\theta_M + \theta_{MH}), M_Z + H_M + H_{RIG}) \)

[3] \( \Delta X = \text{Hp}_X - \text{Piv}_X \)

[4] \( \Delta Y = \text{Hp}_Y - \text{Piv}_Y \)

[5] \( \theta_{BODY} = \arctan(\Delta Y / \Delta X) \) \hspace{1cm} \text{(Angle in} \ x-y \text{ plane relative to positive} \ x \text{-axis)}

[6] \( r = \sqrt{\Delta X^2 + \Delta Y^2} \)

[7] \( \theta_{BOOM} = \arccos((r - O_{BOOM}) / L_{BOOM}) \) \hspace{1cm} \text{(Angle in} \ z \text{ dimension relative to} \ x-y \text{ plane)}

[8] \( \bar{R}_{\text{TRACK}} = \langle \text{Piv}_X, \text{Piv}_Y, \text{Gnd} \rangle \)

[9] \( \bar{R}_{\text{BODY}} = \langle \text{Piv}_X, \text{Piv}_Y, \text{Gnd} + \text{Elev}_{BODY} \rangle \)

[10] \( \bar{R}_{\text{BOOM}} = \langle \text{Piv}_X + O_{BOOM} \cdot \cos(\theta_{BOOM}), \text{Piv}_Y + O_{BOOM} \cdot \sin(\theta_{BOOM}), \text{Gnd} + \text{Elev}_{BOOM} \rangle \)

Figure 1: Labelled plan and elevation views of the module and rigging.
2.5 Dimensioning and Lift Study Layout

An available feature of the program can automatically create a plan view dimension for the lift study. The program generates radial dimensions for the lift radius, tail-swing radius, and super-lift radius. It also creates both horizontal and vertical dimensions from the crane to the pick point. The user can use the dimension grips to arrange the dimensions as they see fit. The dimensions are placed on a layer, called PlanDimension, that the program creates. Once the user is satisfied with the drawing, another function from the custom toolbar can automatically insert a lift study layout into paper space. When this option is selected a command line prompt appears asking the user if the layout is for the final or initial position (pick point or set point). These layouts contain viewports for a plan view, an elevation view, and an additional custom view. The user then creates the elevation dimensions on the layout with a pre-made dimension style on a layer, called ElevationDimension, created by the program. Finally, the user turns off the PlanDimension layer in both the elevation and the custom viewports in order to find a custom view they are satisfied with. The graphical component of the pick point lift study is now complete. An example is shown in Figure 2.

![Figure 2: Completed lift study graphics](image)

2.6 Module Movement Options

Now that the pick point lift study is complete, the crane and module can be manipulated. These options, available on the custom toolbar, include lifting, straightening, swinging, and rotating the module, as well as raising or lowering the boom to move the module backwards or forwards (see Figure 3). The crane will automatically respond to these operations by orienting itself in the correct fashion. Another available option is to simply choose the set point, which will remove the module from its pick position and allow the user to manually select the module's set point and set angle. Again the crane will automatically change orientations to accommodate this (see Figure 4). The user can then create a set point lift study layout in much the same way as with the pick point.

![Figure 3: Module and boom manipulations](image)
3 SMART LIFT PLANNER

The Smart Lift Planner (SLP) is a Windows Form application designed to aid in planning and calculations necessary for lift studies. It accomplishes this through use the combined use of databases and user inputs such as module weight, lifting radius, and matting type. Several databases of technical data are constructed in order to minimize the need to sift through data tables to obtain information. These include a crawler crane database, a capacity database, and a rigging database. The crawler crane database contains hundreds of unique crane configurations, each with 45 parameters including weights, dimensions, and lift form. The capacity database contains the capacities at different radii for many of the configurations. The rigging database contains the specifications for hundreds of shackles, slings, spreader bars, and turnbuckles. The SLP can be used to determine maximum lift radius, percent capacity, total weight, ground bearing pressure, mat pressure, and matting necessary, among other things. Further details pertaining to the SLP are provided below.

3.1 Crane Info Page and Lift Design Page

Dropdown menus allow the user to select the crane manufacturer and the crane model they require. Once these selections have been made a data grid view appears, where the user can scroll through and select the configuration that will meet the specific needs of the project. Crane Info Page 1 then automatically displays information such as weights, lift form, and boom length. It also brings up the capacity table for the chosen crane, which shows how the lifting capacity varies with radius. A hook block table is also available for the user to select a hook block. The dimensions of the chosen crane are automatically displayed on Crane Info Page 2 (see Figure 5). Now moving to the lift design page the user inputs the weights of the module, rigging, and other relevant components. The program then calculates the total weight and checks the capacity chart to provide the user with a range of radii acceptable for lifting modules with the selected crane. The user then inputs the radius for the current lift, and the program outputs the maximum capacity at that radius and the percentage of the maximum capacity that the lift requires.
3.2 Ground Bearing Pressure Page

After the capacity has been determined the ground bearing pressure must be calculated. All of the information needed for this calculation is already available, so the user simply needs to click “calculate GBP”. The required information is retrieved from the database entries for the selected crane, as well as from the lift design page where information has been inputted by the user. By default these values are used in GBP calculations; however, they can be manually overridden if need be. The program also generates a chart that displays the GBP on each side of the crawler as a function of the boom angle. The values given are the maximum pressures on the front boom side, rear boom side, front counter weight side, rear counterweight side, and the crane body angle that gives these maximum pressures. If the GBP at a specific crane body angle is required, then that angle can be specified and the program will give the corresponding pressure values. A screen capture of the ground bearing pressure page can be seen in Figure 6.

3.3 Mat Design Page

GBP information is automatically passed to the Mat Design page. The user is prompted to input the allowable soil bearing capacity for the project site, the number of timbers forming the mat, number of
layers of mats, and sectional dimensions of the mat, and to choose the type of wood for the mats. The program then verifies if the stresses induced by the lift are within the allowable limit. If the allowable limit is exceeded then an error message is displayed along with a message containing suggestions such as “Bending Fail! Please increase the depth of mat or number of layers”. If the pressures are within the allowable limit then the necessary mat length, p value, load on mat, and minimum mat cantilever distance are generated. A screen capture of the mat design page can be seen in Figure 7.

![Figure 7: Labelled screen capture of mat design page](image)

3.4 Generating and Exporting Lift Study Table

With all information required for a lift study table now available, the user returns to the Lift Design Page and clicks “Generate Table”. The generated table has a feature that exports the table into an MS Excel spreadsheet. The spreadsheet can then easily be imported into the AutoCAD layout created by the lift study AutoCAD plug-in.

4 VALIDATION

The Rapid Lift Study Generation system was used to recreate the graphical portion for a total of 34 pre-existing lift studies from a project by NCSG Crane & Heavy Haul Services. The project was located in Fort McMurray, Alberta and involved the assembly of prefabricated pipe racks that had been transported to the site by trucks. The crane featured in the lift studies was the Manitowoc 18000. The 55A configuration was used with a boom length of 280 ft. The studies featured 18 pipe racks weighing up to 211,974 lb with lengths up to 120 ft. All lifts featured were single-crane lifts. The transport truck, pipe racks, custom rigging, and crane blocks had been created by the drafting-people at NCSG for use in traditional lift studies. The blocks were then modified for use with the Rapid Lift Study Generation Program. Information relevant to the insertion of the blocks was measured using existing AutoCAD tools and entered into spreadsheets. Use of the program substantially reduced the time needed to insert the blocks into the drawing. Because of the level of automation offered by the plug-in it was possible to create lift studies with less effort and drafting knowledge. Tedious tasks such as manually inserting, rotating, and aligning the blocks were mitigated. During the process of creating lift studies, it should be noted, it is often necessary to explore multiple crane position options. Through use of the program it is possible to create many versions of the same lift study in a short period of time, making the planning phase more efficient. For a few of the 34 lift studies created the table of crane information was constructed through use of the SLP. The SLP was tested against existing software, “Crane Support Design”, developed by Hasan et al. (2010). A sample comparison between the two programs is provided in Table 1. For actual industrial implementation of the developed system, further and more rigorous validation is necessary.
Table 1: Comparison between SLP and crane support design

<table>
<thead>
<tr>
<th>Calculation</th>
<th>SLP</th>
<th>Crane Support Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boom Side Front Pressure</td>
<td>8,284 psf</td>
<td>8,010 psf</td>
</tr>
<tr>
<td>Boom Side Rear Pressure</td>
<td>2,570 psf</td>
<td>2,732 psf</td>
</tr>
<tr>
<td>Counter Side Front Pressure</td>
<td>6,697 psf</td>
<td>6,429 psf</td>
</tr>
<tr>
<td>Counter Side Rear Pressure</td>
<td>1,982 psf</td>
<td>2,169 psf</td>
</tr>
<tr>
<td>Horizontal Angle For Max Pressure</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Min. Mat Length</td>
<td>47.7 ft</td>
<td>42.7 ft</td>
</tr>
<tr>
<td>Mat Depth</td>
<td>12 in</td>
<td>12 in</td>
</tr>
<tr>
<td>Mat Width</td>
<td>3.8 ft</td>
<td>3.8 ft</td>
</tr>
</tbody>
</table>

Differences between values are assumed to be due to minor differences in the implementation of formulas in creating the respective programs and the way the programs handle values. The difference in mat length is due to the fact that SLP takes into account the bending and shear strength of the wood, whereas the Crane Support System does not.

5 CONCLUSION

In this paper, an automatic system has been introduced for rapid lift study creation for heavy industrial projects. The system has been proven efficient in engineering planning and the design stage for heavy lifts. Many design factors have been considered in the calculations, such as the lifting capacity and ground bearing pressure. The crane is inserted to its predefined pick and set locations in an AutoCAD system using a plug-in developed by researchers at the University of Alberta; lift drawings (2D and 3D views) are automatically generated, which shortens the drafting time and reduces the human component involved. The designed graphical system has been tested by recreating documents for an actual industrial project in Fort McMurray, Alberta, and the SLP results have been compared with the system previously developed by Hasan et al. (2010).

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References


CHARACTERIZING COORDINATION IN BOTH LOOSE AND VERY TIGHTLY COUPLED UTILITY RECONSTRUCTION PROCESSES.

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Abstract: Privatization of the utilities sector created a fragmented multi-client, multi-contractor system in which reconstruction works are, in fact, a constellation of multiple smaller projects. During planning stages, these projects are loosely coupled, since stakeholders limitedly align construction plans. Consequently, coordination of unresolved issues moves toward construction stages, creating very tight on-site couplings. This paper focuses on the coordination activities that balance these loose and very tight couplings in the planning and execution stages of utility reconstruction. To this end, we identified seven well-performing 'utility coordinators' and conducted ethnographic interviews to explore their work practices. To better characterize these different practices, we introduce level of involvement and moment of involvement as two dimensions for coordination within loose and tightly coupled systems. Based on this, we distinguish two dominant approaches for coordination in utility coordination practice: pro-active involvement in early planning stages, and reactive approaches during execution stages. Findings complement to literature by providing dimensions for coordination of loosely coupled systems. Consecutive research efforts should aim at validating these findings and at identifying contextual factors that drive various distinctive coordination approaches.

1 INTRODUCTION

Privatization policies have changed utilities sectors around most of the Western hemisphere. Nowadays, many utility companies own operate and maintain their own subsurface network. Especially in urban space, these networks are often located in the shallow, densely occupied ground. Utility reconstruction processes – defined as the planned activities related to renewal or relocation of utility service networks such as sewage, energy and water pipes, and telecom lines - therefore involve myriads of utility providers. When these companies concurrently re-align or refurbish their infrastructure, each organization is individually responsible for design and construction of its own network. At the same time, they should manage the interfaces with reconstruction work on surrounding utilities and therefore need participation of other utility companies.

In reality, alignment of the various utility companies is difficult for various reasons: First, concurrent utilities reconstructions involve no formal principle client. Instead, all municipalities and utility contractors are clients on their own. They need to collaborate within a shared workspace to reconstruct their own assets. In contrast with ‘common’ construction projects such collaboration cannot be forced through hierarchical coordination mechanisms. Instead, all clients negotiate to decide about design interfaces and
construction methods. A second difficulty for alignment is that clients often hire distinctive contractors to execute reconstruction work. These contractors formally have limited influence on one another's construction plans. Therefore, they mutually adjust plans based on informal improvisation on-site, relying on one another's participation and goodwill.

In short, utility reconstruction comprises of multiple smaller projects – with distinctive clients and contractors. In absence of any mediating or central coordination function, however, organizations often align their construction plans too loosely. Resulting insufficient planning causes interface conflicts. This necessitates troubleshooting and improvisation onsite. Concepts from literature can be used to describe these processes as loosely coupled upfront and very tightly coupled onsite. To address this issue, coordination activities are needed to tighten coordination in planning stages. It is, however, unclear how the activities that balance these couplings can be characterized.

This paper is outlined as follows: To better understand how to loose and tightly couplings in utility projects are managed, the next paragraph explores the activities and behavior of 'utility coordinators'. These 'utility coordinators' are mobilized by utility owners to facilitate collaborative design, planning and execution processes in collaborative reconstruction works. In the research method, we then discuss how we conducted ethnographic interviews with seven coordinators, focusing on their behavior and goals. Outcomes from our qualitative analysis then show that coordination activities differ along dimensions level of involvement and moment of involvement. The paper ends with a discussion and conclusion.

2 THEORETICAL POINTS OF DEPARTURE

The construction industry can be conceptualized as a system of events that are loosely coupled (Dubois and Gadde 2002). Within this system, couplings describe the responsiveness between events. In a loose coupling, mutual relations between events are weak, slow, or infrequent. Loose couplings occur between, for example, individuals, organizations, organizational environments, actions and activities (Weick 1979). These weak couplings allow events to preserve their unique character and create flexibility.

Furthermore, construction industry provides products and systems that are tightly related, i.e. have tight physical couplings. Since these systems have unique and location-centric characteristics and uncertainties, they also need to be coordinated in a tight way. In addition, construction projects often involve a variety of specific trades, contractors and subcontractors (Eccles 1981). These organizations have sequential and reciprocal dependencies (Thompson 1991) that also require tight couplings on the construction project level (Dubois and Gadde 2002). To enhance innovation in construction firms, couplings are also needed between successive construction projects (Dorée and Holmen 2004).

When tight couplings are dealt with in a loose way, however, coordination can become inefficient and erroneous. Similar is shown by Sherman and Keller (2011). They argue that selection of an inappropriate integration mode (i.e. selection of organization structures and means of information processing) decreases coordination performance. One problem in utilities reconstruction is, however that tightly coupled coordination during planning stages is hard to establish. We provide two reasons for this: First, stakeholders may not perceive project-level couplings to be tight. This might be because utility reconstruction works form a constellation of projects comprising of multiple clients and contractors. In this constellation, clients and contractors are not equally committed to streamline project delivery plans. They may even intentionally loosen processes by avoiding making early stage process commitments. This occurs, for example, when clients have different interests with regard to deadlines and use of construction methods. Second, tight integration of project schedules and designs cannot be forced through classical hierarchical coordination. As a result, all clients and contractors individually prepare construction plans. Since they can limitedly influence one another’s work planning processes this often results in a loose, slow planning process.

So, instead of having tight couplings, project planning stages seem to consist of loosely related construction plans and stakeholders. Since limited coordination takes place upfront, coordination issues are postponed and resolved in execution stages. This increases coordination pressure on the jobsite managers and work crew. We conceptualize this situation as loosely coupled upfront and very tightly
coupled onsite. We argue that the couplings could be better balanced to obtain a more desired situation. To this end, early planning stage couplings need to be tightened, for example, by increasing stakeholders’ early stage involvement and by mobilizing a central coordination mechanism (Table 1).

Table 1: overview of existing couplings; a more balanced situation of couplings, and their consequences for planning and execution of utility reconstruction works.

<table>
<thead>
<tr>
<th></th>
<th>Existing situation</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning stage couplings</td>
<td>Loose</td>
<td>Limited alignment of construction plans, coordination issues postponed to construction site</td>
</tr>
<tr>
<td></td>
<td>Tight</td>
<td>Early stage alignment of construction schedules and designs. Interfaces analyzed and potential conflicts anticipated</td>
</tr>
<tr>
<td>Execution stage couplings</td>
<td>Very tight</td>
<td>Large focus on troubleshooting and improvisation. Tight deadlines, little buffer</td>
</tr>
<tr>
<td></td>
<td>Tight</td>
<td>More efficient coordination, increased flexibility onsite, less pressure on construction processes (\rightarrow) overruns less likely</td>
</tr>
</tbody>
</table>

To balance the couplings toward tighter planning stage integration and looser onsite couplings, liaison devices can be used (Mintzberg 1979). The liaison manager, for example, bridges the processes and needs of various clients and contractors. In the utility sector, this important bridging function is executed by a utility coordinator. In the paragraphs below, we explain how we empirically derived dimensions that enable a conceptual description utility coordination. This resulted in two dimensions: level of involvement and moment of involvement.

3 RESEARCH METHOD

To analyze the coordination activities that attempt to tighten loosely coupled planning practices, we conducted ethnographic interviews (Spradley 1979) with utility coordinators. This interview method allows respondents to obtain details and specific about the routines and work practices of respondents. To first identify respondents for our interviews, we searched for representative coordinators that, through years of experience, built up their own work practice to effectively address coordination issues. To this end, we asked service providers and authorities which utility coordinators in their network perform their tasks well. This resulted in a list of seven professionals whose job description relates to coordination of utilities. Their experience varied between two and more than ten years.

As a next step, we conducted the interviews. Two identified coordinators collaborated as a team and were therefore interviewed together; the other five were interviewed separately. The questions in the ethnographic interviews explored the actions, behavior and attitude of the coordinators. We asked the respondents, for example, to describe their common practice, and to elaborate how they deal with unforeseen process disruptions. We collected this data by tape-recording the interviews. We subsequently transcribed the interviews and qualitatively analyzed this data. First, instances of respondents’ actions, behavior and attitudes were identified and labeled. Then, we clustered similar codes and created an overview of stakeholders and their correlating actions, behavior and attitudes. The resulting overview allowed us to identify differences and similarities between work practices.
4 FINDINGS

This paragraph elaborates the identified coordination activities. Subsequently, we inductively derive a categorization scheme to conceptually distinguish these activities.

From the coordination activities we identified, Table 2 (page 5) summarizes fourteen activities that co-occur in work practices of multiple respondents. Surprisingly, though only three activities were executed by more than three utility coordinators, these are: pursuing utility owners to timely request/issue permits and provide work documentation; being aware of all current plans and decisions, and identifying interfaces between various disciplines. The table shows that most other activities were executed only by two respondents. We provide a few examples of identified coordination activities below (all translated from Dutch).

One respondent motivated his actions and behavior in the quote below. Here he argued that he wanted to play a key role in the reconstruction process. It fits the coordination activity 2 ('being aware of all current plans and decisions') from Table 2:

"I find it important to be mobilized by all involved stakeholders. I want to be recognizable. I want to be sure that people know that they can reach me in case they have questions. And I want to be able to answer these questions. In fact, I am a key figure in the whole process."

An example from another respondent relates to the third coordination activity, ‘identifying interfaces between various disciplines’:

"[we] start with the analysis, which should result in an object-code matrix, which is an overview of all utilities within the project boundaries…and, eventually, we identify conflicts between the design and these utilities. We visualize and code these conflicts on a large map. Then you can see, for example … [that there are] low voltage cables, and telecommunication cables. These are object code X at interface 2"

Furthermore, regarding the coordination activity 4 in Table 2, ‘visiting and monitoring on-site work’, another respondent argued:

"Well, I always inspect the construction site at the outset of the project. Just as soon as I get an assignment, I will go there to get a grip of how the street, neighborhood or intersection will look like. Because, when one is in a meeting, you need to know where the trees or culverts are."

Our last quote shows a more exceptional coordination action, number 11 in Table 2: ‘verifying accuracy and completeness of utility location information’

"First, make a good analysis of existing utilities. This creates the basis. Make sure the information and figures are correct. And, as soon as you have any doubt about the location of utilities, check whether the information is correct. This means that one might also need to do a field survey to clarify information".
Table 2: identified co-occurring coordination activities of respondents, the moment in which they are executed; the level of involvement characterizing the activity, and the amount of respondents employing the activity.

<table>
<thead>
<tr>
<th>Activity in work practices of respondents</th>
<th>Moment of Involvmt.</th>
<th>Level of Involvmt.</th>
<th>Nr. of respondents employing the activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pursuing utility owners to timely request/issue permits and provides work documentation (designs, contracts etc.)</td>
<td>Planning</td>
<td>Pro-active</td>
<td>5</td>
</tr>
<tr>
<td>Being aware of all current plans and decisions</td>
<td>Planning</td>
<td>Reactive</td>
<td>4</td>
</tr>
<tr>
<td>Identifying interfaces between various disciplines</td>
<td>Planning</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Visiting and monitoring on-site construction work</td>
<td>Execution</td>
<td>Reactive</td>
<td>3</td>
</tr>
<tr>
<td>Initiating interdisciplinary meetings with utility owners and contractors</td>
<td>Execution</td>
<td>Pro-active</td>
<td>3</td>
</tr>
<tr>
<td>Writing minutes</td>
<td>-</td>
<td>Reactive</td>
<td>3</td>
</tr>
<tr>
<td>Inspecting construction site and utility trench prior to start of the project</td>
<td>Execution</td>
<td>Reactive</td>
<td>3</td>
</tr>
<tr>
<td>Ensuring constructability of construction plans and checking whether plans are followed</td>
<td>Execution</td>
<td>Reactive</td>
<td>3</td>
</tr>
<tr>
<td>Using 'lessons-learnt' from previous projects in existing projects</td>
<td>Planning</td>
<td>Pro-active</td>
<td>3</td>
</tr>
<tr>
<td>Exchanging information about project progress</td>
<td>Execution</td>
<td>Reactive</td>
<td>3</td>
</tr>
<tr>
<td>Verifying accuracy and completeness of utility location information</td>
<td>Planning</td>
<td>Pro-active</td>
<td>2</td>
</tr>
<tr>
<td>Checking whether contractors have a feasible construction schedule</td>
<td>Execution</td>
<td>Pro-active</td>
<td>2</td>
</tr>
<tr>
<td>Creates an overview and distributes contact details of stakeholder involved</td>
<td>Execution</td>
<td>Reactive</td>
<td>2</td>
</tr>
</tbody>
</table>

Further, we categorized the quotes to inductively derive two distinguishing dimensions for coordination in loosely coupled systems: First, one can characterize coordination work practice based on the coordinator's moment of involvement during a reconstruction project's life cycle stage. It seems, for example, that some coordinators are involved during early design and planning stages, while other coordinators participate more actively once construction activities started. Second, the level of involvement also varies between various work practices. Our analysis, for example, shows that some coordinators take a pro-active and leading role. They, for example, shape processes and procedures, initiate meetings and take initiatives to aligning parts of the reconstruction plan. Alternatively, other coordinators are more reactive and only interfere with reconstruction processes once holdups or stagnation occurs.

Figure 1 uses our proposed categorization to characterize the coordination activities of our respondents. This shows that there are essentially two approaches to coordinate loosely coupled utility projects: The first one is characterized by pro-active involvement in planning stages. Here, coordination actions focus on shaping design and scheduling processes and actively solving coordination issues. Second, coordination activities can also be more reactive during execution stage. Then, activities mostly involve information processing and follow only agreed formal procedures. It is unclear whether the coordinators deliberately choose to employ one of the two coordination approaches. We suspect that these decisions depend on the coordinator’s own coordination style and by procedures that the coordinator’s organizations prescribe.
5 DISCUSSION

Utility reconstruction processes are loosely coupled upfront, and very tight on-site. This study identified fourteen activities that are employed to balance the tightness of these two relations. With this, we provide first insight in activities used by coordinators in the domain of utilities reconstruction. We show how liaison roles (Mintzbeg 1979) are mobilized in practice. In the interviews, we found that only three activities were mentioned by multiple utility coordinators, these are: pursuing utility owners to timely request/issue permits and provide work documentation; being aware of all current plans and decisions, and identifying interfaces between various disciplines.

Second, closer investigation of the activities shows that the dimensions moment of involvement and level of involvement characterize the nature of the various coordination functions. The introduced dimensions show which concepts can be used to manage loosely coupled systems. More specifically, two concepts can be distinguished: pro-active involvement from planning stages onward and reactive involvement from execution stage onward. A logical explanation for these two coordination approaches might be that a pro-active involvement in early project stages tightens planning stage couplings. This enhances stakeholders’ commitment and supports their collaborative efforts to solve coordination issues. Instead, later involvement during execution stages does not allow coordinators to obtain these benefits any more. Therefore, onsite couplings are likely to be tightened to compensate for loose coordination upfront. Consequently, coordination actions are more reactive, focus on information exchange and contribute marginally to early-stage stakeholder alignment.

For future research, we suggest to expand the sample of our research to obtain more empirical data on the characteristics of coordination practice. Further, findings suggest that the coordination practices are used in different contextual situations. Hence, we propose future research to explore our differentiated
coordination practices more closely. To this end, one could identify environmental and contextual factors that shape coordination practices (e.g. as in Cynefin 2000, Burns & Stalker 1961).

6 CONCLUSION

This study shows that utility reconstruction processes can be characterized as loosely coupled upfront, and very tightly coupled on-site. We explain how the fragmentation of the utility sector created loose couplings in reconstruction planning, while planning ideally demands tighter couplings. This results in coordination issues on-site: re-planning, improvisation and overruns. To characterize how coordination in this loose-and-tightly coupled utility system takes place, we investigated the role of liaison managers that guide design and scheduling processes of utility projects. To this end, we identified seven professional utility coordinators. We conducted ethnographic interviews to explore the activities, behavior and goals constituting their work practice. Qualitative analysis shows that coordination activities can be characterized based on two dimensions: moment of involvement and level of involvement. This subsequently allows distinguishing two dominant coordination approaches: pro-active early stage involvement and reactive involvement during execution stages. We propose to conduct future research on how contextual factors drive the use of these two approaches. Finally, findings help practitioners to reconsider and categorize their own practices, and stimulates them to explore how new techniques, tools or methods help to achieve coordination practices.

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References


A REVIEW OF THE CURRENT KNOWLEDGE AND PRACTICE RELATED TO PROJECT PROGRESS AND PERFORMANCE ASSESSMENT

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Abstract: Assessment of true project progress and performance is of critical importance in the successful delivery of construction projects. Major challenges related to measuring project progress and performance are the lack of consistent, reliable, and objective metrics and indicators and the lack of appropriate interpretation of these data for establishing suitable corrective action plans. The objective of this paper is to provide a review of existing applied knowledge and practices pertaining to methods, metrics and indicators for progress measurement, performance assessment and forecasting, as well as performance influencing factors, evaluating the shortcomings of the current approaches, and providing recommendations for improvement. The findings of this paper are primarily based on a comprehensive literature review and limited discussions with industry experts in the following areas: (1) methods and metrics used for progress measurement, (2) metrics and indicators used for performance assessment and forecasting, and (3) other metrics that can influence project progress and performance (e.g., risk, safety, and quality). Several industry and academic publications are reviewed including the reports from the Construction Industry Institute (CII), guidelines developed by professional organizations (e.g. Project Management Institute, Association for the Advancement of Cost Engineering International), and scholarly publications. Industry experts serving on the CII research team (RT-322) also provide their insights. Based on the extensive review of the relevant literature, this paper identifies limitations of various measures, metrics and indicators across different project control levels. A framework depicting the current project control process is provided along with a gap analysis related to the problems associated with this approach.

1 INTRODUCTION

Performance inefficiency on construction projects has been adversely affecting the industry. Only 1 in every 20 projects is able to meet both its authorized cost and schedule within an acceptable margin (CII, 2012). Besides, Construction Industry Institute (CII) member industrial-sector EPC contractors are not able to generate any profit in 3 out of 5 projects (CII, 2014). One of the major reasons for the low efficiency in construction project performance is the incapability of the existing methods in providing a "true" measure of project progress and performance.

A review on the existing methods reveals that there is not a systematic, consistent and efficient approach to identifying and interpreting progress and performance assessment metrics in the construction industry.
This results in the true performance of construction projects being potentially misrepresented and causes misunderstandings since the true project progress and performance is not known with certainty. Lack of an integrated approach and standards for assessment of progress and performance prevents not only evaluating the quality of metrics and indicators, but also effective interpretation as a basis for improvement. Absence of objectivity in progress measurement and performance assessment misleads perception regarding the true status of the project.

In a field with a large number of studies and established methods and approaches, a systemic review and synthesis enables gap analysis that inform current and future research. Hence, the first step towards improving progress and performance assessment is to analyze the gaps and limitations in the existing methods and metrics. Despite a vast body of literature in the area of project progress and performance assessment, there are limited studies that provide systemic review and gap analysis related to the existing metrics and methods. To this end, this review paper addresses the following questions: (1) what are the components of progress and performance assessment, (2) what methods and metrics are used for each component, and finally (3) what are the strengths and limitations of the existing methods and metrics for a robust assessment. Section 2 explains the methodology of this literature review study. Section 3 introduces a framework to classify project control functions at a single project level. Section 4 provides an overview of existing literature pertaining to the methods, metrics and indicators used for progress measurement, performance assessment, performance influencing factors and performance forecasting. Section 5 discusses gaps in the existing body of knowledge and practice, as well as identifying areas for improvement. Finally Section 6 provides the recommendations and concludes the paper with highlighting the needed research tasks to address the identified gaps.

2 METHODOLOGY

The research methodology included three steps: (1) identifying relevant work; (2) collecting and summarizing information; and (3) conducting gap analysis. Two sources of information were used: academic and professional literature, and expert opinion from industry professionals with extensive experience in project management and project control.

(1) Identifying relevant work: Through a comprehensive review of literature, 116 relevant documents were identified and reviewed: 64 professional organization reports [e.g., Construction Industry Institute, Project Management Institute (PMI) and Association for the Advancement of Cost Engineering (AACE)], 41 scholarly articles, and 11 government agency reports (e.g., reports from the Department of Energy and Department of Transportation). The identification and selection of documents started with utilizing specific keywords (e.g., performance assessment, KPI, and project control) and continued through snowball method. The search for relevant work stopped when additional searches did not lead to identification of new information.

(2) Collecting and summarizing information: The articles and reports identified in the previous step were reviewed, analyzed and summarized to satisfy the research objectives. The collected information was used to identify the components of a framework for project controls and the methods and metrics associated with each component. The project control framework was then refined based on the feedback from industry professionals (i.e., individuals from eight owner and eight contractor companies, with over 100 years of combined experience) involved with this study through the channels of CII were essential in advancing the framework. Based on the knowledge and experience of industry representatives, the framework was iteratively improved to illustrate the project controls cycle as it occurs in projects.

(3) Conducting gap analysis: The framework created in the previous step was used to identify the existing gaps in the body of knowledge related to metrics and methods for improving project control and management to provide “true” insight about project progress and performance. The identified gaps were further analyzed and refined through multiple rounds of panel discussions with the industry professional participating in this study. The information collected from the panel discussions were analyzed through mind-mapping techniques to systemically evaluate the existing gaps.
3 A FRAMEWORK FOR PROJECT CONTROLS

Core components of a project control structure (i.e., progress measurement, performance assessment, performance influencing factor metrics and performance forecasting) take place in a cyclical nature, which is repeated for every new reporting period, until the project is completed. Figure 1 illustrates the control cycle of a project for a single reporting period. This framework depicts the project control cycle in current practice, obtained through extensive literature search and insights from industry experts serving on Research Team 322 of CII.

![Control Cycle Diagram](image)

Figure 1: Current practice framework for project controls

Although the terms “operational”, “tactical” and “strategic” are frequently used to define different control levels of construction projects, there is no consensus among construction industry stakeholders over what these terms represent in a traditional project controls setting. PMI recognizes operational, tactical and strategic project levels as organizational layers of a portfolio management structure and offers guidelines to identify the work performance structure through information and data flow between project control levels (PMI, 2013). AACE International approaches “strategic” and “tactical” levels as different layers of the investment decision making process, whereas the term “operational” defines ongoing endeavors or activities (AACE International, 2012). However, these approaches lack a single project emphasis. Concentration on project controls structure at a single project level would help identify areas of improvement.

Figure 1 matches project levels with project control functions from a single project perspective. Operational, tactical and strategic project levels are characterized mainly as they relate to metrics and indicators for progress measurement, performance assessment, performance influencing factors and performance forecasting, of a single project. The operational level basically serves the purpose of understanding the current state of the project. It mainly contains measurement of progress in terms of cost and schedule. Some observations and inspections for performance influencing factors also take place at operational level, such as measuring safety and quality aspects of the project. In the tactical level, data from progress measurement metrics and indicators obtained in the operational level are compared against the authorized baseline values in order to identify cost, schedule and efficiency variances and to understand the true current state. Also at the tactical level, performance influencing factor metrics are evaluated, as they relate to interpreting reasons behind why the project is at its current state. Finally, at the strategic level, the future state is predicted based on the current project trajectory.
4 METHODS, METRICS AND INDICATORS RELATED TO PROJECT PROGRESS AND PERFORMANCE

4.1 Progress Measurement

The successful execution of a project hinges on various factors, but one fundamental question that should be answered as the first step in the control process is: What has been accomplished so far? Progress measurement addresses this question at the operational level and serves as the basis for assessing, forecasting, and improving project performance. In this paper, progress measurement is defined as the measurement of outcomes and throughput of a project at a certain point in time. It provides the fundamental information related to “where are we at?”

There are several metrics used to measure construction project progress depending on the activities and work items. Although the names and definitions of these metrics could vary for different projects, they belong to one of the major progress measurement methods. The major methods for progress measurement include: units completed, incremental milestone, weighted or equivalent units completed, resource expenditure, and judgment (supervisor opinion) (CII, 1987; AACE International, 2012). Table 1 provides the definitions, applicable conditions, and implementation examples for each method.

<table>
<thead>
<tr>
<th>Method</th>
<th>Definition</th>
<th>Application Conditions</th>
<th>Implementation Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units completed</td>
<td>quantity surveys or physical measurement of work items</td>
<td>homogenous units of work</td>
<td>linear-feet of wire pulling, cubic-yard of concrete placed</td>
</tr>
<tr>
<td>Incremental milestone</td>
<td>a percent completion be credited for completion of key incremental tasks</td>
<td>one deliverable with multiple activities performed in sequence; output for each subtask cannot be easily measured</td>
<td>Equipment installation, alignment and testing (e.g., 50, 70, and 100 percent of completion, respectively)</td>
</tr>
<tr>
<td>Weighted or equivalent units completed</td>
<td>a hybrid of units completed and incremental milestones</td>
<td>a major effort involving a long period of time; composed of two or more overlapping subtasks, each with a different unit of work measurement</td>
<td>Subtasks in structural steel erection with different units of measure are converted to equivalent tons and then the weighted percent complete is calculated</td>
</tr>
<tr>
<td>Resource expenditure</td>
<td>the percent of the total planned or forecast duration hours, or cost spent for the control account</td>
<td>no discrete deliverables or milestones in the work package; a relatively constant level of effort</td>
<td>Measurement for tasks such as project management, quality assurance, contract administration, and project controls</td>
</tr>
<tr>
<td>Judgment</td>
<td>the person responsible for the work package estimates the percent complete based on his or her informed judgment</td>
<td>only for relatively minor tasks where development of a more discrete method cannot be used</td>
<td>Measurement for tasks such as painting, dewatering, constructing support facilities, installing architectural trim, and landscaping</td>
</tr>
</tbody>
</table>

Some of these methods are identified with different names in practice. For example, resource expenditure is occasionally labelled as Level of Effort (LOE) or cost ratio. Judgment is also recognized as supervisor opinion. Variations of these five basic progress measurement methods also exist. For example, start/finish is a variation to the incremental milestone method in which the only milestones are starting and finishing. Activities in a construction project such as flushing and cleaning, testing and major rigging
operations do not have readily definable intermediate milestones. Workers know when the work starts and when it is finished, but not the percentage completion in between. For this type of activities, start/finish is the most appropriate progress measurement method.

Each progress measurement method has its own strengths and weaknesses. For example, the units completed method provides the most detailed and accurate progress information. However, it can only be applicable to homogenous units of work. Also, it might take a significant amount of time for data collection. On the other hand, the judgment method takes the least amount of time and effort. However, this subjective approach is highly dependent on the experience of the supervisor, and could be inaccurate and misleading. In general, there is a trade-off relationship between accuracy/consistency and efficiency in progress measurement (Chin et al., 2004). Table 2 summarizes strengths and weaknesses of these progress measurement methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units completed</td>
<td>• Most detailed and accurate</td>
<td>• Time for data collection might be lengthy, especially if not applied correctly</td>
</tr>
<tr>
<td></td>
<td>• Does not rely on subjective opinions or evaluations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Claimed output can be readily verified</td>
<td></td>
</tr>
<tr>
<td>Incremental milestone</td>
<td>• Easy to use</td>
<td>• Long periods may elapse before an intermediate milestone is reached</td>
</tr>
<tr>
<td></td>
<td>• Simple to understand</td>
<td></td>
</tr>
<tr>
<td>Weighted or equivalent</td>
<td>• Detailed and objective</td>
<td>• May be inaccurate, especially if there are few items and the activity durations are lengthy</td>
</tr>
<tr>
<td>units completed</td>
<td>• Provides ability to compare and summarize several different subtasks and activity groups</td>
<td>• Weighing or equivalency conversions and calculations might be complex, as well as requiring attention</td>
</tr>
<tr>
<td>Resource expenditure</td>
<td>• Greater detail and objectivity than simply estimating how much work was done</td>
<td>• Requires much more effort than simply estimating the percent complete</td>
</tr>
<tr>
<td></td>
<td>• Less expensive than counting or measuring the units completed of subtasks</td>
<td></td>
</tr>
<tr>
<td>Judgment</td>
<td>• Simple</td>
<td>• Can be very inaccurate and misleading</td>
</tr>
<tr>
<td></td>
<td>• Inexpensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Quick</td>
<td></td>
</tr>
</tbody>
</table>

Since one complete project usually includes different types of tasks, multiple progress measurement methods are often used on a project. One limitation in the existing body of knowledge is the lack of an integrated framework which facilitates applying various progress measurement methods systematically in the project. The implementation of different progress measurement methods are usually based on the project manager's experience instead of objective criteria. The subjectivity may cause problems in providing true measurement of project progress in an efficient and effective way. For example, using the incremental milestone method for measuring the progress of landscaping as a minor component of the project instead of judgment method could improve the accuracy, however, it requires more time and effort to develop the criteria and collect the data.
4.2 Performance Assessment

Progress measurement is essential for successful project execution, although it is not adequate by itself for effective project management and control. It is of vital importance to compare measured progress against the baseline in order to evaluate the current performance of the project. This paper identifies performance assessment as an evaluation of the existing outcomes and results of the project cost, schedule and efficiency at a certain point in the project cycle. It answers the question of “Where should we be at?” There are several metrics and indicators used to assess performance of construction projects based on different approaches. The most commonly used performance assessment method in the construction industry is Earned Value Management (EVM). Due to certain shortcomings of EVM, other methods such as Earned Schedule Method (ESM) and Earned Duration Management (EDM), are offered as viable alternatives. Table 3 explains commonly used methods and their related metrics.

Table 3: Definitions, related metrics and calculations of main performance assessment methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Related Metrics</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earned Value Management (EVM)</td>
<td>Cost Variance (CV)</td>
<td>CV = EV – AC</td>
</tr>
<tr>
<td></td>
<td>Cost Performance Index (CPI)</td>
<td>CPI = EV / AC</td>
</tr>
<tr>
<td></td>
<td>Schedule Variance (SV)</td>
<td>SV = EV – PV</td>
</tr>
<tr>
<td></td>
<td>Schedule Performance Index (SPI)</td>
<td>SPI = EV / PV</td>
</tr>
<tr>
<td>Earned Schedule Management (ESM)</td>
<td>Earned Schedule (ES) *</td>
<td>ES(t) = t + \frac{EV−PV(t)}{PV(t+1)−PV(t)}</td>
</tr>
<tr>
<td></td>
<td>Earned Schedule Performance Index (SPI (t))</td>
<td>SPI(t) = \frac{ES(t)}{Actual Duration}</td>
</tr>
<tr>
<td>Earned Duration Management (EDM)</td>
<td>Earned Duration (ED) **</td>
<td>EDi = BPDi × APIi</td>
</tr>
<tr>
<td></td>
<td>Earned Duration Index (EDIi) ***</td>
<td>EDi = \frac{EDi}{PDi}</td>
</tr>
<tr>
<td>Critical Chain Project Management (CCPM)</td>
<td>Critical Chain Completed (CCC)</td>
<td>number of days of critical chain work completed</td>
</tr>
<tr>
<td></td>
<td>Buffer Consumption Rate (BCR)</td>
<td>total number of days on critical chain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>percentage of project buffer consumed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>percentage of critical chain completed</td>
</tr>
</tbody>
</table>

* “t” stands for the time status that ES is calculated for, whereas “t+1” is for the following time period.

** BPDi stands for Baseline Planned Duration of scheduled activity I, whereas APIi is the Activity Progress Index, measured schedule progress of an activity through whichever method is preferred in the project.

*** PDi is for Planned Duration of an activity i

EVM methodology uses metrics to answer questions such as: what are the actual and planned costs of a project at a given point in time in relation to its earned value (Vanhoucke 2009). At the operational level, EVM captures three major values namely Actual Cost (AC), Planned Value (PV) and Earned Value (EV) (Fleming and Koppelman, 2000). These values represent the measured progress in terms of cost. One significant drawback of EVM is its inability to capture the schedule performance, especially over the last third of the project (Lipke 2009). In order to improve the schedule assessment ability of EVM, ESM was proposed (Lipke, 2003). ESM relies on the same operational-level performance indicators as EVM (i.e. PV, AC and EV); however it uses a new set of time-based performance assessment metrics to identify Earned Schedule (ES) as the time at which the amount of earned value should have been accomplished. Although ESM solves some limitations of time management in EVM, it still uses cost as a proxy to measure schedule performance of a project. Therefore, when a disparity exists between time and cost
profiles of a project, ESM fails to capture the distinctive schedule behavior of the project. To address this limitation of EVM and ESM, Earned Duration Management (EDM) was developed, which decouples schedule and cost performance measures. EDM also identifies a number of indices to measure progress and performance of schedule and cost (Khamooshi and Golafshani 2013).

EVM, ESM and EDM treat delays on critical and non-critical paths equivalently. Also the correlations between time and cost of different activities are not taken into consideration in any of these methods. In terms of performance forecasting, the adaptive behaviors of the project managers is not considered. And finally the assessment of the project in all these methods is limited to time and cost and other performance measures such as quality of the final products are not part of the analysis (Hall 2012; Hazır 2014). Critical Chain Project Management (CCPM), an emerging approach for performance assessment, focuses on resource utilization and minimizing idle capacity (Goldratt, 1997; Leach, 2000). However, issues related to the stability of the critical chain and the network structure, as well as resource efficiencies and multitasking are considered problematic aspects of CCPM.

For different project types and phases, various performance assessment metrics and indicators should be utilized, sometimes in combination with one another. However, one general weakness of current performance assessment methodologies is lack of consistency and implementation guidelines for metrics throughout the construction industry, which eventually diminishes reliability of metrics and indicators.

### 4.3 Performance Influencing Factor Metrics

Performance influencing factor metrics are characteristics of the project or project organizations that influence the performance outcomes of the project (e.g., scope change, risk management, and resource management by answering the question “Why are we here?” Therefore, these metrics explain reasons behind the current state of the project by allowing managers to (1) know where to look if a problem related to cost, schedule or efficiency performance occurs, and (2) interpret performance assessment and forecasting more accurately and develop proactive response plans and corrective actions.

Lack of unified guidelines to tackle problems as they relate to project progress and performance through influencing factor metrics not only leads to inconsistent and unreliable project information, but also makes it difficult to objectively compare one project to another. One exception to this problem is related to safety metrics. Almost every project uses nearly the same metrics and indicators for safety: OSHA Recordable Incident Rate (ORIR), Days Away, Restrictions and Transfers (DART) rate, number of near-miss incidents, people based safety observation, new hire count-vs-recordable injury rate, Total recordable incident rate (TRIR), Lost time incident rate (LTIR) and Total severity rate (TSR) (NRC, 2005; COAA, 2007). In addition to being related to life and death situations, safety is also highly regulated through guidelines. This highlights the importance and necessity of having established guidelines for using other common performance influencing factor metrics in the construction industry.

### 4.4 Performance Forecasting

Performance forecasting uses current state performance information to predict the future outcomes and results. It basically answers the question of “Where will we be at?” Table 4 lists performance forecasting metrics for cost and schedule estimations.

Earned Value Management (EVM) offers several useful metrics to forecast what the expected cost values are for the remainder of the project (Vanhoucke, 2009). These metrics predict the final cost of the project based on the actual performance at the time of assessment and the planned cost of the remaining work. However, these projections are highly dependent on consistency of performance assessment metrics used and management’s opinion on some forecasted elements. (Fleming and Koppelman, 2000). The EVM methodology consists of metrics for schedule performance forecasting as well, similar to the cost metrics described above. However, similar problems can be observed with schedule performance forecasting metrics of EVM. At this point, ESM offers alternative schedule forecasting metrics (Lipke 2009). The same pattern with performance assessment metrics follows here; even though ESM metrics generate better results for schedule, they are yet to offer a robust forecasting alternative due to using cost as a proxy to estimate schedule of a project.
Table 4: Forecasting metrics, definitions and related methods
(Fleming and Koppelman, 2000; Vanhoucke, 2009; Lipke, 2009)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
<th>Calculation</th>
<th>Cost/Schedule</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate at Completion (EAC)</td>
<td>manager’s projection of total cost of the project at the end of the project</td>
<td>EAC = BAC/CPI</td>
<td>Cost</td>
<td>EVM</td>
</tr>
<tr>
<td>Estimate to Completion (ETC)</td>
<td>estimated cost required to complete the remainder of the project</td>
<td>ETC = EAC - AC</td>
<td>Cost</td>
<td>EVM</td>
</tr>
<tr>
<td>Variance at Completion (VAC)</td>
<td>variance on the total budget at the end of the project</td>
<td>VAC = BAC - EAC</td>
<td>Cost</td>
<td>EVM</td>
</tr>
<tr>
<td>To Complete Performance Index (TCPI)</td>
<td>future required cost efficiency needed to achieve a target BAC (budget at complete) or EAC (estimate at complete)</td>
<td>TCPI(BAC) = (BAC - EV) / (BAC - AC) or TCPI(EAC) = (BAC - EV) / (EAC - AC)</td>
<td>Cost</td>
<td>EVM</td>
</tr>
<tr>
<td>Independent Estimate at Completion (IEAC)</td>
<td>a metric to project total cost using the performance to date to project overall performance.</td>
<td>IEAC = AC + (BAC - EV) / CPI</td>
<td>Cost</td>
<td>EVM</td>
</tr>
<tr>
<td>Estimate at Completion (time) [EAC(t)]</td>
<td>manager’s projection of total duration of the project at the end of the project</td>
<td>EAC(t) = PD / SPI(t)</td>
<td>Schedule</td>
<td>ESM</td>
</tr>
<tr>
<td>Estimate to Completion (time) [ETC(t)]</td>
<td>estimated time required to complete the remainder of the project</td>
<td>ETC(t) = EAC(t) - AT</td>
<td>Schedule</td>
<td>ESM</td>
</tr>
<tr>
<td>Variance at Completion (time) [VAC(t)]</td>
<td>predicted variance on the total schedule at the end of the project</td>
<td>VAC = PD - EAC(t)</td>
<td>Schedule</td>
<td>ESM</td>
</tr>
<tr>
<td>To Complete Schedule Performance Index (TSPI)</td>
<td>required time efficiency needed to achieve a target PD or EAC(t). (The TSPI provides a projection of the anticipated performance required to achieve either the PD or the EAC(t))</td>
<td>TSPI(PD) = (PD - ES) / (PD - AT) or TSPI[EAC(t)] = (PD - ES) / (EAC(t) - AT)</td>
<td>Schedule</td>
<td>ESM</td>
</tr>
<tr>
<td>Independent Estimate at Completion (time) [IEAC(t)]</td>
<td>an independent second opinion of the final project duration</td>
<td>IEAC = AT + (PD - ES) / SPI(t)</td>
<td>Schedule</td>
<td>ESM</td>
</tr>
</tbody>
</table>

BAC: Budget at Completion  PD: Planned Duration  AT: Actual Time

5 GAP ANALYSIS AND DISCUSSION

In this study, mind mapping was used to abstract the tacit knowledge of the industry panel regarding two central topics: (1) the problems related to the existing project progress and performance assessment metrics and methods, and (2) the required improvements. In the first step of mind mapping, each individual on the industry panel provided his/her perspective regarding the central topic. The information
was collected and visualized into a preliminary mind map with a tree structure using Free Mind software. In the second step, the preliminary mind map was presented to the industry panel. The panel was asked to cluster the branches in the mind map into categories of problems and required improvements related to the existing metrics and methods. This step was concluded when the panel reached a consensus. Mind map in Figure 2 clearly depicts problematic areas and needed improvement identified through this study.

Review of the current knowledge and practice revealed that there is no consistent set of progress measurement metrics and performance assessment indicators. Due to this lack of consistency, it is difficult to have a true comparison of one project performance to another. Also, there is potential for misrepresentation of progress and performance information, caused by unreliability of metrics and indicators. The existing use of metrics and indicators vary across the industry and depend on the level of the experience of project personnel. There is also limited understanding regarding the importance and effects of performance influencing factor metrics. Hence, there is a need for guidelines identifying what core metrics and key performance indicators (KPIs) should be used consistently on construction projects. Development of such guidelines can help reduce subjectivity in the metrics. Furthermore, in order to improve progress and performance assessment, identification of recommended practices for effective interpretation is necessary. Finally, understanding the significant impacts of performance influencing factor metrics and indicators to progress and performance can provide greater insight for performance improvement and foresight for forecasting project outcomes.

![Figure 2: Mind map for identified problems and improvement areas](image)

6 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this paper was to review common project progress, performance assessment and forecasting methods used in the construction industry. A framework was presented describing the operational, tactical, and strategic levels of project controls. After reviewing the literature and current practices in project controls, it is apparent that construction industry needs certain actions to improve project progress and performance assessment. This paper recommends to: (1) identify core metrics and key indicators, (2) develop guidelines for improving the reliability of metrics and indicators, and (3) establish recommended practices for interpreting metrics and indicators, forecasting outcomes, and responding to variance to plan as they relate to progress and performance assessment.

In order to satisfy the industry needs and fulfill recommended courses of action, CII Research Team 322 (RT-322) is working on a rigorous three-step data collection and validation plan: (1) a web-based survey that uses the findings from the gap analysis presented in this paper to identify core methods, metrics and indicators, (2) case studies to understand the significance of core metrics and how reliability of these metrics can be improved and (3) Delphi method to validate findings using expert opinions.
Problems and suggested improvements identified through this study, can inform future research on applied project controls. Consequentially, real-life applications of these findings have the potential to advance many construction industry practices.

Acknowledgements

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OPTIMIZATION FOR BRIDGE TYPE SELECTION USING ARTIFICIAL NEURAL NETWORKS

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Abstract: Many Researchers have attempted to establish a methodology for the selection of bridge type in a systematic manner. Knowledge based systems (KBS) and other Expert Systems (ES) have been used for this purpose but they have some limitations and restrictions. This paper proposes a methodology to implement a Decision Support System (DSS) in an artificial intelligent environment that aims to suggest a bridge type with its main components at the conceptual design phase, based on the characteristics and performance of existing and similar bridges in order to predict the performance of proposed ones that have been analyzed by decision makers with limited subjectivity. The proposed methodology is divided into three main divisions: 1) this division includes a database that will be structured to store appropriated information besides including models like Point Scale and Quality Function Deployment (QFD) systems that will serve for linguistic conversion to numbers needed for the DSS engine. This division contains as well all the mandatory criteria that have influence on the performance of proposed bridges. 2) this division is the core of the “DSS Engine” where it receives the information from the database that will be implemented in an Artificial Neural Network (ANN) module for training, testing and then predicting the performance of a new case bridge. Afterwards a decision will be made to implement the ANN’s results into a Bridge Information Modeling (BrIM) environment to visualize the suggested design and to predict the potential problems. 3) In this division, a final decision will be made based on the results of the second division. In the proposed DSS, most of the factors are considered as criteria in the database; criteria that have influence on the decision are automatically considered during the analysis process and are introduced in the DSS Engine. The flexibility of the proposed methodology and particularly the database and the method of analysis will make the DSS very helpful in the area of bridge design and management. This will provide bridge engineers with an efficient tool that will minimize the subjectivity in their decisions. A case project will be considered to test the workability and capability of the proposed methodology.

1 INTRODUCTION

Lots of references mentioned that Bridge design is divided into two stages: conceptual & analytical design (Miles & Moore, 1991; Chen Wai-Fah & DuanLian, 2000; Troitsky M.S., 2000). The analytical design stage is very well defined where codes and formulas are widely applied, which is not the case for the conceptual design stage. Lots of studies conducted by engineering and consulting agencies have drawn different opinions that lead to diversity of final decisions (Smith & al, 1994). Based on many factors, designers (decision-makers) will choose the final perception to propose the type of bridge that should be adopted; the decision is based on their own experience and other factors that have remarkable influence on the decision taken. Generally, neither mathematical formulas nor deterministic or stochastic models
are used during the decision making process; just engineering judgments and subjectivities are the core of the final decision. The lack of clarity and the need to be away from the subjectivity issues are the cause of this proposal, which main objective is to propose a methodology that could be a starting point for advanced development toward minimizing shortcomings that influence the decision on bridges during the conceptual design stage.

2 LITERATURE REVIEW

A literature review is conducted in order to highlight the components, characteristics and factors that influence major decisions related to the bridge types and their relevant components.

2.1 Bridge Elements and Components

Tang (2007) has summarized the bridge types, behaviors and forms as follows:

- The anatomy of all structures in the world is a combination of three types of structure elements: Axial, Bending and Curvature; these can be defined as the “ABC” of structure, these elements take one of four basic forms: truss, box, stiffened plate or solid member, and

- Conceptually, he clusters all bridges in the world into four basic bridge types: girder bridges, cable-stayed bridges, arch bridges and suspension bridges.

However, in order to well define such bridge types, it is necessary to recognize the elements and components of every possible bridge. It is important to establish an inventory that will act as a “geometric” database to help decision makers in their selection process. Similar work has been conducted by Thompson and Shepard (2000) in which they proposed an inventory that will be the base for the inspection and maintenance tasks. In their report the bridge components were divided into four main groups: superstructure, substructure, decks and culverts. Those components are important to rate the bridge performance based on their performance and sustainability. Furthermore, the type of materials used in the bridge has its own and special influence. Smith and al., (1994) published the characteristics of some materials and their influence on bridges’ components.

2.2 Influencing Factors and Constraints

Smith et al. (1994) listed many factors that can affect the decision on selecting bridge’s materials. The analytical Hierarchy Process (AHP) has been used to rank the factors that have significant impact on the selection of bridge type. This ranking was based on data collected from over thirteen hundred (1,300) highways and bridges in USA. The collected data focused on non-structural factors that influence the bridge material decision. Out of twenty-three (23) factors, the following have been ranked as the most important ones: past performance, lifespan, maintenance requirement, resistance to natural deterioration, initial cost & life cycle cost. Choi (1993) has grouped the factors that affect the conceptual design of bridges into two sets of constraints: "Hard Constraints - HC" and "Soft Constraints - SC". This proposed methodology will consider only the Aesthetic and the Environmental factors, which influence the final decision of bridge selection.

2.3 Bridge Management System (BMS) and Bridge Information Modeling (BrIM)

The proposed methodology will be implemented within a Bridge Information Modeling environment and will be based on data retrieved from the Bridge Management System. Al-Hajj and Aouad (1999) considered that the design, construction and maintenance of bridges have to be addressed for any holistic productivity study, however the life-cycle cost of the elements should be considered early during the design phase. Abu Dabous (2008) referred to Pontis and Bridgit, which are two applications widely known and used in the USA, while there are other applications used by many agencies to manage the bridge behaviors and to predict its future performance in order to prevent any unexpected situations. Thompson and Shepard (2000) considered the CoRe (Commonly Recognized) elements for bridge inspection as the basic for data collection, performance measurement, resource allocation, and
management decision support. They mentioned that prior to the CoRe elements, bridge managers used data that was based on the National Bridge Inspection Standards (NBIS), which helped them decide on how to address problems related to the limited information available about the four groups of a bridge (Superstructure, Substructure, Deck and Culverts). Nedev and Khan (2011) mentioned that most of the engineers’ decisions are based on past experience and standard solution, which is probably the ideal method. Those engineers claimed that the selection of the different bridge elements and associated materials is not followed in a structural format, and despite of their research and proposed methodology, they revealed some limitations like the number of alternative to be compared, span length, type of bridge, and others. A study conducted by Dekker (2000) showed that engineers in Sweden stated that the biggest obstacle that causes problem is the lack of time. They provided different reasons for that but the final conclusion was that engineers need more time and money in order to create and to produce structures of high performance. As shown in Figure 1 it is obvious that if more time is spent during the conceptual design stage better and more appropriate solutions can be found. Niemeyer (2003) described his methodology in a graphical format where five main keys are identified: 1) need definition, 2) design requirements, 3) key parameter identification, 4) configuration and 5) evaluation. Engstrom (2002) stated that every structure has to meet a wide range of demands out of which six main areas were outlined for buildings in general, which might be also adopted for bridges. 3D modeling has been introduced by many application and tools where their use and benefits have been raised by introducing additional tools and levels of details. As 3D CAD software, Autodesk Revit has been the most known tool; Tekla structures offers a reasonable way of modeling the structural components of concrete bridges, while SolidWorks CAD has been used for terrain model around the bridge.

![Figure 1 - Effect of time spent on conceptual design (Dekker, 2000)](image)

2.4 Existing Methods

Over the time, the construction industry used different methods based on artificial intelligence and human reasoning processes. In recent years, there has been an increased interest among researchers to explore the feasibility of applying artificial intelligence (AI) paradigms in order to improve the efficiency, safety, and environmental-compatibility of transportation systems (Sadek et al., 2003). AI has been used to solve difficult problems that couldn’t be solved by using classical mathematical methods. Quality Function Deployment (QFD), Knowledge-based Systems (KBS), Case-based reasoning (CBR), Expert System (ES), Fuzzy Systems (FS), Artificial Neural Network (ANN), Genetic Algorithm (GA), and other Learning Machine systems (LM) are among the models that have been used while making decisions related to design in the transportation field. The Gradient Descent methods as well as the Regression Analysis
methods are widely used to define some of the functions employed by these models. Otayek et al. (2012 and 2013) considered that researchers have mentioned and introduced these models by highlighting their ability, their functionality and effectiveness, which have been abridged.

3 PROPOSED METHODOLOGY

The proposed methodology is routed on incorporating the minimum necessary factors and restrictions that are needed into any model. Bridge parameters and characteristics are listed in a standard form in order to introduce the bridge identity by these values, which are stored into set of tables that contain the necessary information required to identify the bridge behavior and performance.

3.1 Models and Methods

Problems related to structural design are often unpleasant tasks that need a wide range of experience, good engineering judgment and high level of subjectivity. The Rule-Based Expert System (RBES) approach has the capability to incorporate some of the above-mentioned requirements while other similar approaches are needed to establish some platform for a right decision. Therefore, a Decision Support System (DSS) is proposed in this paper where all the required platform are considered while its development will be based on the following four steps: (a) establishing an accurate library of bridge types and their components, (b) structuring the necessary database that stores appropriate information collected from previous projects, (c) defining the model’s engine that will treat the information and that will provide a convenient solution in the form of output, and (d) using the BrIM concept and tools to provide a 3D visualization of the generated outputs. The most important and expected difficult part of the proposed system is to define and convert some aspects, information and situations into numerical values, such as the soil behavior that an engineer has to evaluate and to consider during his final decision. The performance of a proposed bridge is predicted and evaluated depending on the rate that the following factors will get: Aesthetic, LCC, Environment and public satisfaction/capacity and services. This will be based on existing bridges that have the same conditions as the proposed one. The proposed methodology will generate three different outputs that should be analyzed in order to decide if the values are relevant and acceptable or not. These values are: Total Cost $/m² (TC); Environmental Impact Rate (EIR), which varies from 1 (Friendly to the environment) to 9 (Very aggressive to the environment); and the Aesthetic Impact Rate (AIR), which varies from 1 (considered as very well fitted into its surround) to 9 (Considered as damaging the surround aspect).

3.2 Decision Support System (DSS) Framework

The main components of the DSS include a database module that contains the bridge types with their components (related to their geometric parameters) and the bridges’ parameters that influence their performances (such as the overpass area, soil behavior, bridge capacity, number of lanes, number of spans, total length, etc... ), a DSS engine that includes the input and output parameters, and a BrIM module to visualize and then verify the accuracy and suitability of the selection made by decision makers based on the output values provided by the DSS Engine. Thus, the framework of DSS is shown in Figure 2.

3.3 DATABASE: Components and Included Information

A database is a collection of information that is organized so that it can be easily accessed, managed, and updated. In computing, databases are classified according to their organizational approach. The most prevalent approach is the relational database, a tabular database in which data is defined so that it can be reorganized and accessed in a number of different ways. Thus, the type of information with their characteristics and relationships that will be stored in the database should be well defined. Therefore, Figure 3 describes the information that should be included in a well-structured database that will provide the proper values for the DSS engine. Furthermore, as shown in Figure 3, all criteria are grouped under 5 categories: (1) Administrative Info, (2) Geometric and Structure Info, (3) Restricted Variables, (4) Unrestricted Variables, and (5) Soft Factors.
The linguistic factors will be converted into numerical values by using two methods: the Point Scale method and the Quality Function Deployment (QFD) method. For instance, for the four linguistic bridge types, a 4-points scale is assigned as shown in Figure 4. According to this scale, a value of “1” is assigned to the Girder bridges, a value of “2” to the Arch bridges, a value of “3” to the Suspension bridges, and a value of “4” to the Cable-Stayed bridges. A library of photos is established in order to clarify the point scale assigned to a specific bridge.
3.4 DSS Engine

The main component of the DSS engine is the Artificial Neural Network (ANN) frame, as illustrated in Figure 5, which will retrieve the input data from the database structure and will provide a new data about the proposed Bridge type that will be constructed. The correlation between the number of existing cases to be used and the number of hidden layers, neurons and the activation function are studied, evaluated and defined in order to accurately structure the proposed ANN.

3.5 Bridge Information management (BrIM) Tools

Lots of tools are used to apply the BrIM concept. Some of them focus on the geometric part, which covers the architecture elements, while others focus on the structural parts, which look at the structural elements and their capacity to resist the acting loads, however they are all used by the construction industry in order to control and mitigate the engineer’s tasks. In this proposed methodology, these tools will receive the results from the DSS engine and will transform them into a real world environment. Decision makers (engineers) will verify all the bridge aspects that have already been extracted from the input and output data of the DSS engine, then they will verify and visualize the project’s design via a 3D model; afterwards a decision will be taken concerning the extracted results, which will either be acceptable, or be rejected or modified and in those two cases launching another iteration will be required. For this purpose, different types of software will be used (i.e. Tekla structure/ Bridge CSI for the structure analysis, and Autodesk Civil 3D-CAD and Design and Revit) for verifications and visualizations in a 3D environment.
3.6 Sensitivity Analysis (SA) and Level of Realistic (LR)

As described earlier, the DSS is based on many criteria (category 2, 3 and 4) that affect the results (criteria from category 5). In order to verify the influence of each input criteria on the results, a Sensitivity Analysis (SA) will be performed to understand the relationships between the input and output criteria. Also, the importance of the SA is that it will provide a general idea about the uncertainty in the DSS output that can be apportioned to different sources of uncertainty in its inputs, and accordingly it will identify the DSS inputs that cause significant uncertainty in the output in order to reduce its level.

On the other hand, the level of realistic (LR) will be evaluated for every output value provided by the DSS engine. This aims at quantifying how much the results are realistic. This procedure will be based on a comparative process between the ratio of the estimated over the actual values of a specified criteria (from category 5) of an existing case with the ratio of the estimated value over the value given by the DSS engine for that specific criteria. By this comparison, designers will have a tool to judge how much the output values have a sense.

4 CASE PROJECT

To validate the proposed methodology a real case project is used to test its workability and dependency. In the actual case project, data from 15 existing bridges located in different regions of Lebanon will be considered into the validation.

4.1 Database frame works and contents

The collected information related to the selected existing bridges is stored into tables 1 through 3 based on the appropriate factors for every criteria. Table 1 stores the parameters and factors to be considered based on the information related to the considered bridges. Table 2 contains the values to be considered for the factors that need Linguistic/Numerical conversion based on a Point-Scale of 1 to 9. Table 3 covers the values of the assigned parameters, which are arranged and evaluated especially those that need a linguistic/Numerical Conversion. The last column of Table 4 (Categories 1 through 4) covers the values related to the new bridge that will be entered into the DSS engine and then the output values of the criteria of category 5 is retrieved for analysis and accordingly a decision could be made to be implemented into the BrIM tools. The parameters Di, BTi and Li are defined and stored within separate tables by providing additional information concerning the project description, bridge name and its location respectively. These parameters (category 1) are considered to evaluate (if necessary) some values of the factors that are included into categories 2, 3, 4 and 5. For instance, the year of construction and location are considered to influence the Total Cost that needs to be adjusted.

4.2 Running the DSS Engine

Based on the data shown in tables 1, 2, and 3, the Neural network paradigm will run; based on the input data shown in Table 4 for categories 1, 2, 3 and 4, an output has been provided and shown in the last three rows of Table 4 (category 5). As mentioned in the methodology section, the factors are divided into 4 categories as input and one category as output as given by the ANN tool. Many possible values of the factors (categories 2, 3 and 4) are proposed in order to discover how these values affect the result. The values represented in Table 4 represent the selected case by the decision-maker.

<table>
<thead>
<tr>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
<th>Category 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Name</td>
<td>Bridge Type</td>
<td>Total Length</td>
<td>Number of Span</td>
<td>Total Cost</td>
</tr>
<tr>
<td>Project Description</td>
<td>Column Type</td>
<td>Total Area</td>
<td>Longest Span</td>
<td>Environmental Impact Rate EIR</td>
</tr>
<tr>
<td>Year of Construction</td>
<td>Deck Type</td>
<td>Type of Area to Over Pass</td>
<td>Traffic Capacity</td>
<td>Aesthetic Impact Rate AIR</td>
</tr>
<tr>
<td>Project Location</td>
<td>Structure Type</td>
<td>Highest Point under Bridge</td>
<td>Number of Lines</td>
<td></td>
</tr>
<tr>
<td>Foundation Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 – Categories and Factors
4.3 Results and Analysis

The new case that has been studied is a bridge to overpass a highway with a length of 40 meters. The restricted factors are as follow: the Total Length is 40m and the Needed Traffic Capacity (semi-restricted) is 5,000 vehicles/day (possibility to be modified within a ±20 % interval). Other restrictions are defined by the different possible locations of the vertical elements due to the existing highway that needs to be overpassed and the soil type that will not be necessary to be considered as a deep foundation type. For the other factors, a sensitivity analysis has been conducted where the following ranges of results are received:

Bridge Type (1 or 2): Total Cost [1,229 – 2,259]; EIR [2.9 - 7.8]; AIR [4.6 - 8.6]

Vertical Element Type [1 - 9]: Total Cost [1,000 – 2,459]; EIR [3.1 - 10.9]; AIR [5.2 - 7.9]

After selecting the appropriate values for the factors and with the related output results, BrIM tools (e.i. Autodesk Civil 3D and CSI Bridge) have been used to create a 3D model of the new bridge where a visual inspection is made to preliminary verify the structure stability of the bridge. On the other side, a level of realistic has been verified by comparing the actual cost given by the DSS with the estimated cost provided by the BrIM tools used for this purpose. The ratio of the given actual total cost over the estimated cost is: 1.62, this value falls within the range of 0.9 and 2.1, which represents the same ratio of the existing project cases used in the model.
5 SUMMARY AND CONCLUSION

Based on a number of the existing projects, the implementation of the proposed DSS led to predict the performance (Total Cost, EIR, AIR) of the construction parameters and characteristics of a future bridge. The case project used in this paper is to show the functionality, flow of data and capacity of the proposed methodology. Additional parameters and factors must be added for the different categories and additional methods could be used to convert the linguistic information to numerical values accurately and efficiently, also the range of the sensitivity analysis could be widened by considering the correlation that could exist between the different factors, which makes the results more realistic and accurate. This is an ongoing research where its future works will be based on enhancing the methodology by introducing additional methods and models for risk analysis. Furthermore, additional investigation on the ANN application under its different paradigms and structures will be done in an attempt to get dependable and accurate results.

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A METHODOLOGY TO EVALUATE THE EFFECTS OF SCHOOL BUILDINGS’ OCCUPANCY AND USAGE ON THEIR ENERGY CONSUMPTION

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Abstract: Buildings contribute 20 to 40% of the world’s energy consumption, making the need to regulate and minimize their energy use a priority. Although several parameters can have an impact on buildings' energy use, the impact of buildings’ occupancy and usage seems to have been rarely investigated in the literature. This paper presents a methodology for the detailed assessment of building occupancy and usage, focusing on school buildings specifically. The methodology is part of an ongoing study aiming to evaluate the effects of school buildings’ occupancy and usage on their energy consumption, focusing on Manitoba school buildings. It is being conducted by the University of Manitoba Construction Engineering and Management Group in collaboration with the Government of Manitoba Public Schools Finance Board and Manitoba Hydro’s Customer Engineering Department. An extensive literature review was carried out to identify relevant methods used to evaluate occupants' behaviour and energy use. The review showed how the few studies that have developed such methods focused on commercial or residential buildings, with little emphasis on school buildings specifically. The methodology and study aim to investigate overall building occupancy, as well as real-time usage of specific indoor spaces using surveys, interviews, visual observations and document analysis. The methodology focuses on 1) comparing building occupancy and usage across old, middle-aged, and new green schools 2) evaluating the effects of overall building occupancy on overall energy consumption, and 3) evaluating the effects of occupants' behaviour and usage on space-level electricity consumption. It complements a previously developed methodology aiming to evaluate historical energy data and real-time electricity consumption in specific school spaces. The two methodologies will be validated by applying them at the building level to a sample of thirty-one schools in Manitoba and at the space-level to three representative schools. Once complete, the study is expected to provide a tool that researchers and industry practitioners can use to improve their schools' energy efficiency and thus improve their schools’ design, construction, operation and maintenance.

1 INTRODUCTION

The rapid increase in energy consumption around the world makes the need to regulate its use across various industries a priority, the building industry being the most important of all (Pérez-Lombard et al. 2008). This is because the building industry currently accounts for 20-40% of energy use worldwide (Issa et al. 2011), representing therefore an excellent opportunity to achieve large scale energy reductions, especially with the development of the green building industry (Azar et al. 2012). Green buildings can on average be 25 to 30% more energy efficient than conventional ones (Kats et al. 2003). This is despite a number of research studies showing different results (e.g. Thiers & Peuportier 2012; Kats et al. 2003;
Several factors can affect energy consumption in buildings. For example, buildings’ location and surrounding climate can significantly influence its use of energy for heating and cooling (Yu Zhun Jerry et al. 2011). Additionally, building-related characteristics such as its size and orientation, can directly affect its energy use. Other factors with an impact on energy use include building systems and their operation and indoor environmental quality (Yu et al. 2011). However, one of the key factors rarely studied is occupants’ behaviour and usage (Yu et al. 2011). Due to the subjective nature of this factor, it is often overlooked or estimated at best.

The goal of this paper is to present a comprehensive methodology for quantifying buildings’ occupancy and usage, focusing on school buildings in particular. It is part of a study conducted by the Construction Engineering and Management Group at the University of Manitoba in collaboration with the Manitoba Public School Finance Board and Manitoba Hydro’s Customer Engineering Department to evaluate energy consumption in relation to building usage and occupancy in Manitoba’s schools in Canada. As the study is still in progress and the methodology is currently being deployed, the paper will only focus on presenting it, not the results of its validation. This methodology will aim to evaluate 1) buildings’ overall occupancy in a sample of old, middle-aged and new green schools and 2) space-level occupants’ usage in three schools. This is to investigate the effects of occupancy and usage on building-level energy consumption and space-level electricity consumption.

2 BACKGROUND

Over the past decade, several studies found large differences in the energy consumed by similar buildings, speculating about the contribution of building occupants to these differences (e.g. Ridley et al. 2014; Guerra-Santin et al. 2013). In addition, several studies showed that green buildings do not perform as intended with respect to energy efficiency (e.g. Oates et al. 2012; Menassa et al. 2012; Berkeley & Grove 2011). In many instances, actual energy use exceeded these buildings’ energy models, raising concerns about the accuracy of these models. The models usually relied on predicted average occupant behaviour to predict the buildings’ energy consumption (Guerra-Santin et al. 2009), leading some studies to conclude that actual occupant behaviour may produce significantly different results.

A study by Klein et al. (2012) monitored the use of appliances in active and stand-by modes in an office building over a two week period. Active mode denoted times at which appliances (e.g. desktop computer) were used by building occupants, whereas stand-by mode denoted times at which appliances were not used but were turned on. The study found that 38% of total energy consumed by these appliances was consumed in stand-by mode and therefore, that simple actions such as turning off appliances when not in use, can result in 38% energy savings. (Klein et al. 2012).

Another study by Al-Mumin et al. (2003) surveyed the occupants of 30 residences about their occupancy patterns and their usage of electrical appliances and found an increase of 21% from what was originally estimated. The study found that annual electricity consumption could drop down by 39% with more energy-efficient behaviour (Al-Mumin et al. 2003). Gill et al. (2010) incorporated the Theory of Planned Behavior (TPB) in his survey to establish a relationship between wasteful energy-use and general lack of interest in energy efficiency. The study concluded that occupant behaviour can account for 51%, 37%, and 11% of the variation in heat, electricity, and water consumption, respectively, in residential dwellings.

A number of studies (Hart 1989; Jin et al. 2011) used different methods to evaluate the effect of occupant behaviour on building energy consumption. For example, Yu Zhun Jerry et al. (2011) collected end-use energy consumption, referred to as non-intrusive load monitoring and used it with three data mining techniques: cluster analysis, classification analysis, and association rules mining to analyze occupant behaviour. Another method by Zhou et al. (2008) involved using continuous video monitoring and intelligent video processing to analyze occupant behaviour. Zeiler et al. (2014) used the number of Wi-Fi
connections in building spaces as a proxy for occupancy patterns. Because of the non-applicability of the method to certain settings such as elementary and middle-school buildings where most occupants are not usually connected to Wi-Fi, other studies (Spataru & Gillott 2011) used Radio-frequency Identification technology (RFID) to map the occupancy patterns within buildings. Others (Yun & Lee 2014) used infrared motion detectors to analyze occupants movements. Despite their accuracy, these methods are expensive for large-scale deployments. Moreover they only provide data about occupants’ presence in certain spaces but not necessarily their behaviour or interaction with electrical appliances.

Many studies (e.g. Steemers & Manchanda 2010, Chiou 2009 and Chen et al. 2013) used surveys, such as time-of-use and residential energy consumption surveys for that purpose. Other studies (e.g. Ridley et al. 2014; Pinheiro & Heitor 2014; Durand-Daubin 2013) used walk-throughs and semi-structured interviews. Although these methods can provide more in-depth information about occupants’ behaviour and usage patterns, they can be qualitative in nature and rely on respondents’ ability to remember their actions which raises concerns about their accuracy. Therefore, they are better suited as complimentary methods to the more quantitative ones.

3 RESEARCH METHODOLOGY

Approximately, one hundred and fifty relevant studies were reviewed as part of this study. Of these, only fifty five specifically investigated the effect of occupants’ usage on building energy consumption. The others evaluated occupant behaviour in general. The methodology developed for this study to evaluate historical occupancy and real-time usage in schools at the building and space-level relied in part on methods found in the literature.

3.1 Methodology Development

Four school divisions in Manitoba are participating in this research study, providing a total population of 129 schools. The study involved using a stratified random sampling and Neyman proportional allocation process to select the sample of thirty-one schools to be analyzed based on their age and size. This is to create three categories of schools, with 14 schools representing old schools built on or before 1959, 13 middle-aged schools built between 1960 and 1989, and four new schools built on or after 1990. The cut-off dates used for these schools were similar to the ones used by the United States Commercial Buildings Energy Consumption Survey (CBECS 2003). The stratified random sampling process also aimed to include schools of different sizes, varying between 10,000 and 100,000 ft². Because of the limited resources, cost and manpower available, one school from each age category was selected for space-level occupancy analysis. The third school, representing new schools, is also the only school in Manitoba currently certified to the Canadian Leadership in Energy and Environmental Design (LEED) Rating System. This school will highlight the effect of LEED certification on schools’ real-time usage if any.

This methodology will involve evaluating 1) historical occupancy data at the building level (e.g. enrolment figures) in all schools within the sample and 2) real-time occupant usage data at the space-level in the three schools where advanced energy sub-metering systems were also installed. The data collected using this methodology will be correlated to energy consumption data collected at the building-level and electricity consumption collected at the space-level using a different methodology. Figure 1 shows a simple breakdown of data collection using both the energy and usage methodologies.
3.2 Methods Used

At the building-level, the study involved collecting data about the historical energy usage from the utility provider over the past 24 years. Additionally, the school divisions were asked to complete a data collection form for each of the 31 selected schools. These forms collected data about the schools' enrolment figures for each year over the past 24 years as well as the numbers of teachers and staff in each school. The forms also collected data about the numbers of classrooms, gymnasiums and other spaces in these schools, as well as their typical operating hours. This occupancy and occupancy pattern data will be correlated to the schools' occupancy data in order to determine whether there is a correlation between overall-building occupancy figures and their overall energy consumption.

At the space-level, the study involved installing sub-meters to monitor specific circuits within the schools for one classroom and the gymnasium in each of the three selected schools. Sub-meters were also used to monitor other non-classroom spaces such as one music room in one school and one multi-purpose room in another school. These sub-meters provide electricity consumption data for equipment plug loads and lighting over half-hour intervals. Three different providers were used to source the sub-meters depending on the requirements for each building space and its circuits' configuration.

In order to monitor real-time occupant usage of the selected school spaces, the study will involve using three different methods simultaneously to address the limitations of each method. Figure 2 depicts these methods graphically.
3.2.1 Room Schedules

This method involves collecting room schedules from school administration for six weeks for all classroom and non-classroom spaces used during regular school hours and irregular hours (e.g. evenings and weekends) by their communities. Correlating these schedules with real-time electricity consumption in these spaces will demonstrate the effect of space usage, including usage for non-school functions (e.g. community meetings) on its electricity consumption.

3.2.2 Surveys

The methodology will involve using surveys for real-time usage data collection. Teachers in classroom spaces where sub-metering equipment have been installed will be asked to fill out a daily-use survey over six weeks. This survey will ask about details such as the average duration of using equipment within these spaces. The questions will be tailored to each space listing all the equipment available there. By only indicating an estimated duration in minutes for using each piece of equipment, the respondent will only need 2-3 minutes to fill out each daily-use survey. Table 1 shows a sample of the questions included in the survey.

Table 1: Sample questions from daily-use equipment usage survey

<table>
<thead>
<tr>
<th>Question</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please use your best judgement to estimate the total duration of active use of each of the following equipment today (Only if applicable)</td>
<td></td>
</tr>
<tr>
<td>Projector (if applicable)</td>
<td></td>
</tr>
<tr>
<td>Smart board (if applicable)</td>
<td></td>
</tr>
<tr>
<td>Microwave (if applicable)</td>
<td></td>
</tr>
<tr>
<td>Stereo (if applicable)</td>
<td></td>
</tr>
<tr>
<td>Laptop/computer (if applicable)</td>
<td></td>
</tr>
<tr>
<td>Other (if applicable, please specify)</td>
<td></td>
</tr>
<tr>
<td>For how long were the lights switched off today?</td>
<td></td>
</tr>
</tbody>
</table>

In addition to the daily-use survey, all school teachers and staff will be asked to fill out a more comprehensive general usage and behaviour survey. This survey enquires about their attitudes with respect to energy efficiency and their energy-related behaviour over the period of the study (6 weeks). The general usage and behaviour survey will include questions about the frequency of using spaces and equipment based on the respondents’ location at the school (e.g. classroom, gymnasium) as shown in table 2. The survey results will be correlated to the real-time energy use of each school and evaluated.
across the new LEED-certified school, the middle-aged schools and the older ones. Table 2 provides a sample of the questions that will be administered in the general usage and behaviour survey.

Table 2: Sample questions from the general usage and behaviour survey

<table>
<thead>
<tr>
<th>General Attitudes/ Thoughts about Energy Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>To what extent do you agree or disagree with the following statement?</td>
</tr>
<tr>
<td>• The problem of global warming and/or greenhouse effect is real and needs to be addressed immediately</td>
</tr>
<tr>
<td>• Leaving equipment/lighting on when it is not being used can waste a large amount of energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General Attitudes towards Actions to Save Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>To what extent do you agree or disagree with the following statement?</td>
</tr>
<tr>
<td>• I think I use less electricity than other teachers/staff members at the school</td>
</tr>
<tr>
<td>• I know what to focus my attention on when it comes to saving electricity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency of Using Spaces and Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Please answer the following questions to the best of your knowledge:</td>
</tr>
</tbody>
</table>

**Gym**
- Over the past two months, on average, how many days per week is the gym used for, if any?
- Over the past two months, on average, how many hours per day is the gym used for, if any?

**Plug Loads**
- Over the past two months, on average, how many days per week do you use the projector for in the classroom?
- Over the past two months, on average, how many hours per day do you use the projector in the classroom?

*Please indicate how often you unplug the following equipment whenever they are not being used.*

*Please indicate as N/A for appliances you do not typically use at the school*
- Laptop/computer
- Projector
- Smart Board

**Usage Patterns**

*What is the frequency of these events over the past two months?*
- In my classroom, I use only natural light from the window without switching on the lights
- I switch off the lights at my workspace whenever I leave
- I use an electric heater when I feel my workspace is too cold

### 3.2.3 Observation Forms

In order to compliment data derived from the daily-use survey administered to teachers, point-in-time observations of the state of electrical equipment and space lighting (i.e. on, off, or idle/dimmed) used in specific locations will be conducted at regular intervals over a two week period. An observation form will be developed for that purpose tailored for each space listing all the equipment available there. In addition to giving the three options for observing each state, the sheets will enable the observers’ to write any notes regarding their observations. Two weeks was in general found to provide adequate data about occupants’ usage of indoor spaces in the literature (e.g. Klein et al. 2012). Exact definitions of each state will be identified as per table 3 to avoid human-error when recording these observations. The team will cross validate the observations during a pilot study involving all team members simultaneously to ensure the same understanding of each state definition.

These observations will aim to investigate behaviour as it occurs naturally with no intervention. Therefore, occupants will not have access to the observation form used by the research team to avoid influencing their behaviour. Additionally, the research team will only monitor behavioural activities related to energy consumption. During the visits to the selected locations, it was found that all equipment states can be observed from outside the spaces provided their doors are left open.
Table 3 shows a sample of the observation form used for a classroom space.

Table 3: Sample observation sheet for a classroom

<table>
<thead>
<tr>
<th>Observation</th>
<th>State Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Weather</td>
<td>Completely Clear = No clouds at all in-sight</td>
</tr>
<tr>
<td></td>
<td>Partial Clouds = One or more clouds in sight,</td>
</tr>
<tr>
<td></td>
<td>Completely Cloudy = clouds completely covering the sky, i.e. little-to-no sunlight</td>
</tr>
<tr>
<td>Blinds in use</td>
<td>No = Blinds are completely up (window completely cleared)</td>
</tr>
<tr>
<td></td>
<td>Partial = Blinds are down but not covering the entire window,</td>
</tr>
<tr>
<td></td>
<td>Full = Blinds are covering the entire window</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Projector in use</td>
<td>No = Projector is not being used and is unplugged</td>
</tr>
<tr>
<td></td>
<td>Idle = Projector is plugged in and on-standby but not projecting anything at the</td>
</tr>
<tr>
<td></td>
<td>moment</td>
</tr>
<tr>
<td></td>
<td>Yes = Projector is being used to project something on the board or project a blank blue screen</td>
</tr>
<tr>
<td>Microwave in use</td>
<td>No = Microwave is not being used and is unplugged</td>
</tr>
<tr>
<td></td>
<td>Idle = Microwave is plugged in and on-standby but not being actively used</td>
</tr>
<tr>
<td></td>
<td>Yes = Microwave is being actively used</td>
</tr>
<tr>
<td>Computer in use</td>
<td>No = Computer is not being used or is unplugged</td>
</tr>
<tr>
<td></td>
<td>Idle = Computer is on standby or sleep mode, screensaver or blank screen is on but laptop is plugged in</td>
</tr>
<tr>
<td></td>
<td>Yes = Computer is being actively used or screen is on</td>
</tr>
<tr>
<td>Stereos / Speakers in use</td>
<td>No = Stereo is unplugged</td>
</tr>
<tr>
<td>Fan in use</td>
<td>No = Fan is unplugged</td>
</tr>
<tr>
<td>Other equipment in use</td>
<td>No = equipment is unplugged</td>
</tr>
<tr>
<td></td>
<td>Idle = Stereo is plugged in but not being used</td>
</tr>
<tr>
<td></td>
<td>Idle = Fan is plugged in but not being used</td>
</tr>
<tr>
<td></td>
<td>Yes = Stereo is being actively used</td>
</tr>
<tr>
<td></td>
<td>Yes = Fan is being actively used</td>
</tr>
<tr>
<td></td>
<td>Yes = equipment is actively being used</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lighting</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Classroom Lights</td>
<td>Off = All Classroom lights are off except emergency lights</td>
</tr>
<tr>
<td></td>
<td>Dimmed = Some classroom lights are on and some are off (as long as at least one light bulb is switched off not due to malfunction but using a specific light switch)</td>
</tr>
<tr>
<td></td>
<td>On = All classroom lights are on</td>
</tr>
</tbody>
</table>

4 DATA ANALYSIS

The study will entail comparing historical occupancy data across old, middle-aged and new schools in order to highlight historical trends in occupancy in each of the three categories. The analysis will also involve correlating historical occupancy data to the schools’ historical energy consumption. This is to highlight the relationship between occupancy figures and energy consumption at the building level.

At the space level, the study will involve comparing space-level usage data for classrooms and gymnasiums across the three schools. The study will also compare the results derived using each of the three methods (e.g. daily-use surveys and observations sheets) to determine the accuracy and validity of each. The data collected using each method will be correlated to real-time electricity consumption to demonstrate the effect of specific occupant activities on energy consumption.
5 CONCLUSION

The collected occupancy and usage data for all schools will be correlated to their energy consumption data. This is to demonstrate the relationship between occupancy, usage and buildings’ energy consumption: a topic seldom investigated in the literature. One of the key contributions of this study is its novel methodology which relies on the use of a number of different methods. Correlating the results derived using each method should improve the research community and industry’s understanding of energy use in school buildings. The significance of the study also stems from its evaluation of school buildings in particular as opposed to the more common evaluation of office and residential buildings.

This methodology for evaluating occupancy and usage in schools should serve as a tool that future researchers and practitioners can apply in different contexts to evaluate school buildings in other locations. The methodology can also be used by school operators to identify occupant activities with the most impact on schools’ energy consumption and that can thus reduce it the most. It can also allow for more efficient space-utilization of the schools.

One of the most significant limitations of this methodology is its heavy reliance on human resources which can make it challenging to implement. This can be mitigated by implementing only parts of it through the use of only one of the methods making it up.

Acknowledgements

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References


IMPROVED LOCALIZATION OF CONSTRUCTION WORKERS IN VIDEO FRAMES BY INTEGRATING DETECTION AND TRACKING

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Abstract: Tracking of construction site resources from on-site cameras using vision trackers has been proposed as a means to efficiently track a large number of objects operating in a congested environment. The systems proposed so far use first either a less accurate/faster motion detection approach or a more sophisticated object detection approach to mark the moving entities of interest in the camera view. The marked entities are then passed on to a vision tracker, who follows the entities in all subsequent frames. The major drawback of this two-step process is that the resulting tracking systems are very sensitive to changes and, in most cases, deteriorate and stop tracking effectively after only a few seconds/minutes. The reason is that it is common for construction resources to frequently a) enter/leave the field of view, b) be temporarily occluded, or c) significantly change their pose. To resolve this issue, this paper presents a hybrid method for locating construction workers that interchangeably fuses the methods of tracking and object detection. Specifically, the proposed approach continuously detects construction workers, and tracks them. Continuous detection allows a) for the detection of workers that enter the view or reappear after being occluded at any given time, b) for the effective termination of tracking when workers leave the view or become occluded, and c) for relocating the marked area and detection confidence to fit all object poses. On the other hand, continuous tracking allows for seamless tracking across time and smoothing of the temporal detection variations. The proposed approach was implemented into a C# prototype and tested on videos taken from construction sites in Atlanta, GA. The method could detect and track all workers, preserving stability under occlusions. It enhanced accuracy by 9.6% when compared to the use of a detection method only. This indicates that the proposed approach is a significant improvement over prior work and has the potential to effectively monitor the location of construction workers.

1 INTRODUCTION

Construction sites involve various types of project-related assets that move, including construction materials, equipment and workers that interact with each other continuously. Given the dynamic and complex conditions during construction, it is useful for effective project control to monitor the movements of a large number of entities. As sites become larger and more complex having up to tens of thousands of active entities, it becomes extremely hard to monitor the entities and to provide accurate asset flow data.

In pursuit of effective monitoring of such complex sites, several state-of-the-art sensing technologies have been introduced to automatically track entities and generate real-time information on their spatial locations across time. GPS (Global Positioning System), RFID (Radio Frequency Identification), and UWB (Ultra Wideband) are the most well-known technologies that have been rigorously investigated and
deployed on sites. However, the size and complexity of the site, along with the overhead of installing, maintaining, and decommissioning tags or sensors on entities limit their application in large-scale, congested construction sites. In such cases, only entities with sensors installed can be tracked by such technologies. The limited amount of data leads to inaccurate analysis and improper decisions.

These limitations can be tackled with vision-based approaches that have been proposed to establish sensor-free positioning systems. Vision-based localization can be classified into two categories – detection and tracking. Detection methods can identify the location of construction workers and equipment that appear in cameras’ views. However, detection methods are not enough to provide data that can be transformed to meaningful information for productivity analysis and safety management. They do not link the results across frames, as the results of a frame are independent of those of the next and previous frames. Hence, trajectories of entities cannot be extracted. Also, no methods are so perfect as to provide seamless data across time. Entities are often missed by detection methods in a few frames. On the other hand, tracking methods locate an object in the current video frame based on its positions and image appearance features in previous frames. Accordingly, they can extract trajectories across frames. However, they require manual initialization to locate the object at its first appearance in a camera view. Also, occlusions significantly undermine the performance of the tracking methods.

To resolve these limitations, this paper presents a hybrid method for locating construction workers that interchangeably utilizes vision tracking and object detection algorithms. The proposed method continuously detects construction workers, and tracks them in parallel. Detection mainly acts as an indicator of new entities in the view and their disappearances, and reconfigures the tracking area when it is dislocated significantly. On the other hand, tracking allows for seamless positioning. Tracking links the detection results across frames and finally generates a trajectory of each entity. The proposed approach was implemented and tested on construction site videos. The method could detect and track all workers, properly handling occlusions. Compared to the use of a detection method only, a 9.6% improvement was achieved by the integration with a tracking algorithm. This indicates that the proposed approach is a significant improvement over prior work and has the potential to effectively monitor the location of construction workers.

2 BACKGROUND

Several radio-based technologies such as RFID and GPS have been used to generate real-time position information of construction personnel and equipment across time (Ergen et al. 2007, Goodrum et al. 2006). GPS is generally used for tracking a fleet of heavy equipment, and has evolved into a well-established monitoring system in construction sites. Numerous GPS-based methods have emerged for monitoring construction equipment. Equipment manufacturers have adopted these methods to provide for their customers (Construction Equipment 2010). At the same time, RFID is commonly used for monitoring construction materials and workers. When a piece of material passes through a supply-chain milestone or is installed on the structure, a tag attached to or embedded in it is read to record the event with its ID and timestamp of accomplishment (Engineering News-Record 2008). Another type of radio technology, UWB, has the advantages of wide ranges of frequencies and the low average power requirement (Fontana 2004). Its ability to provide accurate 3D locations in real-time is a definite benefit to tracking in construction sites. The data it provides is accurate. However, its applicability in large-scale, congested sites is weakened by the size and complexity of construction sites, occlusions in the site and the need for tagging entities, etc.

The methods discussed above only partially achieve the ultimate goal of extracting positioning data on demand with minimum human interaction. Vision-based approaches offer a way to further automate the positioning process by using on-site construction cameras. These approaches collect video streams from construction sites, and automatically locate project-related entities. Brilakis et al. (2011) proposed the concept of 3D vision tracking framework. It uses two fixed cameras to locate construction entities in 3D space. The framework is composed of three main steps: (i) object detection, (ii) 2D tracking, and (iii) triangulation. In the framework, construction entities are detected and tracked by step (i) and (ii), respectively. The last step (iii) correlates the results of the step (i) and (ii) to obtain 3D positions.
Several researchers have investigated object detection algorithms that classify and localize construction resources. Chi and Caldas (2011) proposed a method that enables real-time detection of construction entities using background subtraction and machine learning classifiers. Their method extracts motion pixels from video frames and groups them into distinct regions using a connected component algorithm. The features of foreground blobs such as aspect ratio, area size, occupancy percentage, and average gray-scaled colour, are trained for classifying the moving objects into worker, backhoe, and loader. Narrowing down the types of entities to equipment, Rezazadeh Azar and McCabe proposed an equipment detection method that employs HOG (Histogram of Oriented Gradients) features captured from various camera angles (2012a). Also, they introduced a part-based model to detect articulated shapes of equipment (2012b). On the other hand, Park and Brilakis (2012) focused on construction workers. They combined three types of features – motion, shape, and colour. Background subtraction, HOG + SVM (Support Vector Machine), and colour histogram + k-NN (k-nearest neighbour) were used to detect people wearing safety vests of fluorescent colours. The colour histogram is composed of hue and saturation components to eliminate illumination effects. Similar strategies were used in Memarzadeh et al.’s work (2013). HOG and hue-saturation-based color histogram features are integrated into a single feature vector and trained with SVM. The proposed method was applied to workers, excavators, and dump trucks.

Despite the high accuracy of the aforementioned detection methods, they are not capable of detecting 100% of the entities. There still exist missed entities and those few false detections prevent their practical applications. Also, detection itself is not capable of distinguishing the entities of the same type and does not tell the previous location of any entity detected in the current frame. These limitations can be overcome by tracking algorithms. Yang et al. (2010) proposed a machine learning algorithm to train a general spatial model for tracking workers. Park et al. (2011) conducted a comparative study of the tracking methods and suggested that kernel-based methods are the most appropriate for tracking construction entities. However, their method was lack of the function of detection, and thus it required manual interaction to initialize the tracker.

Rezazadeh Azar et al. (2013) presented a tracking method that integrated the step (i) and (ii). The method employed a HOG based detection method and a KLT tracker. It successfully detected and tracked excavators and dump trucks even when they were partially occluded. The proposed method was applied to the estimation of dirt loading cycles. Similarly, Park and Brilakis (2012b) fused the function of detection and tracking algorithms for locating construction equipment. In their method, background subtraction, Haar-like features, and eigen-images were employed for detection. The eigen-images were also used for tracking. Their method effectively handled total occlusions. It automatically identified the event of occlusion based on the absence of detection results and terminated the tracking process. The tracking process was triggered again by reappearance of the object. Notwithstanding the research efforts on the combination of detection and tracking, their object types were limited to construction equipment. The experiments involved a small number of entities with a few events of occlusion. However, the tracking of construction workers is far more challenging because of their nearly identical appearances and frequent occurrences of occlusion. To tackle the challenges, this paper proposes a vision-based hybrid method for locating construction workers.

3 METHODOLOGY

Figure 1 shows the overall framework of the proposed method. It basically employs two methods - detection and tracking. When a worker is detected by the detection method, the tracking method is initiated. After the initiation, both the detection and tracking methods are processed simultaneously. Every frame, the location is determined by matching the results of the two algorithms. The location is represented by a rectangle that fits the image region of the worker. For the rectangle region, the colour histogram is calculated. The details will be addressed in the following subsections.

3.1 Detection and Tracking

We employed Park and Brilakis’ method (2012a) for worker detection. The method is reported to detect workers wearing safety vests at over 99% precision rate. Also, the method is capable of capturing the
workers within a second after they first appear in the camera view. The worker detection plays a role in locating all workers in the camera view. For example, in Figure 2, the detection locates workers at three regions in both $n$-th and $(n+1)$-th frames. Each region is labelled as $R_{k,i}$, where $k$ is the order of the location from left to right, and $i$ is the frame number. The available information from the detection is that three workers are present in each frame $i$, at $R_{1,i}$, $R_{2,i}$, and $R_{3,i}$. However, it does not tell which of $R_{k,n+1}$ corresponds to $R_{1,n}$, $R_{2,n}$, and $R_{3,n}$. In other words, detection results are independent of the image sequence, and the detection does not associate the results across frames. Therefore, the movements of each worker, which can be referred as a trajectory, are unknown.

The links between detection results of consecutive frames are provided by the tracking method. The tracking makes inferences of the region of an object in the current frame based on the history of the object’s appearance and movements. Following the suggestion of Part et al.’s comparative study (2011), a kernel-based method (Ross et al. 2008) is employed for the tracking. This method models the objects’ appearances and movements with eigen-images and particle filtering, respectively. The method tracks an object based on the model template composed of eigen-images, and represents the object as a surrounding affine-transformed rectangle (i.e. a parallelogram). In the tracking process, only the upper half of the workers is taken into account since the lower part experiences continuous appearance changes as they move. In Figure 2, once three workers are detected in the $n$-th frame, three tracking processes are triggered to track them independently, and predict the workers’ new locations in the next frame.

The links between detection results of consecutive frames are provided by the tracking method. The tracking makes inferences of the region of an object in the current frame based on the history of the object’s appearance and movements. Following the suggestion of Part et al.’s comparative study (2011), a kernel-based method (Ross et al. 2008) is employed for the tracking. This method models the objects’ appearances and movements with eigen-images and particle filtering, respectively. The method tracks an object based on the model template composed of eigen-images, and represents the object as a surrounding affine-transformed rectangle (i.e. a parallelogram). In the tracking process, only the upper half of the workers is taken into account since the lower part experiences continuous appearance changes as they move. In Figure 2, once three workers are detected in the $n$-th frame, three tracking processes are triggered to track them independently, and predict the workers’ new locations in the next frame.
3.2 Mutual Compatibility of Tracking and Detection

If the detection and the tracking work perfectly, both provide the probable regions for every worker. In this case, priority is given to the detection region since it is more reliable. If the worker region experiences sharp changes in its appearance, the tracking process grows unstable and occasionally results in a dislocated region. On the other hand, the detection provides more stable results regardless of the appearance changes because, as mentioned in Section 3.1, it processes each frame independently and previous appearances do not affect the detection process at all. Figure 3(a-b) illustrates an example of this case. A worker is detected in a certain frame and represented as a solid rectangle in Figure 3(a). The solid rectangle region is tracked in the next frame, and shown as a dotted rectangle which is a little dislocated (Figure 3(b)). Meanwhile, the detection is also processed, providing a more accurate location (the solid rectangle in Figure 3(b)). The partial overlap of the dotted rectangle and the solid rectangle discerns that they are corresponding to each other. The location of the worker is determined to be the solid rectangle. The tracking process is reinitiated with this new region to eliminate the erroneous components associated with the dislocated rectangle.

Once a tracking process is initiated, it provides the best probable location of the object in every frame. On the other hand, the detection method often fails to locate workers, and does not generate any results. Therefore, as in Figure 3(d), it is occasional to have only the tracking result. In this case, the location is determined to be the tracked region.

3.3 Occlusion Handling

As described in Section 3.2, the tracking produces a result for every frame. However, the process should be terminated when the workers disappear from the camera view. There are three cases of disappearance. The first case is workers moving out of the camera view. This case is identified simply based on the worker location. When the worker’s location comes within a certain margin along the border of the video frame, the tracking process is automatically terminated. It can be expressed as follows.
The second case is workers being occluded by other types of objects such as construction equipment and materials. Figure 4 illustrates an example of the occlusion. A worker tracked in the $n$-th frame (Figure 4(a)), disappears behind a construction machine in the $(n+1)$-th frame (Figure 4(b)). Without any termination process, the dotted rectangle in Figure 4(b) would be stuck at the same position throughout the subsequent frames. This type of occlusion is identified based on two cues – the absence of the detection result and colour histogram transition. When the worker disappears, no detection result is given around the tracked region. In addition, the image feature of the rectangle region exhibits significant changes as the content inside the region is switched from the worker to the machine (Figure 4). Colour histogram is used to identify the appearance transition. The colour histogram of the tracked region is calculated ($C_{n+1}$), and is compared to the one calculated in the previous frame ($C_n$). In short, the tracking process is terminated if no detection result exist and the Euclidean distance between the colour histogram vectors exceeds a threshold determined as 0.25.

The third case is when workers are occluded by one another. This case can be characterized as two tracking results sharing the same detection result (Figure 5). In Figure 5(a), two workers are tracked and represented as dotted rectangles that partially overlapped with each other. Both rectangles intersect the solid rectangle which is a detection result. The proposed method divides the status of occlusion into two levels based on the degree of the overlap as follows.

- **Level 1**: $0 < p < 0.2$  
  ($p$: the proportion of the overlap area)
- **Level 2**: $p > 0.6$

For Level 1, the detection result is ignored since it is uncertain which tracked region is the correct match of the detection result. Also, it was reported that the tracking algorithm for itself generally is stable enough.
to handle the partial occlusion of Level 1 (Park et al. 2011). When the partial occlusion reaches Level 2 as in Figure 5(b), one of the workers becomes nearly invisible from the view and the tracking algorithm grows unstable. In Figure 5(b), Tracking 1 should be matched with Detection, and Tracking 2 needs to be terminated. The correct match is determined based on the Euclidean distances of the centroids and colour histograms. The distances of Tracking 1 and 2 are calculated as follows.

\[ d_{p,1} = |P_{D,n+1} - P_{T1,n+1}|, \quad d_{p,2} = |P_{D,n+1} - P_{T2,n+1}| \]

\[ d_{c1,1} = |C_{D,n+1} - C_{T1,n}|, \quad d_{c1,2} = |C_{D,n+1} - C_{T2,n}| \]

\[ d_{c2,1} = |C_{T1,n+1} - C_{T1,n}|, \quad d_{c2,2} = |C_{T2,n+1} - C_{T2,n}| \]

Here, \( P_{D,j} \), \( P_{Tj} \) represents the centroid coordinates of the detected region and the tracked region of worker \( j \) in the \( i \)-th frame. Similarly, \( C_{D,j} \), \( C_{Tj} \) represents the colour histograms of the regions. The worker that has smaller values of the distances is determined to be the correct match. Accordingly, the tracking of the other worker is automatically terminated.

4 EXPERIMENTS AND RESULTS

The proposed hybrid method was implemented using Microsoft Visual C# in .NET Framework 4.0 environment. To evaluate the performance, the method was tested on on-site videos taken with a HD camcorder. The collected HD videos were resized to 768×432 for the sake of fast processes with similar level of performance. 4-5 people are present in the videos, wearing different combinations of hard hats and safety vests. The “worker” is defined as a person wearing a safety vest as in the experiments of Park and Brilakis’ research (2012a).

Figure 6 shows example frames. It should be noted that, an integer ID was assigned to each worker and kept consistent over the frames. Counting the reappearance of a worker as a new identity, total 53 identities appeared in the videos. All 53 identities were detected in less than a second after their first appearance, and each of them was successfully tracked with a single ID until it disappeared. Regarding the stability against occlusion, total 39 occlusions are occurred, and all are identified correctly. In Figure 6, it is observed that the tracking process of Worker 2 is ceased when it is occluded by Worker 0 in the middle frame. In the third frame, the same entity is newly detected and tracked as a new worker with an ID number 3. A similar case is illustrated in a different way in Figure 7. In the video, the two workers on each side walk to the other sides crossing each other at the midpoint of the frame as in Figure 5(b). The obtained trajectories are shown in separate figures for clear exhibition. In both Figure 7(a) and (b) detection results are expressed as a spread of points without any identity information. When only the tracking algorithm was processed with manual initialization, after crossing each other, the tracking process tracked the other worker resulting in going back to original starting point. On the other hand, the proposed hybrid method successfully tracked the workers until they went out of the frame. It should be noted that the tracking of the worker on the right (the red solid line) was terminated when fully occluded in the midpoint, and newly initiated (the magenta solid line) after the occlusion.

![Figure 6: The result frames](image-url)
The performance of the method was also compared to the use of the detection algorithm (Park and Brilakis 2012a) only. Three metrics were used in the comparison – precision, recall, and accuracy:

\[ \text{Precision} = \frac{TP}{TP + FP} \]

\[ \text{Recall} = \frac{TP}{TP + FN} \]

\[ \text{Accuracy} = \frac{(TP + TN)}{(TP + TN + FP + FN)} \]

- TP: the number of correctly detected or tracked workers
- FP: the number of detected or tracked non-workers
- FN: the number of missed workers
- TN: the number of undetected people not wearing safety vests

Table 1 summarizes the comparison results. The combination of tracking and detection exhibits 1.1% decrease in precision, which is attributed to the tracking of false negatives for 3 seconds. However, the function of the tracking algorithm reduced FN's significantly which is reflected by the 17.1% increase in recall. The proposed method features the overall accuracy of 97.7% that enhances 9.6% from using only the detection algorithm.

5 CONCLUSIONS

Systematic control of the construction activities on dynamic, congested sites places a high demand on the ability to locate project related entities including construction equipment, workers, and materials. The location data can be used for site safety management, productivity measurement, and activity sequence analysis. For this purpose, tracking systems such as GPS, RFID, and vision-based system have been rigorously investigated. Whereas GPS and RFID have been applied to real construction projects to track construction equipment and materials, vision-based tracking systems still remain immature for practical uses. The vision-based system has a potential to track a large number of entities in congested construction sites without tagging each entity. Though several researchers presented methods for detecting construction entities in video frames, they are not adequate for tracking since their result data are lack of links among frames. Therefore, it is necessary to fill the gap between consecutive frames. To resolve the problem, this paper presented a hybrid method that automatically detect and track construction workers in video frames. The method is composed of the detection and tracking algorithms which mutually supplement each other such that each worker is smoothly tracked as an independent identity across frames. The method also works well under various occlusions by identifying the occlusions and terminating the tracking processes. In the preliminary experiments, 9.6% increase in accuracy was achieved by the proposed method, when compared to using only the detection method. The method successfully tracked all workers present in the videos, and retained stability in spite of recurrent occlusions. The experiment results signified the effectiveness of the hybrid method for vision-based tracking system.
References


ROBOTIZATION OF SLIP FORM FOR MONOLITHIC CONSTRUCTION OF TALL BUILDINGS

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Abstract: The paper considers technological features of erecting monolith objects with a variable cross-section, presents the formulated requirements to the robotic complex and the principles of its construction and gives the complex structure. It has been shown that for the control of slip form it is advisable to use a two-level structure; the upper level tasks of which are planning the complex hoisting and synchronization of control mechanisms operation, and the tasks of the lower level incorporate development of control signals having been formed in the previous level. Great attention is paid to the problems of the robotic complex movements planning taking into account restrictions on control and disturbing influences affecting the structure being erected. In order to remove the complex deviation from the designed location we suggest the method of the planning of movements with due account of limitations for control and effects of disturbing influences to the structure being erected. In conclusion the paper deals with the problems of forming adaptive laws of for controlling joint coordinates ensuring development of the planned trajectory.

1 INTRODUCTION

Construction of objects for different purposes requires great labour consumption and a number of regulating operations especially for the structures with varying cross-section and wall width. From the standpoint of control slip forms for erecting objects with variable radius represent a multivariable system with a number of control organs. The position and the shape of the forms as an object of control is determined by the aggregate of external and internal effects. The loading irregularity of the forms working floor, imperfect forms geometry and some other factors result in the forms deflection with respect to the projected axis, the working floor inclination and friction forces change of the forms shields against the concrete. The volume and the tasks of the sliding forms automation is determined by the construction objects appearance, their shape geometrical parameters. The main tasks for sliding forms automation so as to erect object of conic shape are:

- information-measuring provision to control the forms erection;
- the forms mechanical trajectory planning with consideration of external effects and current condition;
- control of slip forms shields erection and radial displacement;
- synchronized work of lifting jacks and mechanisms for the forms radial displacement;
- to keep all lifting jacks in the given plane and to fulfil overall control of jacks;
- compensations of disturbing effects on the control system actuating elements;
• adjustment of the forms position due to control of the working floor inclination within the range of shields taper.

The analysis of monolith construction technology has shown the expediency of designing mechatronic complexes on the basis of slip forms (MSC), they provide automation of the objects erection and continuous-cyclic placement and consolidation of concrete. Solution of the above mentioned tasks is possible on the basis of mechatronic complexes for monolithic construction.

2 THE CONSTRUCTION PRINCIPLE OF MSC

The principle of the mechatronic complexes by the kinematic, design and technological distinctions of the object controlled, the controls distinctions and also by the character and properties of the disturbing effects. Consideration of different variants of the MSC development on the basis of slip forms has led to the idea of using a movable platform 1, bearing against columns 2 with help of lifting posts 3 which are equipped with jacks 4 (Figure 1). The forms 5 are suspended from the platform with help of radial displacement mechanisms (RDM) 6 providing adjustment of panels location.

![Figure 1: MCS on the basis of a slip form](image)

For the purpose of lifting it is advisable to use frequency control electromechanical jacks, which allow to adjust hoisting speed and to synchronize movement. For the RDM it is preferable to use an induction motor drive with relay control. The main tasks of the mechatronic complex control are lifting the platform with forms during the process of concrete placement, change panels location when lifting, correction of the platform position when shifts and torsions occur, synchronization of the equipment operation.

The developed principles of the complexes construction make up the basis of the functional diagram for mechatronic complex control task to which is presented in Figure 2.

Information – measuring system provides control of the main parameters of the mechatronic complex condition. Laser system incorporating a laser set point device for the vertical (LDV) and a photodiode matrix panel (PMP) makes the forms measurements. The system of data processing first scans the photodiode panel PMP about the coordinate axis, records the results of scanning into the image storage area of the photopanel.

According to this information boundary values of the photopanel lit area are determined \((X_{\text{min}}, X_{\text{max}}, Y_{\text{min}}, Y_{\text{max}})\) and the coordinates of the forms position are calculated relative to the
When using two-beam laser control system the values of the coordinates of the beam center on each photopanel $X_{1\min}, X_{1\max}, Y_{1\min}, Y_{1\max}$ and $X_{2\min}, X_{2\max}, Y_{2\min}, Y_{2\max}$ become average.

Checking the vertical position of the erected object and the platform position is carried out with laser devices equipped with photomeasuring panels. The laser device consists of two laser set-point devices for the vertical axis and two photoreceiving panels with modules for reading-out and processing data. Location of the laser beam center on the photoreceiving matrix is determined by the way of photopanels scanning. And the coordinates of the beam center are calculated from the formulae:

$$X = 0.5(X_{\max} + X_{\min}), \quad Y = 0.5(Y_{\max} + Y_{\min}).$$
\[ x_{pr} = 0.5\left[8\left(d_{i}^{(x)} - 1\right) + b_{i}^{(x)}\right] + \left(8\left(d_{i}^{(x)} - 1\right) + b_{i}^{(x)}\right) - N_{pr} \];
\[ y_{pr} = 0.5\left[8\left(d_{i}^{(y)} - 1\right) + b_{i}^{(y)}\right] + \left(8\left(d_{i}^{(y)} - 1\right) + b_{i}^{(y)}\right) - N_{pr} \],

where \( d_{i}^{(x)}, d_{i}^{(y)}, d_{i}^{(x)}, d_{i}^{(y)} \) are initial and last active bytes when scanning along the axes \( X \) and \( Y \);
\( b_{i}^{(x)}, b_{i}^{(y)}, b_{i}^{(x)}, b_{i}^{(y)} \) are initial and last bytes corresponding; \( d_{i}, d_{i}; N_{pr} \) is the number of digits in bits) on the photopanel.

On the basis of the beam location coordinates on the photoreceiving panels we determine the position of the platform center:
\[ x_{pl} = x_{p}^{(o)} = 0.5\left(x_{pr}^{(1)} + x_{pr}^{(2)}\right) \cdot \cos \psi_{p}, \quad y_{pl} = y_{p}^{(o)} = 0.5\left(y_{pr}^{(1)} + y_{pr}^{(2)}\right) \cdot \sin \psi_{p}, \]

where \( \psi_{p} \) is the twist angle of the platform relative to \( Z_{o} \) axis.

On the basis of the obtained average values of the platform deviation from the designed axis we calculate modulus and the direction of displacement:
\[ \delta_{pl} = \left[(x_{pl})^{2} + (y_{pl})^{2}\right]^{1/2}; \beta_{d} = \arccos\left(\frac{x_{pl}}{\delta_{pl}}\right) = \arctan\frac{y_{pr}^{(1)} + y_{pr}^{(2)}}{x_{pr}^{(1)} + x_{pr}^{(2)}}. \]

The data received from the photopanels make it also possible to determine the twist angle of the platform with the forms
\[ \psi_{p} = \arctan\left[\left(y_{pr}^{(1)} - y_{pr}^{(2)}\right)/l_{pr}\right], \]

where \( l_{pr} \) is the distance between photoreceiving matrices.

Vertical position of each jack of the forms is controlled by the hydrostatic system of levelling, which is equipped with level gauges LG(1) - LG(n), mounted on each jack frame. The coordinates of the level gauges LG(1) - LG(n) disposition are:
\[ x_{i} = (R - h / \tan \varphi) \cdot \cos(2\pi i / n), \quad y_{i} = (R - h / \tan \varphi) \cdot \sin(2\pi i / n), \quad z_{i} = h \pm \delta_{j}, \]
where \( x_{i}, y_{i}, z_{i} \) are the coordinates of the level gauge, \( n \) is a number of jacks, \( R \) is the forms radius in the construction base, \( \varphi \) is a slope of the construction, \( h \) is an elevation mark of the forms working floor, \( \delta_{j} \) is a position of the \( i \)-th jack relative to the working floor. The vertical position of the forms centre is determined as an arithmetic mean of the elevation position of \( Z_{j} \) jacks:
\[ z_{0} = \sum_{i=1 \ldots n} z_{i} / n. \]

The platform deviation is closely connected with disturbance of its horizontal position therefore a hydrostatic leveling device has been introduced into the system. It permits checking the platform deformations and the swivel angle and also deviations of some jacks relative to others. Using level detector readings \( \Delta z_{ld}^{(i)} \) we determine upper and lower marks of the platform hoisting jacks position

\[ \Delta z_{ld}^{(max)} = \max\left(\Delta z_{ld}^{(i)}\right); \Delta z_{ld}^{(min)} = \min\left(\Delta z_{ld}^{(i)}\right) \rightarrow i = 1, 2, \ldots, n \]

and calculate the platform swivel angle and the direction of the swivel angle vector:
\[ \alpha_{p} = \arctan\left(\frac{\Delta z_{ld}^{(max)} - \Delta z_{ld}^{(min)}}{4R_{hj}}\right), \quad \beta_{p} = \frac{2\pi}{n} \left[\max\left(\Delta z_{ld}^{(i)}\right) - 1\right]. \]
The data about the jacks’ deviation \( \Delta z_{hj}^{(i)} \) from the horizontal plane are used to synchronize movements of the hoisting jacks. To provide the platform correcting inclination hoisting jacks’ speeds are set according to the required swivel angle \( \alpha_p^* \):

\[
\nu_{hj}^{(i)} = \nu_p \left[ 1 + R_{hj} \cdot \sin \alpha_p^* \cdot \cos \left( \frac{2\pi}{n} (i - 1) - \beta_p \right) \right],
\]

where \( \nu_p \) is the average speed of the platform hoisting.

Measurements of jack frames radial displacements is fulfilled by potentiometric or photoelectric encoding transducers PT(1)–PT(n). The measurement accuracy of these transducers must be \( \pm 1–2\) mm. When considering the system dynamic characteristics there transducers can be regarded as inertia free links. Measurement data processing allows to determine parameters of the mechatronic complex condition and the construction being erected: \( x_0, y_0 \) deviations from the construction line, the forms torsion angle \( \alpha \), the forms inclination angle \( \gamma \), the forms average radius \( R_{hj} \).

Taking into account complexity of MSC as an object of control, a great number of disturbing and adjusting influences, restrictions for control it is of interest to consider the problems of the complex control which include planning its motions, development of the laws of control, solution of the problem of mechanisms operation synchronization.

MSC is a multimeasuring controlled object the states of which at any period of time can be described by the system of equations

\[
\begin{align*}
U_{hj} &= \left[ U_{hj}^{(1)}, U_{hj}^{(2)}, \ldots, U_{hj}^{(m)} \right]; \\
U_{rm} &= \left[ U_{rm}^{(1)}, U_{rm}^{(2)}, \ldots, U_{rm}^{(n)} \right]; \\
Y_{ms} &= \left[ x_n, y_n, z_n, R_0, \alpha_n, \beta_n, \theta_n \right]; \\
F_1 &= [F_w, F_s], \\
F_2 &= [Q_n, F_{mp}, F_{cu}, F_{ms}, F_{m}],
\end{align*}
\]

where \( U_{hj}, U_{rm} \) are the vectors of control actions directed to the hoisting jacks and the mechanisms of radial displacement (MRP); \( Y_{ms} \) is the vector of the output parameters of the MSRS state; \( F_1 \) and \( F_2 \) are the vectors of disturbing influences acting on the erected construction and the mechatronic system.

The system state at any moment is determined by the coordinates \( x_p, y_p, z_p \) of the center position in the system of coordinates of the erected object \( X_0, Y_0, Z_0 \), by the forms radius \( R_0 \), by the angle of the platform inclination \( \alpha_p \), by the direction of the inclination vector \( \beta_p \), and by the platform turning (twisting) angle \( \psi_p \) round the vertical axis. For the structures of conical shape the relation between radius \( R_0 \) and the object height has the form of

\[
R_0 = R_0^* - (h \cdot \tan \varphi_0),
\]

where \( R_0^* \) is the radius of the structures at zero mark.

The process of the system operation is accompanied by influencing on it several kinds of disturbing influences. The first group comprises influences leading to deformation of the erected structure and displacement of the platform with the forms. They cover influence \( F_s \) connected with the structure sun-heating and influence \( F_w \) caused by the wind load. Due to the temperature difference \( \Delta \tau = \tau_s - \tau_c \) of the sunny and shady sides there occurs deformation of the structure and its deviation from the designed axis. The deviation quantity \( \delta_s \) is the function of the height \( h \), the object diameter \( D \), the walls width \( b \), and
the period of heating $t_s$: $\delta_s = f_s(\Delta \tau, h, D, b, t_s)$. In order to evaluate the influence of the object temperature gradient on the MSRS operation we have introduced the coefficient of deformation, which is calculated by the formula: $k^d_s = h \cdot e_s / (16\pi \cdot R_o)$. The platform deviations connected with temperature heating will be

$$\Delta x_s = 0.5k^h_s \cdot h \cdot \Delta \tau \cdot \cos \theta_s; \quad \Delta y_s = 0.5k^h_s \cdot h \cdot \Delta \tau \cdot \sin \theta_m;$$

$$\Delta z_s = k^h_s \cdot R_o \cdot \Delta \tau; \quad \Delta \alpha_s = k^\varphi_s \cdot \Delta \tau.$$

As a result of the wind load there occurs inclination of the structure by the angle of $\alpha_w$ and deviation of the MSC platform center from the vertical. The deviation parameters can be evaluated by the formulae:

$$\Delta x_w = k^{(h)}_w \cdot F_w \cdot \cos \theta_w; \quad \Delta y_w = k^{(h)}_w \cdot F_w \cdot \sin \theta_w,$$

where $k^{(h)}_w$ and $k^{(\varphi)}_w$ are the coefficients determined by the structure shape and its rigidity; $F_w$ and $\alpha_w$ are the quantity and direction of the wind load.

Net deviations should be considered as a sum of deviations due to heating ($x_t, y_t$) and wind deformation of the structure ($x_w, y_w$):

$$x_{sb} = x_t + x_w = \delta_t \cos \alpha_t + \delta_w \cos \alpha_w;$$

$$y_{sb} = y_t + y_w = \delta_t \sin \alpha_t + \delta_w \sin \alpha_w;$$

where $\alpha_t = \psi(time)$ is the direction of sunlight heating; $\alpha_w$ is the direction of wind; $\delta_t = f_1(\Delta \tau, h, \alpha_t, \nu_w)$ is heat deformation; $\delta_w = f_2(h, \sigma_w, \nu_w)$ is wind deformation; $\nu_w$ is wind velocity; $\Delta \tau = \tau_h - \tau_c$ is difference in temperature between sunny and shady sides of the object; $h$ is the complex elevation.

The platform turn caused by actions of external factors is convenient to connect with coordinates of hoisting mechanisms by equations:

$$\alpha_g = \arctg \left[ \max(\Delta z^{(i)}_j) / R_j \right];$$

$$\beta_g = \frac{2\pi}{n} \int \left( \max(\Delta z^{(i)}_j) \right);$$

$$\psi_g = \frac{1}{n} \sum_{i=1}^{n} \left[ \arctg(C) - \frac{2\pi}{n} (i - 1) \right];$$

$$C = \left( \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{y^{(i)}_j - \sum_{j=1}^{n} y^{(i)}_j / n}{x^{(i)}_j - \sum_{j=1}^{n} x^{(i)}_j / n} \right),$$

where $\alpha_g$, $\beta_g$ are the angle and the direction of inclination; $\psi_g$ is a platform torsion.

The second groups of the disturbing influences constitute those applied to hoisting jacks and mechanisms of radial displacement. During the system operation hoisting jacks are under action of static and dynamic loads created by the weight of the platform, forms, equipment and materials: $Q_{\Sigma} = \sum Q_i$ and also under the influence of friction forces $F_f$ and cohesive forces $F_c$ of panels with concrete.

An important factor in lifting jacks work is the interaction of concrete formwork. In the early lifting platform effort sharply increases and reaches a maximum at the time of separation from the concrete formwork (Figure 3). With a further rise formwork occurs overcoming the forces of adhesion between the concrete and sliding formwork. Further, in the contact area and the friction force is observed decreases proportionally to the reduction of contact area.

When the platform lifts, the load changes due to concrete – panels interaction. During the operation irregularity of hoisting jacks’ loads can achieve 75-86% that results in violation of the platform horizontal displacement, its deviation from the designed axis and twisting of the platform with forms. Such condition
of hoisting jacks work make stringent requirements to drives and causes the necessity to synchronize lift speeds.

RDM operation is under the influence of friction and elastic forces appearing when the forms’ elements deformation takes place. When synchronization of operation of hoisting and adjusting units is broken, then reaction forces of concrete additionally act on the RDM and they have a non-linear character (Figure 4). This causes increase of load and decrease of the mechanism speed. Therefore, the operation of the RDM drives should be strictly synchronized with the platform hoisting and coordinated with curvature of the walls being erected.

The characteristic feature of the MSC control is the availability of restrictions for control connected with structural features and technological control cycles. Maximal inclination of the platform with forms in hoisting step cannot exceed conicity of the forms’ panels. Maximal deviation of jacks’ travel from the average meaning in hoisting step is limited by the magnitude:

$$\Delta h_{\text{max}} = \left( h_j^{(i)} \right)_{\text{max}} - \left( \sum h_j^{(i)} \right) n \leq \frac{\Delta D_j l_b}{2},$$

where $\Delta$ is a clearance at the bottom of the forms’ panels, $l_b$ is panels height, $R_j$ is the radius of jacks arrangement.

Therefore, to control the MSC it is necessary to provide measurement and compensation of wind and temperature influences upon the object being erected. The complex lift control should be carried out with due account of limitations for controllability and provision for the trajectory minimal curvature. We suggest to correct the position by the way of the platform inclination in the direction opposite to displacement, and in order to eliminate platform torsion it is suggested to use the method of backward wave which resides in sequential change of the platform inclination direction in each step of hoisting, as a result there appears a spiral motion of the forms in the direction opposite to torsion. This kind of control is based on the forms’ mathematical model, which performs connection of the complex condition parameters with controlling and disturbing influences.

3 THE MATHEMATICAL MODEL OF MSC

On the basis of the slip forms dynamic characteristics and disturbing effects a mathematical model of the complex has been developed (Figure 5).

It makes possible to perform analysis of dynamic characteristics and forecast the forms deviations during the process of its lifting. The mathematical model presents channels controlling the forms lifting and its radius changing, it also reflects connections between then. The controlling effects are voltages of the forms jacks control $U_h$ and radial displacement mechanisms control $U_r$. Coordinates of the forms
centre $Z_0$, $x_0$, $y_0$ and its radius $R$ are considered as adjustable values. While controlling the forms lifting the following external actions are taken into consideration: $F_r$ – the pressure of the lower gripper onto the jack bar; $F_w$ – the forms weight; $F_{fc}$ – friction of the forms shields; $F_v$ – wind load; $F_t$ – additional forces due to thermal gradients. Influence of the force loads on the forms is described by the transfer functions:

$$W_r^{(f)}(s) = k_f; \quad W_w^{(f)}(s) = \frac{k_{fw}}{T_{fw} s + 1}; \quad W_{fc}^{(f)}(s) = \frac{k_{fc}}{T_{fc} s + 1}.$$ 

![Figure 5: Mathematical model of the complex](image)

Influence of wind and thermal effects on the forms position can be represented by transfer functions:
The forms jacks displacement on the step \( \delta_j \) is described by the transfer function

\[
W^{(u)}(s) = \frac{k_{uh}}{(T_{uh} s + 1)s}.
\]

Coefficients matrix \( R \) has the dimensional representation of \( 3\times n \) and sets up the parameters interrelation. The values of its elements are determined from the formulae:

\[
k_{zi} = 1/n; k_{xi} = \left[ 2 \cos(2\pi i/n) \right]/R_h; k_{yi} = \left[ 2 \sin(2\pi i/n) \right]/R_h.
\]

While simulating the channel of mechanisms for radial displacement the following external effects are taken into consideration: \( F_{mp} \) – the mechanism reaction to the displacement forces; \( F_c \) – concrete reaction to the shields displacement; \( F_{pj} \) – elasticity force of jacks; \( F_r \) – shields friction force. The influence of these external effects is described by the transfer functions:

\[
W^{(f)}_{MR}(s) = \frac{k_{uh}}{(T_{uh} s + 1)s}, \quad W^{(f)}_{c}(s) = \frac{k_{uh}}{(T_{uh} s + 1)s}, \quad W^{(f)}_{pj}(s) = \frac{k_{uh}}{(T_{uh} s + 1)s}.
\]

The effect of the controlling voltage \( U_r \) on the operation of the radial displacement mechanisms is described by the transfer function \( W^{(f)}_c(s) = \frac{k_{uh}}{(T_{uh} s + 1)s} \). Transformation functions \( G \) and \( A \) represent matrices of coefficients describing effects of the shields radial displacement on the parameters of the state.

4 CONCLUSIONS AND RESULTS

The approaches and methods of the MSC control discussed in the paper are based on the investigations carried out by the authors in different periods for solving the tasks of monolith construction automation. The presented principles of the MSC control can be used when developing automation projects for erecting monolith objects with a variable radius (chimneys, TV and observation towers, cooling towers etc.). The suggested method of designing the complex lifting makes it possible to develop control algorithms with due account of restrictions for control and disturbing influences acting on the structure. Computer simulation of the described algorithms and laws of the MSC control has shown the efficiency of the suggested methods of movements design and controlling actions formation.

References


DEVELOPING FAILURE AGE PREDICTION MODEL OF HAZARDOUS LIQUID PIPELINES

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Abstract: Pipelines are the most common way of transporting the hazardous materials. They are considered to be the safest way of transporting petroleum products; however, there have been several failures with considerable consequences. As a result, the importance of studying failure of pipelines is not covert to anybody. Failure prediction of pipelines has been the subject of some studies from different perspectives. Estimation of failure age has also been studied from the specific points of view. Most of the studies have focused on producing models with data from inspection tools. These tools are very expensive; although, they are considerably accurate. This research aims to develop a model based on the basic attributes of pipelines without data from the inspection tools to predict the probability of failure. The model predicts the age of failure considering the historical data that was gathered on pipelines' failures. The effect of several variables on the frequency of failures in different age classes is studied in order to identify the effective variables on pipelines' failure. Then, a regression model is developed to estimate the age of failure. Pipe manufacture year, maximum operating pressure (MOP), specified minimum yield strength (SMYS) and pipe diameter over pipe wall thickness are the variables that are considered in the developed model after significant number of modeling iterations. Statistical parameters of the developed regression model prove its soundness. Validation results prove the accuracy of the model with over 80 percent.

1 INTRODUCTION

While pipelines are considered to be the most effective and safe way of transporting hazardous liquids there is probability of failure with monetary and safety consequences. The Pipelines and Hazardous Materials Safety Administration (PHMSA 2013) of US Department of Transportation has gathered data on the failures of oil and gas pipelines in three different date ranges. Over 7,300 failures are recorded from 1986 to 2013 in the United States of America which has resulted in almost 2.9 billion dollar property damages and the leakage of around 4.1 million barrels of hazardous liquids in the environment. Also, records prove the happening of 60 fatalities as well as 2,150 serious injuries which demands significant attention. Accordingly, failures of pipelines specially the ones carrying hazardous liquids (which will be called oil pipelines from now) has become the subject of interest for this study. Literature review proves the insufficiency of studies on the failures of oil pipelines; while, there are a few researches mostly focusing on the safety and reliability-based studies of such pipelines. This study tries to develop a model to predict the age of failure applying pre-mentioned data. The age of failure then will be applied to predict the probability of failure. Risk of failure will be calculated when probability of failure is combined with the consequences of failure. The age of failure can be used to plan the maintenance operations of the pipelines. In order to develop the model, existed data has been studied from different perspectives. Several diagrams have been drawn to analyze the effect of various variables in different classification.
Then, the trend has been studied to find the most effective variables. Data on the selected variables has been embedded to the regression model to produce predictive models of failure age. Then the efficiency of the produced models has been improved by changing the set of the variables considering their importance through analyzing the statistical parameters of the model. Error measuring methods have been used for validation applying test data which consists of randomly selected ten percent of data. Validation phase compares the estimated outputs of model with the actual data from the test dataset. A model has been selected finally which is proved to be the most effective, while reserving the simplicity of the model.

Objectives of this research are to (1) identify and study the most effective factors on the pipelines’ age of failure and (2) develop a model that predicts the age of failure to estimate the probability of failure of oil pipelines.

2 BACKGROUND

Several researchers have tried to model failures of oil and gas pipelines. Parvizsedghy & Zayed (2013) have developed a model for the prediction of failure consequences of oil and gas pipelines. This model has obtained data from the US Department of Transportation. It has identified a series of primary variables including the basic attributes of oil pipelines and some other variables related to the efficiency and quality of the inspection systems in the pipelines. Number of variables are optimized through comparing the efficiency of the produced Neural Networks. The final model is efficiently estimating the monetary consequences of the failures in oil and gas pipelines. Senouci et al. (2013) have developed a model to predict the failure type of oil and gas pipelines. The model benefits from data on the accidents of pipelines which has been published in European database (Davis et al. 2010). The model can predict the potential type of failure out of mechanical, operational, corrosion, third party and natural hazards. Validation results have proven accuracy of the model. Variables that have been applied in this model include product type, location of pipe and land use as categorical variables and pipe age and diameter as the numerical variables. The research gets use of Artificial Neural Network and regression analysis in developing the model. NOOR et al. (2011) have proposed a probabilistic method to forecast the remaining strength of offshore pipelines considering data from the Inline inspection tools. This method is developed based on the assessment rules of DNV’s Recommended Practice for Corroded Pipelines (DNV 2010) considering the standard deviation of inspection tools in determining the defect sizes. Bersani et al. (2010) have proposed a model to predict the probability of failures applying Artificial Neural Networks. For each cause of failure, a set of factors are proposed as the independent variables. Preliminary results on the prediction of third party failures’ probability have been presented; however, results do not prove the importance of the proposed factors and neither the soundness of the model. Caleyo et al. (2009) have developed probability distributions of corrosion depth and rate of growth applying Monte Carlo simulation. Different curves are proposed for underground pipelines considering properties of various soil types. Teixeira et al. (2008) have proposed a probabilistic model to evaluate the reliability of the pipelines under corrosion. The model employs experimental data and estimates the burst pressure of corroded pipelines. Bertolini and Bevilacqua (2006) have developed regression classification tree to predict the failure class of cross country oil pipelines. The model applies data from the CONCAWE (Davis et al. 2010) database in the training phase and aims to recognize the most risky pipelines to help the operators to decide about the maintence of their network of pipelines. A risk-based decision making support system is developed using Analytic Hierarchy Process (AHP) technique. This model applies expert opinions to obtain the weight of variables that have been identified important on the failures of pipelines. Variables are risk factors includig external and internal corrosion, construction and material defects and acts of God. Failure probability is estimated by the scores through the expert judgement. Dey (2004), Sinha (2002) and Ahammed (1998) have developed probabilistic models due to the uncertainties of pipeline parameters. Researches have obtained data from Inline inspection tools to predict the failure probability of oil and gas pipelines under corrosion. These tools are used to gather data on the condition of oil and gas pipelines. The models require data on defects depth and length from Inline inspection tools. Ahammed (1998) has applied reliability theory to estimate the remaining strength and integrity of pipelines.
This study proves deficiency of the researches on the estimation of failure probability of oil and gas pipelines. Current researches are either subjective and based on the expert opinion or have concentrated on physical models which require data from inspection tools. However, inspection tools are very expensive to run regularly and there is a need to develop predictive models based on the attributes of oil and gas pipelines.

2.1 Overview of regression modelling

Regression models are suitable for construction management problems and are used in a wide range of researches. Salman and Salem (2012) have used regression analysis to develop deterioration models for sewer pipelines, Wang et al. (2009) to forecast the annual break rates of water mains, Chughtai and Zayed (2008) to develop structural condition assessment models of sewer pipelines and Zayed et al. (2007) for productivity estimation models of horizontal directional drilling activities. These pattern recognition techniques can discover the relationship between the dependent and independent variables of historical data. Result of a linear regression model becomes in the form of the Equation 1 (Senouci, et al., 2013) where $Y_i$ represents the dependent variable, $x_1, x_2, \ldots$ and $x_n$ represent independent variables and $\beta_0, \beta_1, \ldots$ and $\beta_n$ are the parameters of the regression model.

\[ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \]

This equation represents the best curve that fits the historical data assuming the error in each trial from the training data should be 1) independent of the predictor variable 2) the errors should be normally distributed around each value. (Senouci, et al. 2013) After developing the regression model, it should be assessed via different parameters. Significance of independent variables is evaluated through F-test, the results of which is presented as $P(f)$ values which should be less than alpha level. The acceptable amount of risk for F-test is the value that the user determines as alpha and is usually equal to 0.05. Accordingly, if the value of $P(f)$ for each variable is less than the amount of alpha then that variable is significant; otherwise, the variable should be removed. Then the regression modelling should be repeated with the new subset of the variables. The other parameter that should be assessed is R-squared of the regression model and the closer is the value of R-squared to 100% the more efficient is the regression model. (Wang, et al. 2009)

3 RESEARCH METHODOLOGY

In this section, the methodology of the model that is developed to estimate the age of failure of oil pipelines is described. Figure 1 presents the overall flowchart of the model development. It includes two major phases of pre-processing and regression analysis phases. Data is obtained from the Pipeline and Hazardous Materials Safety Administration (PHMSA 2013). Historical data will be analyzed to discover the variables which can affect the age of failure. Actually, this analysis will look for the trends that different variables can present in various classifications. After that, data will be prepared to be embedded into the model. Data preparation is comprised of removing missing and technically irrational data and combining existing categories of the database to produce new effective variables. Then data is normalized to make all in the same range of zero to one. In the next phase, training dataset which includes 90 percent of the data that is randomly selected from the prepared dataset is embedded to the regression analysis model. Then the produced models are assessed, based on the basic diagnostic parameters such as R-squared, $P(f)$ and $P(t)$. Different subsets of the primary variables are tested and the satisfactory models are selected. Selected models have gone through the residual analysis. This analysis plots residuals against the normal distribution and tests normality of residuals. This test tries to prove the assumption that the produced errors should be normally distributed around each value. After that, test dataset is applied to validate the satisfactory models. The validation step assesses the accuracy of the produced models against actual data via different methods.
Table 1 depicts frequency of the failures in each age class versus the failed pipelines’ wall thickness, pipe diameter, Specified Minimum Yield Strength (SMYS) and Maximum Operating Pressure (MOP) Classes. Age of failure is classified in seven groups, in the first ten years of pipelines’ life, number of failures increases due to the bathtub theory, as a result this period is divided into two groups of zero to five and six to ten years. The other classes include the groups of a decade till 50 years after which the older pipelines are classified in the same category. As it can be seen from the graph, there is a visible trend in all of the failure age classes versus pipe wall thickness except for the group of zero to 0.2 inches. The same happens to the total failures and number of failures is decreasing by growing the wall thickness of the pipes. That could be as a result of increasing strength of the pipes. Accordingly, pipe wall thickness is identified as a significant variable in the model. There is a clear trend in the frequency of the failures in the failure age classes versus pipe diameter classes. The number of failures in almost all of the failure age classes decreases by increasing the diameter of pipes. However, there is an exception for the group of pipes with diameter less than five inches in which the number of failures is less than the other groups of larger diameter. Semi-regular trend proves the importance of diameter of pipes in the age of failure. The same is true for the total number of failures in diameter classes which means by growing the pipe diameter, number of the failures are dropping meaningfully. Frequencies of failures in the failure age classes versus the classes of SMYS are also presented in table 1. A decreasing trend is visible in some of the age classes such as zero to five and six to ten. However, all of the failure classes do not display a similar pattern. Totally, the number of failures decrease from zero to 45,000 psi but the group of 45,000 to 55,000 psi does not follow the previous pattern and the number of failures increases. Then, the diminishing pattern continues in the next group. Although SMYS does not follow a very strong pattern in different classes, this variable will be inserted to the model and the significance of the variable will be determined through the statistical values of the regression model. Frequencies of failures in different age classes versus Maximum Operation Pressure classes have also been printed in the following table. As it can be predicted, increasing the operating pressure of the pipelines raises the number of failures in almost all of the failure age classes. There exists an exception of pipelines over 50 years when the
Operating pressure exceeds 950. In this group the number of failures drops; while, the previous groups confirm the increasing trend. An increasing trend of incident frequencies happens in the total failures of pipelines too. Muhlbauer (2004) suggests combining pipe diameter and wall thickness to form a new variable, namely pipe diameter over pipe wall thickness (D/th.). This variable can determine the crack potential or strength of the pipe.

Table 1: Frequency in Different Failure Age classes versus Various Pipe Wall Thickness, Diameter, Specified Minimum Yield Strength (SMYS) and Maximum Operating Pressure (MOP) Classes

<table>
<thead>
<tr>
<th>Variable Classes</th>
<th>Total</th>
<th>0-5</th>
<th>6-10</th>
<th>11-20</th>
<th>21-30</th>
<th>31-40</th>
<th>41-50</th>
<th>&gt;50</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wall Thickness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>th&lt;0.2</td>
<td>538</td>
<td>49</td>
<td>28</td>
<td>76</td>
<td>152</td>
<td>114</td>
<td>52</td>
<td>67</td>
</tr>
<tr>
<td>0.2&lt;=th&lt;0.3</td>
<td>1279</td>
<td>92</td>
<td>43</td>
<td>110</td>
<td>237</td>
<td>271</td>
<td>215</td>
<td>311</td>
</tr>
<tr>
<td>0.3&lt;=th&lt;0.4</td>
<td>860</td>
<td>73</td>
<td>22</td>
<td>54</td>
<td>81</td>
<td>129</td>
<td>157</td>
<td>344</td>
</tr>
<tr>
<td>th&gt;=0.4</td>
<td>140</td>
<td>24</td>
<td>16</td>
<td>24</td>
<td>24</td>
<td>19</td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-5</td>
<td>214</td>
<td>33</td>
<td>11</td>
<td>34</td>
<td>38</td>
<td>38</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>5&lt;=d&lt;11</td>
<td>1595</td>
<td>123</td>
<td>58</td>
<td>125</td>
<td>282</td>
<td>272</td>
<td>235</td>
<td>500</td>
</tr>
<tr>
<td>11&lt;=d&lt;17</td>
<td>625</td>
<td>48</td>
<td>19</td>
<td>62</td>
<td>105</td>
<td>139</td>
<td>100</td>
<td>152</td>
</tr>
<tr>
<td>17&lt;=d&lt;23</td>
<td>181</td>
<td>12</td>
<td>7</td>
<td>18</td>
<td>27</td>
<td>39</td>
<td>47</td>
<td>31</td>
</tr>
<tr>
<td>23&lt;=d&lt;29</td>
<td>107</td>
<td>13</td>
<td>8</td>
<td>10</td>
<td>18</td>
<td>20</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>29&lt;=d&lt;35</td>
<td>61</td>
<td>8</td>
<td>4</td>
<td>8</td>
<td>21</td>
<td>12</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>&gt;=35</td>
<td>31</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>5</td>
<td>11</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>SMYS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMYS&lt;=25,000</td>
<td>817</td>
<td>59</td>
<td>36</td>
<td>68</td>
<td>131</td>
<td>124</td>
<td>112</td>
<td>287</td>
</tr>
<tr>
<td>25,000&lt;SMYS&lt;=35,000</td>
<td>653</td>
<td>54</td>
<td>17</td>
<td>34</td>
<td>61</td>
<td>94</td>
<td>147</td>
<td>246</td>
</tr>
<tr>
<td>35,000&lt;SMYS&lt;=45,000</td>
<td>417</td>
<td>44</td>
<td>20</td>
<td>42</td>
<td>25</td>
<td>124</td>
<td>85</td>
<td>77</td>
</tr>
<tr>
<td>45,000&lt;SMYS&lt;=55,000</td>
<td>616</td>
<td>37</td>
<td>17</td>
<td>76</td>
<td>176</td>
<td>154</td>
<td>74</td>
<td>82</td>
</tr>
<tr>
<td>SMYS&gt;55,000</td>
<td>96</td>
<td>18</td>
<td>8</td>
<td>22</td>
<td>13</td>
<td>14</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td><strong>MOP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOP&lt;=250</td>
<td>198</td>
<td>21</td>
<td>14</td>
<td>20</td>
<td>27</td>
<td>23</td>
<td>27</td>
<td>66</td>
</tr>
<tr>
<td>250&lt;MOP&lt;=600</td>
<td>444</td>
<td>37</td>
<td>13</td>
<td>35</td>
<td>53</td>
<td>53</td>
<td>68</td>
<td>185</td>
</tr>
<tr>
<td>600&lt;MOP&lt;=950</td>
<td>733</td>
<td>31</td>
<td>17</td>
<td>44</td>
<td>113</td>
<td>115</td>
<td>138</td>
<td>275</td>
</tr>
<tr>
<td>MOP&gt;950</td>
<td>1326</td>
<td>127</td>
<td>53</td>
<td>155</td>
<td>290</td>
<td>321</td>
<td>187</td>
<td>193</td>
</tr>
</tbody>
</table>

Figure 2 illustrates the average age of failures in each diameter by wall thickness class versus the manufacturing year of pipelines. As it can be seen from the graph, there is a regular pattern in each diameter by wall thickness class. Actually, the average age of failure is decreasing in each classification by increasing the manufacturing year of pipelines. This fact reveals the importance of the factors of diameter over pipe wall thickness and pipe manufacturing year. Study of the other variables did not either result in any regular patterns or did not have enough data to be studied. Due to the results of these studies, manufacturing year of pipes (Man. Year), Diameter (D), wall thickness of pipe (th.), Diameter over pipe wall thickness (D/th.), Specified Minimum Yield Strength (SMYS) and maximum operating pressure (MOP) are identified as the primary effective variables in modeling the age of failure.
4 DATA COLLECTION

Pipeline and Hazardous Materials Safety Administration (PHMSA 2013) of US Department of Transportation has recorded data on the failures of the hazardous liquids and gas pipelines. PHMSA (2013) Data includes different date ranges from 1986 to 2001, 2002 to 2009 and 2010 to 2013. Each dataset includes different categories and the last dataset includes more categories than the previous ones. Data is also classified into the pipelines of hazardous liquids, gas distribution and gas transmission. This paper focuses on only hazardous liquid pipelines which includes the pipelines carrying liquid products such as crude oil and refined petroleum products. This database provides data on the basic attributes of pipelines such as pipe manufacturing year, pipeline installation year, incident date, Specified Minimum Yield Strength (SMYS) of pipe, Maximum Operating Pressure (MOP), pipe diameter as well as the pipe wall thickness. It also, includes data on the failures such as the cause of failures among internal and external corrosion, material and weld defect etc. Due to the existence of the missed data on some of the required variables, those data points with missing values have been removed. Then, data are normalized applying equation 2 in order to change the values of all of the variables to the range of zero to one.

\[ \text{VI} = \frac{V_i - V_{min}}{V_{max} - V_{min}} \]

Where \( V_i \) represents the value of each variable and \( V_{min} \) and \( V_{max} \) are the minimum and maximum value for that variable accordingly. After preparation of data and removing the missed datapoints, 2,236 data points remained that are divided into two datasets of training and test with the ratio of 90 to 10. Table 2 displays the minimum and maximum values of preliminary selected variables before normalisation.

![Figure 2: Average Failure Age in Manufacturing Year Classes versus Diameter Divided by Pipe Wall Thickness Classes](image)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Age</th>
<th>Pipe Man. Year</th>
<th>MOP</th>
<th>D</th>
<th>Th.</th>
<th>SMYS</th>
<th>D/Th.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>0</td>
<td>1905</td>
<td>3</td>
<td>0.13</td>
<td>0.03</td>
<td>15</td>
<td>0.35</td>
</tr>
<tr>
<td>Max.</td>
<td>102</td>
<td>2009</td>
<td>3,650</td>
<td>50.00</td>
<td>1.00</td>
<td>80,000</td>
<td>533.33</td>
</tr>
</tbody>
</table>

5 MODEL DEVELOPMENT

The results of model development and the validation tests are illustrated in this section. As mentioned before, data is divided in two datasets of training and test data. Training data is embedded to the regression analysis and test data is preserved for the validation purposes. Different subsets of primary variables are considered for the models and regression analysis is iterated for the subsets. Regression
models are analyzed considering statistical values such as correlation coefficient ($R^2$), $P(f)$ and $P(t)$. Higher correlation coefficient values prove the efficiency of the regression models. F-test is carried out against alternate hypothesis ($H_a$). This hypothesis assumes that regression coefficients could be equal to zero the results of which are presented as $P(f)$ for each variable. Values less than alpha reject the alternate hypothesis which proves the significance of the variable. If more than one model is produced, the validation results determine the selected model. The higher validation parameters verify the efficiency of the model. In the next section, results of the regression analysis will be presented.

The training dataset is embedded to the Minitab 16 Statistical Software (Minitab 2013) and the regression analysis has been done with three different subsets of the primary variables. It has resulted in three models. Due to the satisfactory results of these models considering their statistical values, validation test has been done on all of them, the results of which are presented in Table 3. As it can be seen, Model No. 2 and 3 are very close in validation values and more efficient than Model No. 1. However, as the Model No. 3 is a non-linear quadratic model, it is recommended by (Kutner, et al. 2005) to select the linear model and preserve the model's simplicity.

Table 3: Correlation coefficient, variables and validation results of three different models

<table>
<thead>
<tr>
<th>Models</th>
<th>$R^2$</th>
<th>Variables</th>
<th>AIP</th>
<th>RMSE</th>
<th>MAE</th>
<th>AVP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model No. 1</td>
<td>87.7%</td>
<td>Man. Year, MOP, D, Th., SMYS</td>
<td>21.708</td>
<td>0.008</td>
<td>0.064</td>
<td>78.292</td>
</tr>
<tr>
<td>Model No. 2</td>
<td>87.6%</td>
<td>Man. Year, MOP, SMYS, D/th.</td>
<td>19.493</td>
<td>0.004</td>
<td>0.056</td>
<td>80.507</td>
</tr>
<tr>
<td>Model No. 3</td>
<td>87.6%</td>
<td>Man. Year, MOP, D, SMYS, D$^2$, SMYS$^2$</td>
<td>19.306</td>
<td>0.004</td>
<td>0.056</td>
<td>80.694</td>
</tr>
</tbody>
</table>

The results of the regression analysis for model No. 2 which is selected to predict the age of failure of oil pipelines is presented in Figure 3. This model includes four variables: pipe manufacturing year, MOP, SMYS and Diameter over pipe wall thickness. All of the variables are proved to be significant as the value of $P(f)$ for all of them is around zero which is smaller than the amount of alpha (0.05). As a result, it can be claimed that this model is the best model to represent the relationship between the age of failure and pre-mentioned variables. Correlation coefficient of the model equals 87.6% which verifies the efficiency of the model.

Regression Analysis: Age versus Man. Year, MOP, SMYS, D/Th.

The regression equation is

$\text{Age} = 0.859 - 0.899 \text{ Man. Year} - 0.131 \text{ MOP} + 0.0562 \text{ SMYS} - 0.0936 \text{ D/Th.}$

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.859489</td>
<td>0.005501</td>
<td>156.23</td>
<td>0.000</td>
</tr>
<tr>
<td>Man. Year</td>
<td>-0.899431</td>
<td>0.007567</td>
<td>-118.87</td>
<td>0.000</td>
</tr>
<tr>
<td>MOP</td>
<td>-0.13132</td>
<td>0.01163</td>
<td>-11.29</td>
<td>0.000</td>
</tr>
<tr>
<td>SMYS</td>
<td>0.056170</td>
<td>0.007177</td>
<td>7.83</td>
<td>0.000</td>
</tr>
<tr>
<td>D/Th.</td>
<td>-0.09356</td>
<td>0.02809</td>
<td>-3.33</td>
<td>0.001</td>
</tr>
</tbody>
</table>

$S = 0.0685833 \quad R$-Sq = 87.6% \quad R$-Sq$(adj) = 87.5$

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>4</td>
<td>73.783</td>
<td>18.446</td>
<td>3921.54</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
<td>2230</td>
<td>10.489</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2234</td>
<td>84.272</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Regression Analysis Results

5.1 Residual Analysis

Satisfactory results of model’s statistical parameters, leads us to the next phase which is the residual analysis. Figure 4 illustrates histogram of the frequency of residuals along with the normal distribution

Figure 4
curve. Distribution of the residuals is almost normal with a small skew to the right. Results are satisfactory and acceptable as it is close to a normal distribution. Figure 5 presents normal probability plot of the residuals of the model. The same results are drawn from this graph as the results are almost linear, although showing some discrepancies in the tail of the plot. Discrepancy can be as a result of the outliers; however, historical data shows that they are not outliers and these scenarios are possible.

5.2 Validation of the model

Validation tests the estimated results of developed model against the actual data and it is done through utilizing four equations. In all of the equations, $E_i$ represents the $i_{th}$ estimated value through the model and $C_i$ represents the $i_{th}$ actual value of failure age; while, $n$ is the number of data in the test dataset. Equation related to the Root Mean Square Error (RMSE) is presented in equation 3. The closer is the value of RMSE to zero; the more efficient is the estimation function. Mean absolute error (MAE) is presented in equation 4 and as it can be predicted, the closer is the value of MAE to zero; the more accurate is the prediction. Equations related to the calculation of average invalidity percentage (AIP) and average validity percentage (AVP) are presented in equations 5 and 6 accordingly. In an accurate prediction the value of AIP should be closer to zero; while, the value of AVP is closer to one. AIP of the selected model equals to 19.5%, RMSE equals to 0.004, MAE equals to 0.056 and AVP equals 80.5% which prove the accuracy of the model.
Estimated ages of failure are plotted versus the actual ages of failures in the test dataset which is presented in figure 6. The best fit is depicted by the line drawn on the graph. The relationship of the estimated and actual values is presented with the function on the graph and the correlation coefficient of the generated values versus the actual ones equals to 87% which proves the efficiency of the prediction.

![Figure 6: Estimated age of failure versus actual age of failure](image)

### 5.3 Probability of Failure

Accuracy of the model is proved by the statistical parameters and the validation results. The model can predict the age of failure and it is possible to calculate the probability of failure over time. Equation 7 is proposed to forecast the failure probability assuming the failure probability increases linearly through the time. Failure age is the estimated value through the model and "t" represents the number of years from now before which the failure could happen. In this equation, individual failure probability in all of the years has been assumed to be identical.

\[
P(f(t)) = t \times 100^{ \frac{1}{(Pipe\ mana.\ year + Failure\ age) - Current\ Year}}
\]

### 6 CONCLUSION

The pipelines of Hazardous Liquids are considered to be the safest way of transporting these products. However, recorded data on the failures of these mega infrastructures has proved the importance of research on them. Literature review has also verified the shortage of studies in this field. Operators of these pipelines need inspection tools to predict the failures of their pipelines before happening of the incidents. Due to the fact that inspection tools are expensive to run regularly, predicting models are
required. This study has developed a model to predict the age of failure of these pipelines. The model benefits from the historical data (1986-2013) that is gathered through the PHMSA (2013). First, the effect of different factors is studied to identify the most effective variables on the age of failure. Four variables that have been recognized through this process are pipe manufacturing year, maximum operating pressure, diameter over pipe wall thickness and the Specified Minimum Yield Strength. Then, data is inserted into the regression analysis and several functions have been produced with different subsets of pre-defined variables. Functions are assessed through the statistical values such as R-squared and F-test values. Results proved the efficiency and appropriateness of some of the models. Selected functions are then compared by validation results. Validation is done through the test dataset which includes ten percent of the data. The best function is the most accurate one with the Average Validity Percentage (AVP) equal to 80.5%. Residual analysis over this regression function presents sound outcomes. Finally, the estimated values of failure ages are compared with the actual values in a graph and the best fit is determined. Correlation coefficient of the regression model equals to 87% which proves the efficiency of the model. Finally an equation is proposed to calculate the probability of failure applying failure age that is estimated through the model.

References


A CONCEPTUAL ACCIDENT CAUSATION MODEL BASED ON THE INCIDENT ROOT CAUSES

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Abstract: The measurement and control of incident root causes allows for proactive actions to mitigate risk in advance. In practice, however, it is difficult to identify and collect data that represent the root causes due to the complexity of incident occurrence processes. Despite previous studies on incident causation modelling, the identification of root causes in practice still relies on the investigator's subjective opinion. This research presents a conceptual model that explains the causal relationships between the root causes and the site unsafe level, and eventually assesses incident investigation processes. A case study was conducted to evaluate the 13 root causes in a company's investigation practice. The causal relationship between the root causes was observed based on the company safety database, interviews, and literature review. Then, the detailed model, which explains the incident occurrence process, was explored. Additionally, a hypothetical simulation model that allows for evaluation of the influence of each root cause on the safety level was built and tested to discuss the potential use of the conceptual model. Based on the company database, this paper also suggests and discusses the types of data to measure the root causes in practice. The model demonstrates that not only do safety personal and safety strategies affect the site unsafe level, but other factors also do, such as procurement, engineering, human resources, etc. As a result, the proposed model can be used to help identify the root cause in incident investigation practice and to develop strategies to improve safety performance.

1 INTRODUCTION

Incidents in the construction industry can influence project cost, schedule and quality. According to the Association of Workers’ Compensation Boards of Canada (2012), the incident rate in the construction industry is 30% higher than in any other industry. Moreover, the fatality rate of the construction industry is approximately three times higher than the industry average. Incidents can affect the worker’s family, the community, and will also decrease the amount of worker resources available to the industry.

Incidents can generate accidents. According to Bird and Germain (1996), an accident is an event that results in unintended harm or damage, and when it is related to the worker, can result in injury. Any accident can be avoided; however, preventing accidents is difficult, mainly due to the difficulty of understanding accident causes, since several factors, such as worker and management commitment, schedule, and training, can affect it.
Construction companies usually perform an incident investigation to identify the root causes leading to an incident. Based on this investigation, the companies take actions (e.g. safety training, audits) that allow proactive management of safety performance by mitigating the risk in advance. Although several studies have developed accident causation models, the identification of the root causes in practice relies on investigator experience.

Besides identification of the root causes, the measure and control of the incident root causes can also contribute to improvement of the risk mitigation process. However, construction companies have difficulty identifying and collecting relevant data that represent the root causes due to the complexity of the incident occurrence process. Moreover, relevant data could be used to produce simulation models to better predict or estimate the site unsafe level.

The difficulties in identifying, measuring and controlling incident root causes could be due to the difficulty of understanding the causal relationship between them. Nevertheless, the relationship between the root causes should be determined, since projects usually have a limited safety budget, and better results can be achieved if the company can identify the best safety strategy to allocate the resources available (Wirth and Sigurdsson, 2008).

The objective of this research was to develop a conceptual accident causation model in order to explain the causal diagram between the root causes and the site unsafe level.

2 BACKGROUND

Accident causation models aim to “understand the factors and processes involved in accidents in order to develop strategies for accident prevention” (Arboleda and Abraham, 2004; Mitropoulos et al., 2005). According to Hovden et al. (2010), the main reasons for discussing the accident causation models are to: (1) create a common understanding of the accident phenomena; (2) help structure and communicate risk problems; (3) guide investigation on data collection and accident analyses; and (4) analyze the relationship between the factors.

Researchers have developed methodologies to identify incident root causes. Wagenaar and Schrier (1997) developed the TRIPOD model. This model classifies the causes for an incident into 11 General Failures Groups (e.g. design and training). Abdelhamid & Everett (2000) developed the Accident Root Causes Tracing Model (ARCTM). This model uses a decision tree to identify the main root cause of an incident. Suraji et al. (2001) developed a model that classifies the factors that cause an incident into distal and proximal factors. Leveson (2004) developed the Systems-Theoretic Accident Model and Process (STAMP). In this model, the accident occurs when external disturbances, component failures or dysfunctional interactions are not adequately controlled. However, these models are only able to pinpoint the main factors that cause the incident, not support the dynamic relationship between them.

As the previous models are not able to deal with the dynamic relationship between the factors, researchers have developed system dynamic models to understand how factors cause an incident. Cooke & Rohleder (2006) focus on how worker risky behavior and the learning process can cause an incident. Han et al. (2014) verified how the production pressure is related to incidents. Jiang et al. (2015) and Shin et al. (2014) developed models to understand the influence of the worker’s unsafe behavior on the incidents. It is possible to verify that these models are not able to deal with different root causes specified in practice by construction companies. Moreover, these models are generally conceptual and it is difficult to apply them to company safety routines.

The models and techniques presented have difficulties measuring the root causes that influence incidents. In practice, the incident investigation is usually only able to classify the occurrence of a pre-established root cause as Yes/No. The incident investigations utilized by construction companies usually collect information to describe the incident, but do not collect data to measure the influence of each root cause on the incident. Therefore, the companies have difficulty finding preventive actions to avoid further incidents.
3 METHODOLOGY

A case study was conducted to evaluate the root cause in a company's incident investigation practice. The incident root causes were identified. Although the root causes were established based on Bird and Germain (1996), there was no definition about how to classify each root cause during the incident investigation procedure. Therefore, the root causes were defined based on literature review and the company incident investigation.

After identifying and describing the root cause used by the construction company, the causal diagrams were developed. These diagrams were built based on the company's incident investigation, safety database, interviews, HSE Manual and further literature review.

The last step was to define empirical equations and build a hypothetical simulation model to understand the model behavior and evaluate the influence of each root cause on the site unsafe level. Moreover, data types were suggested to measure each root cause based on the safety database and the incident investigation.

4 IDENTIFY AND DEFINE THE ROOT CAUSES

According to the company safety policies, for every incident that occurs on the construction site, an incident investigation should be conducted. The company established 13 root causes of incidents, and the investigator should choose at least one cause based on his/her experience. A short description for each root cause is shown in Table 1.

Besides the incident root causes, the incident investigation defined by the construction company also collects information about the date and time of the incident, weather and lighting conditions, worker information, worker schedule, injury details, activity type, tools and equipment utilized in the incident, substandard act, substandard conditions, witness statement, etc.

5 CONCEPTUAL MODEL

The conceptual model established two main categories as the cause of the site unsafe level: worker behavior and site conditions. These categories were defined based on the incident investigation and literature review (Lingard and Rowlinson 2005). The site unsafe level can cause an incident. An incident, in this research, is every occurrence likely to lead to grave consequences. Accidents are every occurrence that decreases worker availability in the project. Therefore, incidents and accidents are positively correlated.

Three main loops were identified in the conceptual model. Loop R1 is related to the site condition. The company and some researchers (Mitropoulos et al. (2005) and Han et al. (2014)) stated that the accident affects the schedule pressure causing congestion, and increasing the site unsafe condition. Moreover, factors such as temperature, project type, activity type (Lee et al. 2012), and site layout (Anumba & Bishop, 1997), can also affect the site unsafe condition.

The other two loops (B1 and B2) are related to the worker behavior. The schedule pressure can affect the worker intention to work safe (Mitropoulos et al. 2005), and consequently, the worker safe behavior. Moreover, incident investigations can increase worker knowledge and also the perception of risk (Construction Industry Institute, 2002), improving the worker safe behavior (Han et al. 2014). Figure 1 shows a conceptual model of the influence of the worker safe behavior and site conditions on the site unsafe level.
### Table 1: Incident root causes description

<table>
<thead>
<tr>
<th>N</th>
<th>Root Cause</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hazard Identification and Control</td>
<td>Worker characteristics influence the identification and control of hazards.</td>
</tr>
<tr>
<td>2</td>
<td>Human Resource / Professional Development (HR/PD)</td>
<td>The hiring process was not able to verify the workers’ skills and knowledge.</td>
</tr>
<tr>
<td>3</td>
<td>Standard Operating Procedures Practices</td>
<td>The safety procedures to perform a task in a safe manner were not defined.</td>
</tr>
<tr>
<td>4</td>
<td>Leadership and Administration</td>
<td>Attitudes from the management do not demonstrate commitment to safety.</td>
</tr>
<tr>
<td>5</td>
<td>Inspection and Audits</td>
<td>The inspection and audits of equipment, processes, and workers were not defined/realized. In this research, the worker perspective of the inspection and audits will be considered.</td>
</tr>
<tr>
<td>6</td>
<td>Orientation and Training</td>
<td>The orientation/training was not able to transfer knowledge to the worker.</td>
</tr>
<tr>
<td>7</td>
<td>Site Specific Safety Plan</td>
<td>There is no recommendation about the safety procedures that should be followed in the construction site.</td>
</tr>
<tr>
<td>8</td>
<td>Communication Systems</td>
<td>The communication system was not able to inform the worker about the risks on the site.</td>
</tr>
<tr>
<td>9</td>
<td>Security/Emergency Response Engineering</td>
<td>There are no procedures to follow if an incident occurs.</td>
</tr>
<tr>
<td>10</td>
<td>Procurement</td>
<td>Verify problems related with the project design.</td>
</tr>
<tr>
<td>11</td>
<td>Sub / Trade - Contractor Management</td>
<td>Verify errors in the procurement process, such as lack of material specification and delay in delivery.</td>
</tr>
<tr>
<td>12</td>
<td>Environment</td>
<td>Verify the climate conditions that can influence an incident.</td>
</tr>
</tbody>
</table>

![Basic conceptual model](image)

**Figure 1: Basic conceptual model**

The root causes defined by the construction company were categorized between the worker safe behavior and the site conditions categories. Each loop is explained in further detail below.

**Site Condition** (R1): Figure 3 shows the influence of the incident root causes on the site unsafe conditions. The site unsafe level increases the quantity of incidents and accidents. According to Han et al. (2014) and Mitropoulos et al. (2005), an accident can cause delays, increasing the schedule pressure. To compensate for the delay, the company can hire new workers. However, these workers increase the site congestion. The congestion increases the site unsafe condition because it increases workers' exposure to struck-by or struck-against incidents (Fortunato et al. 2012). According to the company safety investigation, the site safety conditions can also be affected by the root causes Environment (e.g.
temperature, lighting, and wind), Standard Operating Procedures, Site Specific Safety Plan and Security Emergence Response.

![Diagram](image)

**Figure 3: Influence of the root causes on the site unsafe conditions**

The site conditions are also affected by the root causes Engineering and Procurement. Both of these root causes can also contribute to the schedule pressure. Procurement can lead to material delay and poor design can increase rework.

**Hazard Identification (B1):** Figure 4 shows the influence of worker knowledge on the site unsafe level. If the investigation is able to identify the root causes and the results are shared with the workers, they will increase their knowledge. Workers' previous experience can also affect worker knowledge. According to the company safety database, worker experience and incidents are negatively correlated. Therefore, during the hiring process, it is important to identify workers with more experience. Furthermore, according to the company safety database, the quantity of pre-task meetings is negatively correlated with the quantity of incidents because it increases worker hazard perception (Construction Industry Institute, 2002). In this model, the root cause Safety Communication represents the pre-task meeting.

![Diagram](image)

**Figure 4: Worker knowledge influence on the site unsafe level**

The improvement of workers' knowledge facilitates worker perception of hazards (Jiang et al., 2015). However, worker perception can be affected by the root cause Hazard Identification and Control. This
root cause represents worker physical conditions such as work shift, worker’s age, health condition and other personal characteristics that can prevent the worker from recognizing a hazard.

Worker Intention (B2): Figure 5 shows the influence of the worker intention on the site unsafe condition. Because of the particularity of the worker intention, it was divided in two sub-loops: Fatigue (B2.1) and Safety Climate (B2.2).

Fatigue (B2.1): The schedule performance can make the company increase the workers’ shifts. According to Alvanchi et al. (2012), prolonged working hours can produce fatigue due to decrease in the muscular strength and mental stress. Fatigue can make the worker take shortcuts, not follow the safety recommendations, and consequently, decrease the worker’s intention to work safely (Jiang et al., 2015). Moreover, mental stress can cause distraction and decrease the worker’s capacity for hazard recognition (Hinze, 1997).

Safety Climate (B2.2): In this sub-loop, accidents increase the safety pressure and consequently increase management’s commitment to safety. However, Mitropoulos et al. (2005) stated that the schedule pressure may prevent management from providing and maintaining required safety measures, decreasing efforts to control the worker behavior. Moreover, management commitment is affected by the Leadership and Administration. According to the company HSE manual, the Leadership and Administration considers factors such as lack of discipline, lack of enforcement, lack of safety resources and lack of safety planning. The Management Commitment consequently affects the safety climate (Chinda & Mohamed, 2008). Although not specified as a root cause, safety climate is also affected by the Foreman Behavior (Choudhry and Fang, 2008). The root cause Sub-Contractor Management also affects Safety Climate.

The worker perception of safety (Han et al. 2014) is influenced by the safety climate and inspection and audits. One example of inspection is the Behavior-Based Observation (BBO) Card. The BBO improves worker safe behavior because the worker feels that he/she is being watched by the safety personnel (Vaughen et al., 2010).

Figure 6 shows the complete conceptual model.
6 MODEL EXPERIMENTS AND DISCUSSION

A hypothetical simulation model was built and four scenarios were tested to evaluate the influence of each root cause on the site unsafe level. In the first three scenarios, three different root causes were tested individually: 1) Environment, 2) Orientation and Training, and 3) Inspection and Audits. To better understand the influence of the root cause in each scenario, its value was set to 0 (worst condition), 0.5 and 1 (best condition). The other root causes had their values set at 0.5. The last graph compares the site unsafe level when all root causes are equal to 0.1 and 1. The time defined to visualize the root causes’ influence on the site unsafe level is 90 days. Figure 7 shows the site unsafe level obtained in each scenario.
It is possible to verify that the root causes defined by the construction company can affect the site unsafe level. The root causes defined in the model are inversely proportional with the site unsafe level. Moreover, it is possible to verify that after day 40, the site unsafe level is almost constant. This behavior is due to the schedule pressure, since the work hour overload and the crew size can compensate for the delay caused by incidents and rework. The similarity between the results of the three first graphs demonstrates that different root causes should be improved concurrently to decrease the site unsafe level (graph 4).

To improve the root causes, it is necessary to measure them. Furthermore, Table 2 suggests types of data to measure each root cause.

Table 2: Incident root causes description

<table>
<thead>
<tr>
<th>N</th>
<th>Root cause</th>
<th>Suggested types of data to measure the root causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hazard Identification and Control</td>
<td>Work shift; worker’s experience on the project; worker’s age</td>
</tr>
<tr>
<td>2</td>
<td>Human Resource / Professional Development (HR/PD)</td>
<td>Average of workers’ experience on project; worker’s previous ability</td>
</tr>
<tr>
<td>3</td>
<td>Standard Operating Procedures Practices</td>
<td>Activity risk level</td>
</tr>
<tr>
<td>4</td>
<td>Leadership and Administration</td>
<td>Management site inspection; participation in safety meetings</td>
</tr>
<tr>
<td>5</td>
<td>Inspection and Audits</td>
<td>Quantity of BBO filled per month; quantity of workers per foreman</td>
</tr>
<tr>
<td>6</td>
<td>Orientation and Training</td>
<td>Worker training hours; evaluate of workers’ learning of the course content</td>
</tr>
<tr>
<td>7</td>
<td>Site Specific Safety Plan</td>
<td>Equipment and tool maintenance per month; safety program level of maturity</td>
</tr>
<tr>
<td>8</td>
<td>Communication Systems</td>
<td>Quantity of pre-job inspections completed per month</td>
</tr>
<tr>
<td>9</td>
<td>Security/Emergency Response</td>
<td>Escape route facilities (clear, indicated and shorter path)</td>
</tr>
<tr>
<td>10</td>
<td>Engineering</td>
<td>Engineering quality by discipline</td>
</tr>
<tr>
<td>11</td>
<td>Procurement</td>
<td>Procurement quality by discipline</td>
</tr>
<tr>
<td>12</td>
<td>Sub / Trade - Contractor Management</td>
<td>Evaluate observation of safety practices in the project</td>
</tr>
<tr>
<td>13</td>
<td>Environment</td>
<td>Temperature; wind speed; noise</td>
</tr>
<tr>
<td></td>
<td>Foreman</td>
<td>Foreman skill level; foreman age; safety supervisor experience</td>
</tr>
</tbody>
</table>

Besides the data types presented in Table 2, the company can also collect information about other factors used in the model, such as congestion (worker ramp up and ramp down), schedule pressure (delays), rework (project quality) and safety pressure (total recordable incident rate – TRIR).

The incident investigation can be improved to collect the data type suggested. Moreover, as some of the company’s incident investigations were not fully completed, the model could reinforce the importance of collecting all data requested by the investigation. In this case, the investigation will not be utilized just to describe an incident, but also to measure and control the incident root causes. The definition of the root cause can also help to better identify the incident causes, especially for those investigators who have to conduct the investigation.

The conceptual model was developed to identify the relationships between the root causes, but it is not recommended to be used to predict the site safety level. For this purpose, other simulation techniques, such as hybrid models combining discrete event simulation with system dynamics, or agent-based models, can achieve better results. According to Sawhney et al. (2003), an agent-based model “can be used to mimic the construction environment in which the worker [is] performing [his/her] work, along with
heterogeneous set of agents representing these workers to study various aspects of safety." Furthermore, root causes such as Environment, Procurement and Engineering can change values during the simulation and improvements are necessary to better predict the site unsafe level. However, the relationship between the root causes identified in this research can be used on other simulation models to improve the results.

Based on the model and the data type suggested to measure the incident root causes, construction companies can adopt strategies to improve the site safety level, such as improve the selection of engineering, suppliers, and sub-contractors in aspects related to safety; implement inspection procedures such as the BBO card and measure the supervisor’s commitment to safety.

7 CONCLUSION

The accident conceptual model developed in this research was able to demonstrate the relationship between the incident root causes defined by the construction company and the site unsafe level. It is also possible to conclude that not only are safety procedures, safety personnel, and field workers responsible to improve safety performance, but other company departments are as well. In this way, it was possible to conclude that, root causes such as project design, procurement, and HR/PD can affect the site unsafe level. Moreover, all departments that can cause project delays or influence the quality can influence the site unsafe level.

The company can improve the incident investigation procedures based on the conceptual model. Factors to measure each root cause were suggested and it is recommended to collect them during the incident investigation. Although this conceptual model cannot be used to predict the safety level, it is believed that the relationship defined in this research can be used in the future to develop a simulation model to measure and forecast how different safety strategies can affect the incident root cause and consequently the site unsafe level.

Ongoing research on the company safety database has been developed to validate the relationship between the root causes. Further steps are to define to which degree the different root causes affect the site unsafe level and validate the data type to measure the root causes with the safety managers.

Acknowledgements

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References


INVESTIGATING MODEL EVOLUTION IN A COLLABORATIVE BIM ENVIRONMENT

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Abstract: As the adoption and implementation of building information modeling (BIM) continues to gain momentum, the benefits and challenges of its implementation and use are becoming better defined. However, there still lacks an understanding into the reconfiguration of practice that is being induced by BIM within multi-disciplinary project teams. Part of this reconfiguration of practice involves the development of the model through the generation, authoring and exchange of project information. This paper presents the finding of a research project that investigated the evolution of a BIM developed by a vertically integrated project team on a large institutional project for design and construction purposes. The objective of the research project was to develop measures to investigate the evolution of a BIM in a collaborative and multi-disciplinary project setting. The research team analyzed the bi-weekly iterations of the models produced by the design team following a rigorous protocol. Timesheets were obtained for all project team members involved in the modeling process. The measures developed adopt both the product and the process perspective of BIM. These measures were tested to verify how they correlated to one another and to the overall time spent in the project and in BIM. Four categories of measure are developed: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. These measures can serve as a benchmark to evaluate the efficiency of the modeling and ultimately the project delivery process.

1 INTRODUCTION

The transition to building information modeling (BIM) based practice in the Architecture, Engineering and Construction (AEC) industry promises considerable benefits over traditional practice mainly due to the possibility for project teams to co-develop, coordinate and optimize the digital prototype of a product (building, infrastructure, etc.) prior to its execution. This prototype is developed as a parametric model, acting as a database containing a product’s information available for reuse during its entire lifecycle (Eastman et al., 2011). These benefits are accrued through better information authoring, exchange, management and retrieval (Crotty, 2011); in theory BIM is allowing project teams to mitigate information chaos in the project lifecycle (Dubler et al., 2010). Considering that project teams can be considered information processing systems (Winch, 2010), this push to eliminate information chaos within the project team is central to one of the core tenants of BIM which is to improve the efficiency and performance of the AEC industry (Eastman et al., 2011). On the other hand, the transition to BIM constitutes a departure from traditional practice (Dossick and Neff, 2011). As such, organizations are currently caught in a period of disruption in the AEC industry: the promise of BIM is alluring to many and in this regard, they are
moving forward with its implementation. However, they are being confronted to deeply entrenched practices, hence the notion of paradigm shift and the need to reconfigure these practices to leverage the benefits of BIM (Taylor and Bernstein, 2009). While theoretical developments in the area of BIM implementation are taking root, there is still a need to define and assess how this shift is affecting practice and more precisely how it is impacting the generation, authoring, exchange and management of project information across a project’s lifecycle. From this perspective, this paper aims to increase our understanding of how a BIM evolves throughout a project and the factors that mediate its progression by developing measures to investigate its evolution in a collaborative and multi-disciplinary project setting. This paper specifically aims to answer the following questions: (1) what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? (2) How do these measures correlate between themselves, across time and across disciplines? And (3) what do these measures tell us of how a BIM is evolving throughout the project? The case study of a new institutional building procured under a design-build delivery mode is used to develop these measures and answer these questions. Four categories of measure were developed: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. Other measures that have been developed are discussed in the paper, however they were not operationalized. These measures are: measures of project complexity, measures of information quality and measures of information flow. The paper concludes with a discussion about the implications of these measures as well as opportunities for future work.

2 BACKGROUND

The transition to BIM is not without its set of challenges (eg. Eastman et al. 2011), chiefly amongst them, interoperability, or the ability of heterogeneous information systems to communicate (IEEE, 1990) is consistently ranked as a top barrier to BIM. Amongst the many dimensions of interoperability identified (Poirier et al., 2014), technological interoperability remains one of the most important issues which hinders the flow of information in current BIM-based project environments. While strategies to overcome these issues have been developed, namely the OpenBIM standards developed by buildingSMART International, they are still in development. Furthermore, organizational, procedural and contextual barriers, that have been documented in the past, prior to the emergence of BIM, (e.g.Egan, 1998) are still having as important, if not a bigger, impact on the flow of information within the project team than the newly introduced technological barriers. In light of these challenges, different approaches to formalize information handoffs in a BIM-based collaborative environment have been developed, namely the information delivery manual (IDM) part of the OpenBIM standard from buildingSMART International (ISO 29481-1, 2010), the model elements table developed by the American Institute of Architects (AIA) in 2008 (AIA, 2008), the Level of Development (LOD) Specifications developed by the BIMForum released in 2013 (BIM Forum, 2013), as well as the COBie data exchange format developed by the USACE in 2007 and in particular the Data Drops developed in conjunction with the BIM task group in the UK (East, 2007). While these approaches allow to either map out or align model based information authoring and exchanges expectations, they represent set points in time and are often aligned to the tradition project phases, further contradicting the required change in practice to move towards seamless information flow through BIM. Furthermore, these approaches do not allow to assess the dynamic nature of information throughout a project.

Sparse work has looked into the assessment of model evolution in the AEC industry. As such there are little metrics to perform a comprehensive evaluation. However, some work has been performed to investigate specific elements which touch on model-based information evolution. Leite et al. (2011) investigate the effort that it takes to develop a model from a LOD 400 to LOD 500. The main objective is to evaluate the modeling effort in relation to the level of detail. They then evaluate the impact of LoD in supporting MEP design coordination. The study shows that additional modeling effort can lead to more comprehensive analyses and better decision support during design and construction. Sacks et al. (2005) provide a set of benchmarks to evaluate the BIM implementation process in terms of productivity gains between a traditional 2D CAD workflow and a 3D modeling workflow. They go on to find that the transition to BIM has improved productivity between 15% and 41% for design and detailing in structural engineering practice (Sacks and Barak, 2008). East and Bogen (2012) propose an experimental platform and a
methodology to consistently evaluate building models. The tools proposed are experimental and mainly for research purposes. Du et al. (2014) propose a cloud-based BIM performance benchmarking application, called BIM Cloud Score, to allow an overall view of BIM utilization in the AEC industry and facilitate performance improvement for individual companies. The authors developed a series of 6 indicators and 21 measures for the assessment of both the process and the product (the model). The BIM Cloud Score is still a hypothetical tool and has yet to be commercialized. Furthermore, some of the metrics, information quality as an indicator of performance for instance, are summarily discussed and lack robustness. To that effect, Berard (2012) develops 8 specific metrics and describes a scale of observable phenomenon (akin to a maturity model) to evaluate information quality from the contractor's perspectives. He operationalizes these metrics to validate their applicability and usefulness in the AEC industry. While useful, the contractor perspective is narrow and the author doesn’t differentiate between quality of information processes and quality of the product information itself. Dubler et al. (2010) look into the question of process information and study information exchanges through BIM from a lean perspective. They develop the 7 types of waste identified in the Lean approach and map that to types of waste related to information exchanges through BIM. Manzione et al. (2011) develop a BIM Integrated Management Model (BIMM) comprised of four stages, called loops, and a total of 11 steps. In the control loop they operationalize the 6 indices (or measures) of information flow developed in Tribelsky and Sacks (2010) and based on lean concepts. These indices allow measurement of information flow in the process of detailed design where construction documents are prepared. The indices develop in Tribelsky and Sacks (2010) identify information flow bottlenecks, large batch sizes and accumulation of work with the objective of finding faults or bottlenecks in the project development process. They also developed an index for measuring rework which was later validated in Tribelsky and Sacks (2011). In this subsequent paper, the authors find that an unpredictable information flow results in unpredictable project outcomes. This body of work pertaining to evaluating information flow is highly relevant and speaks to the shift in practice from this perspective. In parallel, the BIMM offers a framework to structure how this information should be managed in a project delivery setting. However, certain areas of evaluation are lacking such as information quality, design evolution and productivity. Other domains have looked into assessing the evolution of design and production. Namely, the field of software engineering has developed many measures to evaluate the development (e.g. Ampatzoglou and Chatzigeorgiou, 2007) and quality of software design (e.g. Yacoub et al., 1999). In order to close the gap identified in terms of comprehensive evaluation of design development and evolution in the AECO industry in light of the reconfiguration of practice prompted by BIM, the developments in these fields could be leveraged and applied to the AEC industry. The table below presents various metrics to evaluate different aspects of design and product evolution (table 1)

<table>
<thead>
<tr>
<th>Author</th>
<th>Domain Purpose</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Du et al. 2014</td>
<td>AEC Product and process performance</td>
<td>Productivity – speed of development Effectiveness Quality Accuracy Usefulness Economy</td>
</tr>
<tr>
<td>Berard 2012</td>
<td>AEC Information quality</td>
<td>Relevance Consistency Correctness Precision Availability Distribution Flexibility Amount of information</td>
</tr>
<tr>
<td>Dubler et al. 2010</td>
<td>AEC Information exchange waste</td>
<td>Overproduction Inventory Extra Processing Motion Defects Waiting Transportation</td>
</tr>
<tr>
<td>Tribelsky and Sacks 2010</td>
<td>AEC Information flow</td>
<td>Action rate package size work in progress rework batch size development velocity bottleneck</td>
</tr>
<tr>
<td>Ampatzoglou Chatzigeorgiou 2006</td>
<td>Software size &amp; complexity</td>
<td>Size (Lines of code, number of classes) Complexity Coupling Cohesion</td>
</tr>
<tr>
<td>Yacoub et al. 1999</td>
<td>Software quality</td>
<td>Complexity Coupling Dynamic coupling</td>
</tr>
</tbody>
</table>

Table 1: Measures to evaluate design and product evolution from various domains
3 RESEARCH METHODOLOGY

This research project is part of a larger more comprehensive research project aimed at studying the impact of BIM on project delivery in the AEC industry. The aim of this particular scope of the research project was to investigate the evolution of a BIM in a collaborative, multi-disciplinary project environment by answering the following questions: (1) what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? (2) how do these measures correlate between themselves, across time and across disciplines? And (3) what do these measures tell us of how a BIM is evolving throughout a project? In light of this, the objective of this scope of the research project was to develop and test measures to evaluate the development of information through a BIM. To fulfill these objects, a mixed-method case study methodology was employed. The case studied is that of the new construction of a major institutional building in Edmonton, Alberta, Canada. The $260 million, 39,000 m², project was procured under a design-build contract with the government of Alberta. The project team was made up of 29 different stakeholder organizations.

For the scope of research described in this paper, the research team performed data collection over an 18 month period, which corresponded to the construction documentation phase of the project. More precisely, the research team collected the bi-weekly iterations of the models produced by the design team over this 18 month period and analyzed them following a rigorous protocol. 41 iterations of the model were analyzed for the four main disciplines: architecture, structural, mechanical and electrical, for a total of 164 models. The models were analyzed in their native format (Autodesk Revit 2012 & 2013) and in a model checking and coordination software (Autodesk Navisworks Manage 2014). The models were all purged to remove all unused elements prior to analysis to ensure consistency. Furthermore, Industry Foundation Class (IFC) files were produced for every model and analyzed using the text file, the NIST IFC Analysyser (Lipman, 2011) and Solibri Model Checker v.9.5. This was done to expand the scope of analysis to include measures such as Lines of Code in the IFC schema, number of entities, model components and model revisions. Table 3 presents these measures. Timesheets were obtained for all project team members involved in the design and model development process. The total hours spent on the project and the number of hours spent by BIM personnel (individuals who were working directly in the model) were compiled. The measures were analyzed in three ways: the correlation between the measures, the correlation of the measures between the disciplines and the evolution of the measure across time were calculated for all disciplines and between disciplines. The 'R' language and environment for statistical computing was used (R, 2008). Spearman's rank correlation coefficient (ρ) was used to evaluate the correlation between variables due to its sensitivity to monotonic relationships over linear relationships. A cluster analysis was also performed in R to evaluate the appropriateness of the measures developed. The analysis were run for both absolute values (cumulative, ρabs) and relative values (variance per time period, ρvar) for each measure.

Table 3: Data collection points for model analysis across all disciplines

<table>
<thead>
<tr>
<th>Native model</th>
<th>IFC file</th>
<th>Timesheets</th>
</tr>
</thead>
<tbody>
<tr>
<td>File size (purged)</td>
<td>File size</td>
<td>Total hours per discipline</td>
</tr>
<tr>
<td>Scheduled Objects</td>
<td>LOC in the schema</td>
<td>BIM hours per discipline</td>
</tr>
<tr>
<td>Quantities – all</td>
<td>Entities</td>
<td></td>
</tr>
<tr>
<td>Clashes</td>
<td>Components</td>
<td></td>
</tr>
<tr>
<td>Sheets created</td>
<td>Model revisions</td>
<td></td>
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<tr>
<td>Views created</td>
<td></td>
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<tr>
<td>Annotations (Legends, etc.)</td>
<td></td>
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</tbody>
</table>

3.1 Project setting

The context of the case studied was characterized by the following elements: it was a publicly funded project procured under a design-build agreement with the provincial government. The design team was from a vertically integrated firm offering architectural and engineering services. As such, the core design team was working on the same network in real-time. Bi-weekly updates of the models were published to a
cloud-based project management software to be distributed to the general contractor and sub-trades. Key sub trades were contracted in a design assist role and provided a gross maximum price upon completion of design development. The contracts with the sub-trades and with the client were based on 2D drawings and specifications. As such, the model represented the core database containing project information, however a lot of effort was put into preparing and distributing 2D documents, which themselves contained annotations and specifications that were not found in the model. Therefore, it cannot be said that the model contained all relevant project information. A BIM project execution plan (PxP) was prepared to outline the scope and uses of the model in the project. On key element that was introduced in the PxP was the “Statement of Collaboration Intent” which outlined the intentions of each project stakeholder with regards to BIM use in the project. This is where the level of development was detailed for all disciplines and for all model elements. For example, the statement of collaboration intent for the architectural discipline was the following: “Most elements will only have as much data as we need to produce a 2D set of drawings”. This particular statement was made because the contractual documents and all deliverables for the project were to be 2D documents. Any further modeling that was required for coordination and fabrication purposes would have to be performed by the trades. The active participants in the modeling process on the project were the following: architecture, interior design, structural engineer, mechanical engineer, electrical engineer, general contractor, structural steel contractor, mechanical contractor, electrical contractor. Furthermore, the project context was particular in that, even if this was a design-build project, the client still had considerable involvement during the design phase. The project team had to release progress documents at set milestones, both internally for costing updates and externally for project review by the client. Therefore, two parallel work streams were developed whereby part of the design and documentation effort was put on developing the model and part of that effort was put on producing the 2D documents. Despite this particular context, it is still possible to say that this project was a collaborative BIM-enabled, multi-disciplinary project, with early involvement of key trades and general contractor. In this regard, the evolution of the BIM was intimately tied to the evolution of the project. In the evaluation of the various models, it is assumed that the modeling process is consistent throughout the project and across the project team.

4 FINDINGS

4.1 Measures developed

All disciplinary models were thoroughly analyzed to answer the first question: what measures can be extracted from a BIM for its assessment, from both a product and a process perspective? The thorough investigation of the models allowed us to extract the 12 variables presented in the first two columns of table 3 and view their evolution across time for all four disciplines. Addressing the second question (how do these measures correlate between themselves, across time and across disciplines?) facilitated a categorization of the measures as follows: measures of information quantity, measures of information content, measures of information representation and measures of product evolution. Lastly, the third question (what do these measures tell us of how a BIM is evolving throughout a project?) was addressed for each category to evaluate how the measures identified vary in relation to time spent on BIM by the various disciplines in the project team. Figure 1 illustrates the relationships between the measures of model evolution. Figure 2 illustrates the percentage variance of the four measures at a given period for all disciplines. This percentage variance could be compared to the project average for each measure, compared against a given target, or in the case of a retrospective study such as this one, against the final model which serves as a benchmark.

4.1.1 Measures of information quantity: File size and lines of code in the schema

The measure of information size is a reflection of the overall information contained within the model in terms of bytes of encoded data or information. This measure is represented by file size (both from the purged native file and the IFC file) and the number of lines of code in the IFC schema (LOC) (from the IFC file). The main issue with file size as a measure is in the way the information is encoded by the software platform or how the model is created, with issues associated to the modeling process and elements included in the model. Native file size includes all geometry in the model, properties, relations, annotations, views, sheets, images or renders and other representations that would support the project.
development process, whereas the IFC files only contain the information that was processed at export, which in itself introduces variability due to the potential loss of information during export (Koch and Firmenich, 2011). It must be noted that a version upgrade was performed (from 2012 to 2013 version) for the native software used in the project, which could impact how the IFC files were exported. Regardless, IFC file sizes and LOC are very strongly positively correlated across all disciplines ($\rho_{var} = 0.898$ for architectural). There is a mid-positive correlation between purged native file size and IFC file size for mechanical ($\rho_{var} = 0.506$), while it is considerably lower for electrical ($\rho_{var} = 0.265$) and architectural ($\rho_{var} = 0.163$), which could be caused by information that is not directly included in the model, such as renders, or level of detail of model elements. A quasi-null, although negative, correlation was found for structural
While the number of entities in a model can be interpreted as a direct measure of the raw yet structured information contained in the IFC schema - there is a perfect correlation between LOC (consequently, IFC files size) and number of entities ($\rho_{var} = 1.000$) across all disciplines - the export to IFC process can introduce variability as mentioned. Therefore the measures of components and scheduled objects, which are attributable to model authoring and the project development process, would seem better suited for this measure. Indeed, individuals interact directly with these components in developing the model. The main difference between scheduled objects (extracted from the native file) and model components (extracted from the IFC file) are their practical use: scheduled objects are related to model uses whereas model components are related to model authoring. A mid to strong positive correlation was found between between the number of entities and the number of components for all disciplines ($0.655 < \rho_{var} < 0.810$). There was also a mid to strong positive correlation between the number of scheduled objects and the number of components for all disciplines ($0.415 < \rho_{var} < 0.688$) In the evaluation of the correlation of measures of information content between disciplines, specifically components, a low to mid positive correlation was found between all disciplines ($0.103 < \rho_{var} < 0.696$). A low to mid positive correlation was found between the time spent in BIM and the variation of number of views for all disciplines ($\rho_{var arch} = 0.309$, $\rho_{var struc} = 0.405$, $\rho_{var mech} = 0.702$, $\rho_{var elec} = 0.670$), which indicates a direct relationship between time spent in BIM and the purged native file size. The weaker correlations in architecture and structure could be in part due to the negative variations in size, for instance when certain elements in the model were rationalized. In investigating the evolution of measures of information quantity in relation to time spent in BIM over the course of the project, it was observed that the native file sizes for all disciplines progressed in a linear fashion whereas IFC files sizes jumped drastically at set points in time for both mechanical and structural.

### 4.1.2 Measures of information content: Entities, components, scheduled objects and quantities

The measure of information content relates to the geometry and properties of the elements in the model. While the number of entities in a model can be interpreted as a direct measure of the raw yet structured information contained in the IFC schema, there is a positive correlation between LOC (consequently, IFC files size) and number of entities ($\rho_{var} = 1.000$) across all disciplines - the export to IFC process can introduce variability as mentioned. Therefore the measures of components and scheduled objects, which are attributable to model authoring and the project development process, would seem better suited for this measure. Indeed, individuals interact directly with these components in developing the model. The main difference between scheduled objects (extracted from the native file) and model components (extracted from the IFC file) are their practical use: scheduled objects are related to model uses whereas model components are related to model authoring. A mid to strong positive correlation was found between between the number of entities and the number of components for all disciplines ($0.655 < \rho_{var} < 0.810$). There was also a mid to strong positive correlation between the number of scheduled objects and the number of components for all disciplines ($0.415 < \rho_{var} < 0.688$) In the evaluation of the correlation of measures of information content between disciplines, specifically components, a low to mid positive correlation was found between all disciplines ($0.103 < \rho_{var} < 0.696$). A low to mid positive correlation was found between the time spent in BIM and the variation of number of views for all disciplines ($\rho_{var arch} = 0.309$, $\rho_{var struc} = 0.405$, $\rho_{var mech} = 0.702$, $\rho_{var elec} = 0.670$), which indicates a direct relationship between time spent in BIM and the purged native file size. The weaker correlations in architecture and structure could be in part due to the negative variations in size, for instance when certain elements in the model were rationalized. In investigating the evolution of measures of information quantity in relation to time spent in BIM over the course of the project, it was observed that the native file sizes for all disciplines progressed in a linear fashion whereas IFC files sizes jumped drastically at set points in time for both mechanical and structural.

### 4.1.3 Measures of information representation: Views, sheets and annotations

The creation of views, sheets and annotation supports the design process and become the deliverables for the project. Views are embedded into sheets and annotated to create project documents. The presence of these elements are a characteristic of the parallel 2D – 3D modeling and documentation process. Whereas measures of information content tends to stabilize during the construction documentation workflows; the number of views and sheets continues to grow as the need for additional representations are required to translate and communicate project information to the various project team members. While the definition of what is represented on sheets is an industry standard (ie. plans, elevations, sections, details and schedules), views are highly contextual and not only discipline specific but subject to individual workflows, meaning that there is limited correlation between the number of views and sheets; each sheet will contain at least one view or schedule, but not all views and schedules will be included in a sheet. A low positive correlation was found between number of views and sheets across each disciplines ($0.181 < \rho_{var} < 0.277$); this measure is unrelated between disciplines. A low to mid positive correlation was found between the time spent in BIM and the variation of number of views for all disciplines ($\rho_{var arch} = 0.112$, $\rho_{var struc} = 0.101$, $\rho_{var mech} = 0.284$, $\rho_{var elec} = 0.446$). In the investigation the evolution of measures of information representation over the course of the project, the architectural discipline has the highest total number and the most rapid progression of views, however structural
discipline has the highest views to sheet ratio at 12.82 views per sheet on average. Understanding the rate of information representation progression can allow to evaluate the time spent on the production of 2D drawings, a relatively redundant procedure given the emerging uses of BIM directly on site and in facilities maintenance.

4.1.4 Measures of product evolution: Clashes and Revisions

The overall variation of the above measures (quantity, content and representation) over time will be measures of information evolution. Product evolution and information evolution are differentiated in this case. As such, the number of clashes and revisions in the model can be interpreted as a measure of the refinement of the model as design progresses. The measure of clashes is extracted through clash detection software and is a standard process in current BIM based practice. Three classes of clashes have been developed: true-positives (identified as a clash and is a clash), false-positives (not identified as a clash but is a clash) and false-negatives (identified as a clash but is not a clash) (Leite et al. 2011). In addition, clashes were totaled for each discipline. The number of revisions is extracted by directly comparing model iterations in a model checking software. Three classes of revisions were extracted: elements added, elements removed and elements modified (elements that have one or more characteristic modified). Evaluating the correlation of measures of product evolution between disciplines, the number of revisions showed mid positive correlation ($0.393 < \rho_{var} <0.641$), whereas the number of clashes show higher positive correlation ($0.608< \rho_{var} <0.915$). One element of note is that the design team did not start purposefully addressing clashes before the very end of construction documentation, therefore the measure of the evolution of clashes throughout the project is more or less a valid measure in this case. Furthermore, the models were released on a bi-weekly thus allowing the project team to complete any coordination cycle and thus the clashes that were found would be resolved in the upcoming cycle. Moreover, evaluating the correlation between the number of clashes and the number of revisions would seem a valid point of investigation, indeed this could indicated that clashes reduce as revisions increase, which would be a valid statement. The contrary however wouldn’t make sense. In evaluating this measure, the research team found a null to low correlation ($-0.214< \rho_{var} <0.227$), which confirms that the two measures are weakly related, if not unrelated. A null to mid correlation was found between the time spent in BIM and the variation of number of clashes ($\rho_{var arch} = 0.146$, $\rho_{var struc} = -0.073$, $\rho_{var mech} = 0.420$, $\rho_{var elec} = 0.494$) and the variation of the number of revisions ($\rho_{var arch} = -0.024$, $\rho_{var struc} = 0.230$, $\rho_{var mech} = 0.573$, $\rho_{var elec} = 0.370$). In the investigation the measures of product evolution over the course of the project, no clear trend was discernible for both number of revisions and number of clashes. It would be expected that both would tend towards 0 over time.

4.2 Additional measures: Measures of project complexity, information quality and flow

The measure of model complexity and of level of development are difficult to quantify. While specifications exist for level of development (eg. AIA, 2008), the exercise is carried out manually and remains somewhat subjective. In terms of complexity, some measures could be used such as use of generic model elements and place holders or number of objects per area (Du et al. 2014). Clevenger and Haymaker (2011) have developed some measures of complexity in the design process which could be further investigated in the context of model evolution. However, further work is required to develop measures of complexity that are relevant and directly computable as both measures of product and process in a BIM environment, namely in the investigation of complexity, coupling and cohesion in the IFC schema. Lastly, as discussed, measures of information quality and flow are core to the AEC industry. While the question of information flow has been tackled from various perspectives, the question of information quality is seemingly underrepresented in the AEC research domain. One could say that information flow is a subset of information quality as a measure of process efficiency and quality. The work performed by Dubler (2010) and Berard (2012) speak to these measures, however, they remain difficult to operationalize. For instances, measures of information accuracy and precision have to be validated in the field and compared to a suitable referent. Measures of information relevance are highly subjective and dependent on a stakeholder’s perspective. Trieblesky and Sack’s (2010, 2011) as well as Demian and Walters’ (2014) work tackled some of these issues with information flow, however, the authors acknowledge that the work performed was extremely onerous. Furthermore, while information exchanges can be more readily mapped and measure, information quality is highly subjective and
dependant on the stakeholder’s point of view. Information, its value and its quality in the model is a field of research that requires much more investigation.

5 DISCUSSION AND CONCLUSION

This paper presented the findings of a research project with the aim of investigating model evolution in a collaborative multi-disciplinary BIM-based project setting. Measures were developed to assess this evolution and allow a consistent empirical approach to information evolution in the project delivery process. The measures were tested for correlation between each other, across disciplines and their variation was evaluated across time. While most measures identified were correlated within their categories, further investigation is required to understand this implication across other project settings. Work is also necessary to understand proportionality in the evolution, for instance spending a lot of time on a particular 2D detail will not increase the weight of the model as adding or duplicating a specific component, say a piece of furniture, which takes a lot less time and contributes . Furthermore, in developing these measures and gaining access to data, the research team was faced with multiple challenges. A clear advantage was gained through BIM in this research project due to the possibility of querying project information in a structured manner. However, it would have been advantageous to have access to weekly iterations instead of bi-weekly iterations of the model. The exercise would have gained in precision. In addition, a main challenge was faced in developing a coherent measure of time spent in BIM versus time spent on the model. The research team did not have access to the file logs, nor did the time sheets completed by the employees contain relevant cost codes for various BIM activities. Time spent in BIM had to be extrapolated from the personnel that were identified as BIM users in the project. An additional challenge lay in exporting the IFC files in a consistent manner across different versions of the native software platform. IFC 2x3 was the standard format for export, and a special IFC export plug-in was used, however the mechanics behind the export were unknown to the research team and was seen to introduce a lot of variability between versions of the software platform. There is also some inherent loss in information in the transfer process (Koch and Firmenich, 2011) Moreover, while it was assumed the modeling process be consistent across the project team, each individual has their own way of working and interacting with the model, for instance creating 2D views to modify the model rather than working directly in 3D. This differences introduce variability in the investigation. In analysing the data, the research team was confronted with the choice between absolute values (ie. the compiled value or sum of values since the start of the project) and relative values (the variation between model iterations). Absolute values were used for correlation analysis in this paper whereas, the relative values were used in the time analysis. In the data extraction process, a rigorous protocol was required to replicate every step across the entire project. The research team is looking into automating this process for future work. It is also seeking to expand the scope of data extraction through the use of tools such as COBie data drops and the spreadsheets produced as a formal way to validate project progress. Further work is also required to replicate this evaluation across various project settings. However, in expanding this investigation to include different models, a considerable effort to normalize the data across the different project contexts will have to be carried out. For instance, the uses of BIM which impact the development of the model will have to be factored. The analysis of additional models would allow the regression analysis of multiple data sets to validate the evolution of the measures developed in this paper.

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References


Bim Forum 2013. Level Of Development Specification For Building Information Models


DO STRONG OR WEAK TIES MATTER IN KNOWLEDGE NETWORKS?

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Abstract: Construction and engineering organizations have increasingly implemented knowledge exchange strategies with the goal to facilitate knowledge exchange across the organization. However, despite these efforts, many knowledge strategies fail in practice, as it is not well known when knowledge access is most beneficial. This research analyzes the correlation between group level knowledge exchange and perceived individual benefits. Specifically, we focus on the time saved (in hours per month) on work tasks as a result of accessing knowledge with others in the department. To conduct this research, we used social network analysis and a modularity optimization algorithm to identify the existing knowledge-based subgroups (KBS)—subgroups that share more knowledge internally than externally—within a large engineering and construction organization. To identify whether these knowledge-based subgroups offer time benefits, we compared the time benefits from receiving knowledge within these subgroups and outside these subgroups. Results found that individuals are more likely to perceive saving time on work tasks as a result of receiving knowledge within their subgroups. As a result, our results indicate that the type of benefit received matters to determine whether weak ties or strong ties are important.

1 INTRODUCTION

The importance of knowledge sharing in construction and engineering organizations has gained an unprecedented interest and many scholars view knowledge as the most important resource of the firm (Grant 1996). The efficient allocation of money and labor is not sufficient enough to gain competitive advantage anymore. Instead, knowledge and its use at the right place and time is what allows projects to achieve successful results (Argote and Ingram 2000).

While this view is shared largely in the literature, there are many debates about how and when knowledge exchange brings the most benefits. To address this debate, previous studies have focused on knowledge exchange primarily at the group level, with emerging studies at the individual level. At the group level, the literature has focused on the importance of knowledge exchange on group performance (Cummings 2004; Landaeta 2008; Tsai 2001). For instance, Tsai (2001) showed that business units which are more central are more likely to receive diverse knowledge from other business units which in turn affects innovation and performance. While studying the effects and benefits at the group level is important, it provides an incomplete understanding of how knowledge exchange adds value to outcomes. Specifically, aggregating group level outcomes offers a good understanding of the effect of group level attributes (e.g. size, composition) on final outcomes, but it neglects intra-group dynamics, which represent the core of group outcomes. To address the dearth of literature on individual level outcomes, Wanberg and Javernick-Will (2014) studied the relationship between frequency of individual knowledge exchange and
individual work outcomes in informal organizational groups. They found that infrequent interactions provided individuals with more unique knowledge than frequent knowledge interactions.

As such, individual level knowledge exchange has been analyzed for individual level performance and group level knowledge exchange has been analyzed for group level performance. As a result, the connection between the group level characteristics and individual level benefits has been largely neglected with the exception of Poleacovschi and Javernick-Will (under review) who found that individuals spanning knowledge across highly connected knowledge subgroups are more likely to receive higher individual performance evaluations in a construction and engineering organization.

This research proposes to further address the missed macro-micro link by analyzing the relationship between group knowledge exchange and individual level outcomes. Previous research has identified that individuals gain benefits from their position in the network structure. Nahapiet and Ghoshal (1998) found that individuals share intellectual advantages, such as knowledge exchange, as a result of being part of highly connected groups. Thus, we expect that individuals who are part of highly cohesive knowledge exchange groups will gain benefits from the network connectivity of their group. However, we expect that this relationship is sensitive to the type of relationship, or tie, between the individual and the group. This thinking is in line with the theory of weak ties (Granovetter 1973) which argues that the type of ties matter in a network. To translate Granovetter’s study at the level of subgroups, strong ties are part of highly connected groups while weak ties connect individuals from different subgroups. Considering the importance of project time in construction and engineering organizations, we define individual benefits as the time an individual saved (in hours per month) on work tasks as a result of receiving knowledge from other employees, whether within their knowledge based subgroup or outside of their knowledge based subgroup. Thus, this research asks: Do individuals save more time as a result of their weak or strong ties within knowledge exchange networks?

To answer this question we employed a unique method that identified knowledge-based subgroups (KBS) within a department of a large construction and engineering organization (Poleacovschi and Javernick-Will under review). The method used a social network optimization algorithm that identified subgroups that shared more knowledge internally than externally. Then, using survey data, we identified the perceived time savings as a result of receiving knowledge within their KBS as compared to receiving knowledge outside of their KBS.

This research is important both for theory and practice. To contribute to theory, this research links group and individual level constructs by testing the strength of weak ties theory in KBS. By translating weak and strong ties concepts to KBS, knowledge connections in KBS are strong ties because these subgroups are dense and cohesive, while connections outside KBS are weak ties. By focusing on the specific benefit of time savings, we contribute to theory by extending previous work on different types of benefits that can be received from strong or weak ties. In practice, construction and engineering organizations can choose to invest resources based upon the benefits they seek—in our research, this relates to saving time on work tasks.

2 THEORETICAL BACKGROUND

2.1 Knowledge-based subgroups

The interest in knowledge-based subgroups, or groups that share more knowledge internally than externally, is rooted in the knowledge-based theory of the firm (Grant 1996). In this view, the ability to efficiently exchange the “know what” and especially the “know how” is what differentiates organizations from markets (Kogut and Zander 1992). In other words, construction and engineering organizations exist because they successfully manage to integrate the knowledge of professionals from different disciplines (e.g. structural engineers, project managers) that can easily exchange knowledge, or “know how”, to achieve project goals. Another option is to look for professional knowledge (e.g. structural analysis and project management) on the market. However, this would be less efficient as separate transactions with different professionals would be costly. The knowledge-based theory of the firm also believes that an organization gains competitive advantage whenever it manages to coordinate knowledge exchange better
than other organizations (Argote and Ingram 2000; Grant 1996). Unfortunately, this is not easy as there are many organizational structures and boundaries that impede knowledge exchange (Wanberg et al. 2014; John Wanberg et al. 2014).

As a result of these boundaries, knowledge-based subgroups—subgroups that share more knowledge internally and less externally—can form. The common belief is that subgroups disrupt knowledge exchange, which may be detrimental for the larger performance of the group or organization. For instance, individuals are more densely connected to others within their subgroup and limited knowledge may flow between subgroups, resulting in a boundary that may impede members of the group to search and access knowledge outside their own subgroup. However, this assumes that knowledge exchange with others outside one’s own subgroup is actually valuable—which may not be true. More importantly, valuable in terms of what and valuable for whom? As previous research has mainly focused on the effects of subgroup formation on group level outcomes, we do not know the effect of subgroup formation on individual benefits in terms of time saved on work tasks. Using theory of weak ties we build our hypothesis about the relationship between network ties with KBS and individual time benefits.

2.2 Ties within and between knowledge-based subgroups

The most influential papers addressing individual benefits from network structure are the structural hole (Burt 1995) and the strength of weak ties (Granovetter 1973) theories. A structural hole means the absence of a relationship between two individuals in a network. The theory states that individuals who link two unconnected others are likely to gain benefits. The strength of weak ties theory was the antecedent of structural hole theory and focused on the types of ties and benefits results those ties (Granovetter 1973). Individuals who manage to create ties outside their own subgroup of close relationships (weak ties) gain benefits as a result of reaching for novel resources and information. For instance, in his thesis, Granovetter discovered that weak ties are the most beneficial connections for a job search. Figure 2 shows a visual representation of weak and strong ties. Straight lines represent strong ties while dotted lines represent weak ties.

While this theory is quite influential, it was initially conceptualized and tested in the context of people who were searching for jobs. The theory has been tested less in the context of knowledge networks or considering individual time benefits. KBS are subgroups whose members share more knowledge internally and less knowledge externally. Thus, ties in KBS are strong because of the high connectivity between members, while ties outside of, or between, KBS are weak as they connect distant subgroups, which are highly connected. In contrast to Granovetter’s study, we expect that highly connected subgroups will save individuals more time as a result of the short distance between subgroup members. Conversely, accessing a new subgroup of knowledge through weak ties requires many more steps. As such, individuals will save more time from accessing knowledge in their highly connected network then from accessing knowledge in other subgroups. For instance, member B will access member G’s knowledge easier than member D’s knowledge, although it takes the same number of steps (Figure 1). In other words, members of KBS will use their subgroup connectivity to access knowledge fast. Thus, we expect that the type of tie between the individual and the highly connected network further benefits the individual. If the tie is strong (within a KBS), we expect that the individual will gain more time benefits from accessing that knowledge.
Hypothesis: Individuals will save more time from accessing knowledge from strong ties (within subgroups) than from weak ties (between subgroups)

3 RESEARCH METHODS: DATA COLLECTION

We were provided access to a large set of network data within the department of a large construction and engineering consultancy. The organization has focused on improving their knowledge management strategies for the past decade. They initially implemented knowledge management in the IT department, which was where the data was collected. Survey questionnaires were administered to all employees within this department, with questions focused on with whom they share and receive knowledge and whether these connections help to save them time through the knowledge provided. The response rate for the knowledge network data was 88% (n=142). Non-respondents were excluded from the final analysis.

3.1 Knowledge sharing networks

Questionnaires were administered to all 161 employees in the department. Using definitions of knowledge as information and "know how" (Liebeskind 1996), employees were asked to indicate, on a 6-point scale, the level of knowledge that they receive from other departmental employees. Specifically, they were asked:

"Often we rely on the people we work with to provide us with information to get our work done. For example, people might provide us with simple routine administrative or technical information that we need to do our work. Alternatively, people might provide us with complex information or engage in problem solving with us to help us solve novel problem. Please indicate the extent to which people listed below provide you with information you use to accomplish your work?"

Response options included: 0 – I do not know this person/I have never met this person; 1 – Very infrequently; 2 – Infrequently; 3 – Somewhat infrequently; 4 – Somewhat frequently; 5 – Frequently; 6 – Very frequently.

The data was transferred into a matrix format where questionnaire respondents were listed as rows, and the level of knowledge sharing with each other departmental employee was indicated in columns. The data was then analyzed using social network analysis (SNA) software to determine the composition of knowledge-based subgroups.

3.2 Time Benefits

To identify time benefits accrued as a result of receiving knowledge within and outside KBS, individuals were asked to indicate the time they saved per month (in hours) as a result of receiving knowledge from each individual in the department. They responded to the prompt:

"Please provide an estimate for the typical time saved per month as a result of information, or other resources received from each person."

The respondents assessed the time benefits for each other departmental employee based on a 5-point scale, including: 0 – I do not know this person/I have never met this person; 1 – No time saved; 2 – 1-3 Hours per month; 3 – 4-8 Hours per month; 4 – 9-12 hours per month; to 5 – more than 13 hours per month.

3.3 Individual attributes: hierarchy, tenure and gender

To identify individual attributes, individuals were asked to identify their hierarchy level and tenure (in years) within the organization. Hierarchical levels were determined from a scale of one to five (1 – individual contributor/team member; 2 – supervisor/team leader; 3 – project manager/program manager; 4 – manager/BU [business unit] manager; 5 – director). For tenure, individuals mentioned the number of years they have spent with the organization. Finally, the department provided the data on gender. This
information was later used for the linear regression analysis as control variables. We controlled for hierarchy, tenure and gender as women and newcomers are not expected to gain the same benefits from their position in the network (Burt 1992), while individuals in higher hierarchy levels are expected to be central in networks and gain more benefits (Poleacovschi and Javernick-Will under review).

4 RESEARCH METHODS: DATA ANALYSIS

In this section we present methods used to analyze the collected data with the goal to identify KBS and the average time saved in versus outside of KBS.

4.1 Identifying Knowledge-based Subgroups

We analyzed structural aspects of the department by analyzing the knowledge sharing connections between individuals within the network. We used SNA to identify KBS, which is described in (Poleacovschi and Javernick-Will under review), using Gephi (Bastian et al. 2009), a visualization and network analysis software. Gephi includes a tool that uses the Louvain modularity optimization algorithm (Blondel et al. 2008) to determine groups within the network that share more knowledge internally and less knowledge externally. The algorithm is based on calculating the modularity gain, or, in our case, the change in the level of knowledge exchange within a group as a result of adding a new member to it, compared to the level of knowledge exchange outside the group once the member joins. This determined the number of KBS—which, for this network was four, and the composition of, or employees that belonged to, each of the four KBS. We validated the KBS by running a ‘blockmodel’ in Netminer (Netminer 2014). The blockmodel allowed us to calculate and compare the network density, or the ratio of existing connections to all possible connections, between different KBS. This helped to validate the algorithm, as higher network densities were observed within subgroups compared to network densities between subgroups.

4.2 Identifying Time Benefits in Knowledge-based Subgroups

After the KBS were determined, we analyzed whether individuals within the subgroups received greater time benefits (saving more hours per month) from the knowledge received from employees within their KBS or external to their KBS. To do this, we conducted several steps, outlined below.

1. We constructed a matrix of 142 rows by 142 columns (number of people who took the questionnaire). The rows represented questionnaire respondents, and the columns included the average amount of time they saved per month (on a scale from 0 to 5) based upon receiving knowledge from each other person.

2. We replaced the time benefit scores in the database with the minimum number of hours from questionnaires. For example, a rating of “1” was replaced with 0 hours, a rating of “5” was replaced with 13 hours, etc. This was done to obtain results that can be interpreted from linear regression analysis.

3. We divided the matrix data into four other matrices, which represented the number of subgroups identified in the knowledge network. Each matrix’s rows contained the identified members of one KBS and the columns contained each member’s perceptions of time saved from all 142 participants. We obtained four subgroups (further explained in the next section) which included 35, 33, 42 and 52 members each. Thus, the four matrices were a 35 by 142, a 33 by 142, a 42 by 142 and a 52 by 142 matrix.

4. In each matrix, the column scores were summed for each of the 142 participants in order to obtain perceptions of all members in one subgroup about time saved from receiving knowledge from each of the 142 employees. The 142 values in each of the four datasets were further used for the linear regression analysis.

5. A new variable was added to each of the 142 participants in each of the four datasets – entitled subgroup membership. If members belonged to the subgroup analyzed, then they were assigned a score of 1 and if they belonged to one of the three external subgroups then they were assigned a score of 0. This was done to differentiate between time benefits members gained in their subgroup (1) compared to time benefits gained between subgroups (0).
6. We conducted linear regression analysis using SPSS (SPSS 2013) to identify whether the time benefits were more likely to be associated with knowledge receiving in KBS or between KBS. The dependent variable included the time benefits in hours per month (continuous), while the independent variables included subgroup membership (dichotomous), hierarchy (continuous), tenure (continuous) and gender (dichotomous).

5 RESEARCH RESULTS

5.1 Identifying Knowledge-based Subgroups

Four subgroups were identified using Louivian modularity algorithm: KBS A, KBS B, KBS C and KBS D (Figure 2).

![Figure 2: Visual representation of KBS](image)

The size of the subgroups varied from 27 to 50 members (Table 1). KBS D was the largest subgroup and included 50 members, while KBS A was the smallest subgroup and included 27 members. The blockmodel analysis (Table 1) revealed that the subgroups’ internal density is higher than its external density, validating the existence of subgroups. In this case, members within subgroup A were connected 30% of the time to members within subgroup B while members within subgroup A were connected to 66% of other members within subgroup A. These results were especially meaningful due to the overall density of the network, which was 45%, meaning that of all possible knowledge connections within this department, 45% actually existed.

<table>
<thead>
<tr>
<th>KBS</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>66%</td>
<td>30%</td>
<td>21%</td>
<td>22%</td>
<td>27</td>
</tr>
<tr>
<td>B</td>
<td>34%</td>
<td>97%</td>
<td>44%</td>
<td>46%</td>
<td>29</td>
</tr>
<tr>
<td>C</td>
<td>18%</td>
<td>32%</td>
<td>82%</td>
<td>60%</td>
<td>36</td>
</tr>
<tr>
<td>D</td>
<td>23%</td>
<td>45%</td>
<td>65%</td>
<td>91%</td>
<td>50</td>
</tr>
</tbody>
</table>

5.2 Time Benefits

Initially, we obtained descriptive statistics of all independent variables (Table 2). Then, we ran linear regression analysis to identify whether knowledge receiving in KBS brought more time benefit then across KBS (Table 3). All fours models found that receiving knowledge was perceived to be more beneficial within KBS. Specifically, members saved, on average, 46.5 hours per month more by receiving
knowledge from other members within KBS A then other subgroups, 56.2 hours per month in KBS B, 74.7 hours per month in KBS C, and 89.5 hours per month in KBS D. As a result, we found that strong ties were more likely to offer individual time benefits compared to weak ties.

Interestingly, increased network density (Table 1) within a KBS meant more hours saved in three cases (Table 3). Subgroup B had larger network density then Subgroup A (84% compared to 70%), and was more likely to save more hours (56.2 hours compared to 46.5 hours) from receiving knowledge. Subgroup D had a larger network density then Subgroup C (87% compared to 67%) and Subgroup B (87% compared to 84%), and was more likely to save more hours than Subgroup C (89.5 hours compared to 74.7 hours) and Subgroup B (89.5 hours compared to 56.2 hours) respectively. However, Subgroup C was an exception. While its network density was lower than Subgroup B’s network density (67% compared to 84%), individuals in that subgroup saved more time then Subgroup B (74.7 hours compared to 56.2 hours).

Another set of results show that individuals in higher hierarchy levels are more likely to offer time benefits to others. Three of the four KBS (KBS A, KBS C, and KBS D) were positive and significant in the amount of time they saved to others. For instance, an increase in one hierarchy level is likely to be associated with an increase of 2 hours a month (KBS A) and up to 7 hours a month (KBS D) time benefits. Other control variables such as tenure and gender were not significant in any of the four models.

### Table 2: Descriptive Statistics

<table>
<thead>
<tr>
<th>Regression variable</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hierarchy</td>
<td>1</td>
<td>5</td>
<td>1.84</td>
<td>1.24</td>
<td>142</td>
</tr>
<tr>
<td>Tenure</td>
<td>1</td>
<td>32</td>
<td>6.04</td>
<td>5.16</td>
<td>142</td>
</tr>
<tr>
<td>Gender</td>
<td>0</td>
<td>1</td>
<td>.34</td>
<td>.47</td>
<td>142</td>
</tr>
<tr>
<td>Time Benefits KBS A</td>
<td>0</td>
<td>125</td>
<td>11.8</td>
<td>22.2</td>
<td>142</td>
</tr>
<tr>
<td>Time Benefits KBS B</td>
<td>0</td>
<td>159</td>
<td>18.7</td>
<td>28.2</td>
<td>142</td>
</tr>
<tr>
<td>Time Benefits KBS C</td>
<td>0</td>
<td>187</td>
<td>28.24</td>
<td>40.1</td>
<td>142</td>
</tr>
<tr>
<td>Time Benefits KBS D</td>
<td>0</td>
<td>205</td>
<td>49.8</td>
<td>51.7</td>
<td>142</td>
</tr>
<tr>
<td>Subgroup Membership A</td>
<td>0</td>
<td>1</td>
<td>.19</td>
<td>.394</td>
<td>142</td>
</tr>
<tr>
<td>Subgroup Membership B</td>
<td>0</td>
<td>1</td>
<td>.20</td>
<td>.405</td>
<td>142</td>
</tr>
<tr>
<td>Subgroup Membership C</td>
<td>0</td>
<td>1</td>
<td>.25</td>
<td>.437</td>
<td>142</td>
</tr>
<tr>
<td>Subgroup Membership D</td>
<td>0</td>
<td>1</td>
<td>.35</td>
<td>.479</td>
<td>142</td>
</tr>
</tbody>
</table>

### Table 3. Linear regression analysis of time benefits in KBS from subgroup membership

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hierarchy</td>
<td>2.2***</td>
<td>1.5</td>
<td>3.2***</td>
<td>7***</td>
</tr>
<tr>
<td>Tenure</td>
<td>.2</td>
<td>-.8</td>
<td>.2</td>
<td>-.9</td>
</tr>
<tr>
<td>Gender</td>
<td>-.7</td>
<td>-3.8</td>
<td>-1.8</td>
<td>-10.8</td>
</tr>
<tr>
<td>KBS A membership</td>
<td>46.5***</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>KBS B membership</td>
<td>-</td>
<td>-</td>
<td>56.2***</td>
<td>-</td>
</tr>
<tr>
<td>KBS C membership</td>
<td>-</td>
<td>-</td>
<td>74.7***</td>
<td>-</td>
</tr>
<tr>
<td>KBS D membership</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>89.5***</td>
</tr>
</tbody>
</table>

*, **, *** indicates statistical significance at 10%, 5% and 1% respectively.

### 6 DISCUSSION AND IMPLICATIONS

Our results found that members of KBS were more likely to report saving time as a result of receiving knowledge from others within their KBS compared to receiving knowledge from employees outside their KBS. While large engineering and construction organizations allocate resources to improve knowledge exchange, it is important to strategically identify when knowledge exchange is most efficient and results in benefits to the employees and organizations. Our results found that individuals are more likely to save
time, and thus benefit, from others within in their KBS. Specifically, we identified a statistically significant relationship in all KBS between group membership and time benefits. An individual is likely to save an average of 46.5 to 89.5 hours more a month as a result of receiving knowledge within their KBS then between KBS (Table 3).

A major implication from this study is linking group level characteristics with individual level benefits and testing the strength of weak ties theory (Granovetter 1973; Wanberg and Javernick-Will 2014). Previous research has focused primarily on either the effect of group level knowledge exchange on group level benefits (Cummings 2004; Landaeta 2008; Tsai 2001) or the effect of individual level knowledge exchange on individual level benefits (Wanberg and Javernick-Will 2014). Instead, this paper bridges the two levels of analysis. Specifically, we found that network connectivity and the type of tie (strong or weak) within a highly connected network play a role in individual time benefits. Strong ties are knowledge exchange connections that are part of a highly connected network (KBS) while weak ties are knowledge exchange connections that link two people of different knowledge based subgroups. As a result, they benefit individuals differently. Weak ties likely require more introduction and steps to access particular knowledge external to the knowledge seeker’s KBS. Conversely, strong ties likely require less steps for introduction as the connectivity between members (knowledge providers and knowledge seekers) is quite high. It is important to note, however, that our results do not suggest that weak ties are unimportant in knowledge networks. Instead they show that weak ties are less important when it comes to saving time on immediate project- and organizational- related tasks. In all likelihood, weak ties in KBS are important for innovation and accessing knowledge that differs from the knowledge seeker’s immediate KBS. As such, our study builds upon existing theory of strong and weak ties by different outcomes (time benefits).

Interestingly, we also found a relationship pattern between KBS density and time benefits. This suggests that network density may play a role in the level of time benefits obtained from knowledge receiving, which validates our previous propositions that a knowledge network’s connectivity mediates the effect of strong ties on time benefits. However, these results require further research and a larger subgroup sample for validation.

7  CONCLUSIONS

Many construction and engineering organizations increasingly understand the importance of intra-organizational knowledge sharing for achieving competitive advantage. However, few studies have studied the benefits of knowledge exchange, and even fewer have analyzed when receiving knowledge offers best individual benefits. Specifically, previous literature has focused on individual and group level outcomes separately, with a dearth of literature linking group level knowledge sharing and individual level benefits. Based upon the strength of weak ties theory (Granovetter 1973), we tested whether strong ties in knowledge-based subgroups (KBS) – subgroups that share more knowledge internally than externally – bring more time benefits, based upon the minimum hours per month saved on work tasks, than weak ties between members of different KBS. To do this, we used social network analysis and a modularity optimization algorithm (Blondel et al. 2008) to first identify knowledge-based subgroups (KBS). Then, we identified the hours saved from receiving knowledge within KBS and outside of KBS. We found that members of KBS are likely to perceive more time saved per month from receiving knowledge within, versus outside of their KBS. These results contradict previous theory on the importance of weak ties (Granovetter 1973) which showed that weak ties are more valuable than strong ties. Instead, we showed that strong ties are perceived as more important, specifically when it comes to saving time, in knowledge networks.

8  LIMITATIONS AND FUTURE WORK

There are several limitations in this work. First, this study was conducted in the department of one construction and engineering organization, making generalizations across other construction and engineering organizations more difficult. Second, while we have a large sample size, the analysis suggests
through correlations, the effects of weak and strong ties on obtaining time benefits, but is unable to show causation. To address these limitations, we propose reproducing this research across additional construction and engineering organizations and conducting qualitative analysis to better understand why weak and strong ties have differential effects on individual time benefits.

Acknowledgements

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ADVANCED WORK PACKAGING AS EMERGING PLANNING APPROACH TO IMPROVE PROJECT PERFORMANCE: CASE STUDIES FROM THE INDUSTRIAL CONSTRUCTION SECTOR.

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Abstract: Despite the progress made in the development of scheduling techniques and tools, the industrial construction sector is frequently characterized by informal and unstructured procedures during initial planning stages. This results in planning deliverables that are scarcely aligned across the different business divisions and poorly structured to support field operations. Advanced Work Packaging (AWP) methodology consists in an enhanced project breakdown structure that prescribes an organized planning approach, aiming at the alignment between construction, engineering, and procurement disciplines since the preliminary planning phase. AWP is an emerging planning approach in the industrial construction sector and the present article is aimed at exploring AWP impact on project performance. Research methodology is based on multiple case studies concerning two industrial construction projects. The case studies involved the construction of projects with identical scope, one with and one without AWP implementation. These case studies were performed at the same time, in neighboring sites, and by the same project participants, thus representing reliable units of analysis to investigate AWP impact. Findings show that AWP implementation is related to improved performance in terms of project cost, schedule, quality, and safety. The present article contributes to the validation of an emerging project planning methodology and highlights the criticality of the early planning phase, which systematic characterization represents a valuable and still under-explored research avenue.

1 INTRODUCTION

Recent research performed by the Construction Industry Institute has highlighted the poor execution performance in the industrial project sector, where almost 70\% of projects exceeded 10\% variation from expected cost and schedule values (CII, 2012). This poor performance is inescapably tied to the lack of reliability of the planning process (Gibson et al., 2006), which is not able to offer reliable estimates and to manage the increasing complexity of industrial projects (Bosch-Rekveldt et al., 2011).

Among the most common project planning concepts, work-packaging has been extensively used and recommended within Project Management theory to divide the scope of work into manageable units for execution (e.g., PMI, 2004). The erratic adoption and the lack of updated standards for existing work-packaging theory motivated a four-year research project by the Construction Industry Institute (CII) – together with the Construction Owner Association of Alberta (COAA) – aimed at defining and recollecting the current work-packaging best practices in the industrial construction sector. The efforts of this research resulted in a codified and systematic planning approach named Advanced Work Packaging (AWP).
The AWP approach provides a holistic process for work-packaging execution with a project lifecycle orientation, from preliminary planning to system turnover and commissioning (CII IR 272-2 Volume 1, 2012). AWP prescribes an organized planning approach through the continuous alignment between construction, engineering, and procurement disciplines, emphasizing the application of work-packaging concepts beyond field implementation to reach the initial phases of project development. AWP has still an emerging connotation within the industrial construction sector and further empirical evidence is required to demonstrate its beneficial impact and to corroborate the logics underlying this beneficial impact. The objective of present research is to explore AWP role in improving project performance. By pursuing this goal, the researchers started addressing two main challenges of current work-packaging literature, one conceptual and one methodological.

The first main challenge involves the limited attention paid by extant research to early integration between project participants (Yang, 2013). Hence, traditional concepts place most of the emphasis on schedule definition and field implementation activities, almost neglecting the importance of alignment practices during the preliminary planning stage. The present research addressed this challenge by emphasizing the traits and features of AWP that foster initial alignment and integration within the project management team. The second main challenge regards the difficulties of project management literature in providing reliable and replicable empirical evidence (Koskela and Howell, 2002). Isolating the impact of specific techniques or practices is a complex methodological issue that is a direct consequence of project uniqueness, characterized by distinctive environmental conditions, scope, and project participants’ interactions (e.g. Aloini et al., 2012). To minimize this issue, the present research identified and analyzed two projects with identical scope, project team, and location that are performed in parallel with- and without-AWP implementation.

The theoretical novelty of the present work resides in the emerging treats of AWP, which challenges the traditional work-packaging approaches towards a more integrated planning process. From a practical perspective, the present article can support construction managers implementing AWP with detailed insights throughout the various project stages.

This paper has the following structure. Section 2 introduces the AWP approach and formulates the research objective. Section 3 highlights research methodology. Section 4 offers and discusses the results. Finally Section 5 is dedicated to conclusions and future research developments.

2 THEORETICAL BACKGROUND

The term "work-packaging" is used to cover "any method of organizing work execution process within the scope of a construction project" (CII IR 272-2, 2013). Despite the widespread adoption of work-packaging principles in the construction industry, extant research has sporadically indicated systematic approaches that are able to effectively integrate the planning and the execution processes (Yeo and Ning, 2006). Previous research “has been devoted to examining the conceptual applicability of the work-packaging concept and applying it as a general managerial tool. Only limited attention has been paid to the actual work-packaging process” (Kim and Ibbs, 1995). This lack of empirical evidence is particularly marked for the industrial construction sector (Azambuja et al., 2014; Jacoby, 2012), so that the underlying work-packaging theory has been considered obsolete and inadequate to effectively execute projects in practice (Choo et al., 1999; Koskela and Howell, 2002). One of the main problems has been identified in the poor integration between the engineering, construction, and procurement disciplines (Goodman and Ignacio, 1999), mainly because of the delayed involvement of project participants during the initial project phases (Gibson et al., 2006).

Since 2009, a research project conducted by the joint effort of CII and COAA has been investigating the work-packaging issue through the analysis of current best practices in the industrial construction sector. The outcome was a framework for AWP that prescribes the breakdown structure of project scope into three main stages (Figure 1): Preliminary Planning/Design, Detailed Engineering, and Construction (O’Brien et al., 2013). Compared to previous work-packaging efforts for the industrial sector – most notably the WorkFace Planning concepts (Ryan, 2009) – AWP shifts the focus to the early planning stages and provides a holistic process for work-packaging execution with a project lifecycle orientation.
During the first stage – Preliminary Planning – the project management team identifies the critical planning elements to achieve a coordinated planning sequence. This sequence is obtained through the iterative definition of work-packaging deliverables. The project is initially broken into a set of Construction Work Packages (CWPs), which define the logical and manageable division of work within the construction scope. CWPs are aligned with the project execution plan and with engineering deliverables or Engineering Work Packages (EWPs). EWPs are enclosed within CWPs, so that engineering and procurement disciplines are delivered to support construction. The identification of EWPs is accomplished by system, eventually crossing CWP boundaries through the positioning of decoupling elements (e.g. valves).

The second stage – Detailed Engineering – builds on and refines the work started during preliminary planning. From an engineering and procurement perspective, the output of this phase includes the detailed specification of EWPs. The breakout of construction work hours for the project is provided at this stage and it enables the resource loading of a Level 3 schedule, which is prepared for engineering (by discipline), for procurement (by commodity and by construction need date), and for construction (by area). The different plans are constantly aligned to ensure consistency.

The third stage – Construction – includes the detailed planning and the execution of operational work-packages, named Installation Work Packages (IWPs) that contain all necessary and pertinent documents in support of the safe and efficient installation for a specific system portion. IWPs are developed by a dedicated AWP Planner, who collect the necessary documentation and ensures the resolution of operation constraints. IWPs are issued to the field three weeks before the starting date and they have to be approved by the frontline personnel, who become accountable for their execution. IWPs are pulled by the responsible superintendent/foreman, adhering in a dynamic manner to construction requirements. After execution, IWPs are controlled by owner representatives, who perform the quality check and update project estimates.

The AWP approach is gaining increasing attention from the industrial practitioners’ community in North America (i.e. through dedicated conferences and communities of practice). However, this approach still requires further rigorous analysis and empirical validation. As various scholars advocated a closer connection between theory and practice in project management (Koskela and Howell, 2002), the present research aims to:

- Provide in-depth insights on the AWP implementation process throughout the three project phases.
- Explore the impact of AWP on key project performance dimensions (cost, schedule, quality, safety).

3 RESEARCH METHODOLOGY

The explorative nature of this research has driven the methodological choice towards a qualitative approach (Yin, 2014). Case-based research has been selected as the most suitable technique to
empirically investigate the research objectives. Hence, multiple case studies are useful to obtain in-depth results on phenomena that are embedded in a complex and uncertain environment (McCutheon and Meredith, 1993), such as the industrial construction sector.

The unit of the analysis of the case studies is the project, which is analyzed from initial scope definition to the completion of field activities. Two industrial projects have been selected because involving the separate construction of identical systems as part of the same project. These systems were also executed in parallel, on contiguous sites, and by the same project companies (different crews but equivalent contractual and incentive structures). The systems can be considered identical apart from AWP adoption. AWP was adopted only for the execution of one system, while the other one was performed with traditional planning approaches. This duplication allowed using a replication logic (Yin, 2014) to isolate as much as possible the impact of AWP on project performance – increasing results reliability.

The first case study involved the construction of the necessary infrastructure to build twelve additional wells on two existing extraction sites in a North Eastern region of the United States. Construction activities were equally divided between the two sites and AWP was implemented only in one of them. The project had a duration of 4 months for a total of 160,000 construction hours. Project scope included also a modularization component for the construction of four pipe-racks. The remoteness of project locations, the limited duration of the construction season, and the high labor demand all necessitated effective integration between construction and engineering. This represented the main motivation for the Owner to test AWP effectiveness.

The second case study involved the construction of the necessary infrastructure to progress mining activities into two sites neighbouring an existing extraction facilities in Alberta, Canada. The project was mainly characterized by intensive civil and piping activities, which included the completion of two dykes and the partial development of a dedicated disposal area. As for the first case study, project activities were equally divided between the two sites and AWP was implemented in only one of them. The project had a duration of 12 months for approximately 1 million construction hours. The Owner decided to implement AWP to improve constraint mitigation during the upfront planning stage.

Table 1 highlights the main characteristics of the two case studies, namely: project sector, scope, construction hours, construction duration, and interviewees’ role.

<table>
<thead>
<tr>
<th>Case Study ID</th>
<th>Sector</th>
<th>Scope</th>
<th>Construction hours</th>
<th>Duration (month)</th>
<th>Interviewees (role*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oil&amp;Gas</td>
<td>Infrastructure (e.g. pipe-racks) to support drilling activities</td>
<td>160,000</td>
<td>4</td>
<td>Project Manager (O) – Superintendent (C) – Engineering Manager (E)</td>
</tr>
<tr>
<td>2</td>
<td>Oil&amp;Gas</td>
<td>Infrastructure (e.g. dykes) to support mining activities</td>
<td>1,000,000</td>
<td>12</td>
<td>Project Manager (O) – Construction Manager (O) – Superintendent 1 (C) – Superintendent 2 (C) – Project Scheduler (E)</td>
</tr>
</tbody>
</table>

*The role can be: Owner (O), Constructor (C), and Engineering (E).

The data collection process involved four main areas: AWP process; project performance; organizational implications; discussion on implementation challenges, and lessons learned. To increase the validity and reliability of the data collection process, the following measures have been adopted:

- The interviews were conducted through a semi-structured questionnaire (Voss et al., 2002). Each interview had a duration of approximately 1 hour. The questionnaire was sent in advance to the interviewees to increase the efficiency of the data collection process.
Multiple informants were consulted for each case study. Interviewees were selected to represent key project participants (see Table 1) – thus taking part to AWP implementation from different perspectives in order to triangulate the results and increase findings reliability (Gibbert et al., 2008).

Each interviewee provided a feedback on case study results to ensure data reliability (Creswell and Miller, 2000).

4 RESULTS AND DISCUSSION

Each case study is reported separately and focuses on:

- The AWP implementation process from preliminary planning to construction.
- The performance differences between the site with-AWP and the site without-AWP.

4.1 Case Study 1

In this first case study, the owner began the definition of AWP procedures during preliminary planning together with the Engineering and the Contractor companies. The goal of this early planning stage was to achieve AWP buy-in and obtain a reliable high-level scope decomposition in accordance with the construction sequence. The owner hired dedicated planners to provide constructability input during the engineering phase.

At the Level 2 Schedule, the project management team defined the deadlines for the development, issuance, and review of CWPs and EWPs. As detailed engineering neared completion, the project management team handed off the remaining planning efforts to the contractor’s planning team. Recognizing the value of pre-mobilization planning, the owner brought the contractor’s planning personnel to the home office two months prior the initial construction date.

The contractor did not utilize dedicated AWP planners – because of the limited project size – but rather traditional construction field personnel, who were responsible to perform the planning process. These personnel included superintendents and discipline foremen – such as electrical, instrumentation, piping, structural, and scaffolding – that were selected because they would be directly executing IWPAs and had substantial planning experience. The planning team dissected the scope of work in accordance to the separate parts of the construction assembly sequence and created IWPAs to support this sequence. IWPAs were developed to a Level 3 Schedule. IWPAs were broken-down by construction areas, module interfaces, and termination points. They were not homogeneous in terms of construction hours, so that different disciplines had IWPAs of different size. The project resulted into 40 IWPAs. As systems neared completion, the focus shifted from construction by area to system commissioning. Consequently, all IWPAs were designed to include turnover specifications.

After planning completion, IWPAs were sorted by discipline and issued in total to the responsible foremen. The issuance process was not in line with prescribed methodology that recommends to deliver the packages three weeks before the beginning of field activities. This lump IWP distribution generated a document control management issue, which arose when minor engineering specifications changed and then needed to be updated. The foremen became accountable for work completion and organized IWPAs execution into a logical construction sequence. To control working activities, foremen updated a weekly progress spread-sheet, by recording installed quantities. Planning meeting were held weekly between superintendents and project controls personnel to determine project progress. Upon completion, IWPAs were returned to the field office to incorporate lessons learned.

In terms of project performance, the interviewees reported various differences between the site with-AWP and the site without-AWP (see also Table 2):

- Cost. Although the project on the site without-AWP was completed on-budget, work stopped several times as a result of ineffective planning. Plans delivered to construction personnel were not
constraint-free and not developed at a sufficient level of detail. This led to inefficient field operations, which were often relocated across different construction areas, compromising field productivity. The site with-AWP completed the project under-budget and with a cost savings of $740,000 in labor. This result was obtained by minimizing the waiting time for materials and drawings for the crews. IWPs were effectively delivered to support construction activities. Moreover, the contractor reported that the inclusion of complete scope portions into specific IWPs allowed the crews focusing on one specific area at the time. As such, productivity was 20% higher than estimates.

- Schedule. The project without-AWP was delivered on-schedule. Crews were re-assigned to other tasks when their work was stopped, so that the overall project schedule was maintained. The project with-AWP was completed ahead of schedule, allowing the systems to be placed in service five days earlier than planned. Schedule savings were caused by the improved field productivity of construction operations, which allowed anticipating or parallelizing activities.

- Quality. For this project, welding activities represented the biggest portion of field activities so that quality is here measured in relation to this process. The site without-AWP highlighted a 2% weld reject rate, which was in line with contractor’s historical performance. The site with-AWP highlighted a 0% weld reject rate. This performance was linked to the more accurate planning process that is achieved through AWP. On the site without-AWP, welds were performed in the field under the influence of inclement weather, with little or no protection from the external environment. On the site with-AWP, the planning team was able to analyze the locations of field welds during IWP development. This analysis allowed grouping the weld areas together to perform the construction process under temporary shelters. These shelters provided better protection from the environment and, thus, improved process quality. In general, the owner qualitatively reported a reduction of reworks in the site with-AWP, mostly due to reduced scope and engineering changes. Most of the engineering changes were identified and mitigated during detailed engineering, rather than during construction when the impact of changes is higher.

- Safety. The site without-AWP reported one recordable injury. This injury was attributed to the re-direction of the crew to another area and to the worker’s self-imposed pressure to complete a scope of work that was unfeasible. The site with-AWP reported zero recordable injuries. This performance was attributed to improved risk identification and mitigation during IWP development and execution. Because the work was better planned, there was significantly less re-direction of crews on-site due to unforeseen constraints. Also, safety considerations were included into each IWP, so that the foremen were able to increase crew’s safety awareness during the daily briefing before operations started.

<table>
<thead>
<tr>
<th>Table 2: Performance from Case Study 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
</tr>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>Schedule</td>
</tr>
<tr>
<td>Quality</td>
</tr>
<tr>
<td>Safety</td>
</tr>
</tbody>
</table>

4.2 Case Study 2

In this second case study, the owner set up an AWP team together with members from the Owner, Engineering, and Contractor companies during the preliminary planning phase. The aim of the team was to obtain early alignment on AWP planning procedures and definitions. During the preliminary planning process, the AWP team divided the project scope into CWPs and integrated the various plans accordingly, checking for scope gaps and overlaps. Involving the contractor at this stage was fundamental to include constructability principles since the very beginning of the design process.
Subsequently, CWPs and EWPs were finalized and integrated in accordance with the scope and the complexity of construction activities. For example, the piping discipline allowed including many decoupling points across the construction areas (e.g. valves), so that one CWP typically included multiple EWPs. For other disciplines, such as electro-mechanical that is characterized by a larger amount of work-hours per system, boundary definition was more problematic and one CWP might have contained a single EWP. The planning team performed constraint minimization for every CWPs and EWPs, ensuring the definition of long-lead time items and turnover sequence. Also, major equipment requirements were identified and evaluated at this stage.

After the generation of EWPs, the detailed planning phase was managed by the contractor and supervised by the owner. Most involved organizational roles were: Superintendents, Materials Coordinators, and AWP Planners. The role of Owner’s AWP Planners was oriented at the support and coordination of the detailed planning process. CWPs were divided into multiple IWPs following the “one crew – one shift” principle. A shift included 10 working days and approximately 2000 working hours. IWPs were completed three weeks before the start of construction. Then, they were issued to Superintendents one week before the construction date to check and approve the documentation. The progress of each IWP was controlled on a daily basis by Foremen and Owner’s representatives through specific scorecards.

The comparison between the two sites (with- and without-AWP) highlighted substantial differences in each performance dimension. Results are described below and highlighted in Table 3:

- **Cost.** The trend for the project without-AWP resulted in budget overruns for $100,000. The project with-AWP was concluded 10% under budget. The owner reported that AWP allowed a more precise and accurate budget definition. The contractor highlighted an increased profitability related to AWP implementation. The profit for the project with-AWP was approximately three times higher (300% increase) compared to the project without-AWP. Such profit increase was mainly due to the better utilization of major equipment.

- **Schedule.** At the time of the interviews, the project with-AWP was concluded on schedule while the project without-AWP was still requiring three months of work. This delay was due to the unsophisticated schedule definition that took place only at a macro-level and that was supported by unsophisticated paper-based tools. The lack of transparency and the poor definition of details resulted in schedule overrun and to consequent reactive measures to cope with it. On the other site, AWP implementation required the contractor to provide accurate and reliable schedule estimates for IWPs. Hence, the contractors had to review, agree, and sign each IWP.

- **Quality.** The owner reported that the site without-AWP was characterized by a lack of consistent upfront planning that resulted in poor control over site activities. The contractor provided a large amount of Request For Information (RFIs), opposing the sequence and the feasibility of operations that resulted in widespread delays and reworks. The site with-AWP highlighted a smaller number of field reworks. Hence, the sequential release of IWPs allowed mitigating the effect of delays and errors by reducing the variability of field activities, so that each IWP was shielded by the variations occurring on other work-packages. The site with-AWP was also characterized by a smaller number of RFIs, which shifted from the execution to the planning phase when their impact on project cost and schedule is substantially minor.

- **Safety.** After one million hours, zero safety incidents were recorded for the project with-AWP. This result was particularly relevant if compared with the trend of the site without-AWP, which consisted of a recordable injury every month. The structure of IWPs constrained the workforce to focus on a single area, reducing useless and dangerous movements around the site. Also, IWPs prescribed that materials and equipment had to be cleared away from the working area after each shift, providing a cleaner and safer jobsite. AWP procedure was used to influence psychologically the workforce by highlighting safety rules and procedures at the very first chapter of each IWP. Superintendents and foremen got used to think to safety since the beginning of construction activities.
### Table 3: Performance of Case Study 2

<table>
<thead>
<tr>
<th>Performance</th>
<th>Without-AWP</th>
<th>With-AWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>$100,000 over budget</td>
<td>$1.5 million below budget</td>
</tr>
<tr>
<td>Schedule</td>
<td>3 months delay</td>
<td>On schedule</td>
</tr>
<tr>
<td>Quality</td>
<td>RFIs paralyzing operations</td>
<td>RFIs solved before operations</td>
</tr>
<tr>
<td>Safety</td>
<td>12 recordable incidents</td>
<td>0 recordable accident</td>
</tr>
</tbody>
</table>

4.3 Discussion

The two case studies highlighted many commonalities but also differences with regard to AWP implementation procedures (e.g. lead-time before issuing IWPs to the field, level of owner involvement during IWPs development). In both case studies, however, AWP emerged as an important factor that contributed to achieve consistent project performance improvements. These improvements have been directly related to AWP adoption by the various interviewees, who stressed the importance of implementing systematic procedures to decompose project scope in a systematic and integrated since the initial planning phase.

Besides the quantitative improvements in terms of key performance dimensions, the interviewees reported additional “qualitative” benefits related to AWP:

- **Integration between Construction and Engineering.** The involvement of construction representatives since the initial planning phase allowed including consistent constructability input to the whole project sequence. The owners acknowledged higher collaboration between construction and engineering as well as between different construction disciplines (e.g. electrical and mechanical). The early involvement of engineering and construction representatives shaped a proactive team culture that benefited from the know-how of both departments especially during the constraint minimization process.

- **Execution Accountability.** AWP methodology required the contractors to provide accurate estimates for the execution of each IWP. Contractors, in exchange, received a complete and constraint-free documentation to execute IWPs. To foster accountability, Superintendents participated to the development of the same IWPs that they would execute in the field. They were able to edit, negotiate and correct the construction plans, taking ownership of scope execution by signing each IWP before the beginning of field activities.

- **Workforce Retention.** AWP was credited for lower employee turnover rates within craft personnel in both case studies. Lower turnover rates for the projects with-AWP were attributed to three main factors. First, the extensive training activities performed on AWP topics resulted in higher workforce engagement. Second, the development of a safe and organized construction environment enhanced workers’ satisfaction. Third, the early involvement of constructors made them feel part of the team, increasing their commitment to the project with a proactive role.

Both owner companies reported that the primary difference between AWP and traditional planning methods was the ability to identify and resolve construction constraints prior to field mobilization. However, AWP implementation did not come “effortless” and every company had to overcome consistent change resistance at the functional and at the inter-organizational level. In both case studies, the owner was the main driving subject to push for AWP adoption, which propagated from the final risk-taker (the owner) to other project participants (Engineering and contractors). Hence, interviewees underlined that AWP has to be fully supported at the various hierarchical levels to be effective, from top-management to craft personnel. The interviewees reported that the inclusion of AWP guidelines into the contractual terms fostered personnel buy-in. This contractual inclusiveness should be supported by a dedicated AWP training process in order to avoid that procedures are adopted only for bureaucratic purposes.
5 CONCLUSIONS

This research is aimed at providing empirical evidence of the performance improvements related to AWP implementation. The results of the case studies highlighted that the projects adopting AWP performed better than the projects without AWP in terms of cost, schedule, quality, and safety performance. The reason for this improvement can be traced back to the more systematic planning process undertaken since the initial project development phase. The early involvement of key stakeholders resulted in a reliable set of plans that are iteratively decomposed and delivered to support construction activities. Identifying and solving project constraints – such as materials and engineering drawings availability – fostered the productivity of field activities by reducing the amount of waiting time and the subsequent re-allocations of crews to unplanned activities.

From a theoretical perspective, the present article highlighted the shortcomings of current work-packaging literature and investigated the applicability of AWP as an emergent approach for the industrial construction sector. AWP contributes to previous research by extending the traditional work-packaging principles to the early planning stages. This approach enhances the development of collaborative relationship between project participants, providing further evidence on the importance of early integration practices for Construction Management literature. From a practical perspective, the present article provides in-depth details to Construction Managers on successful AWP implementation. This research highlights empirical results from real industrial projects that can be used to replicate AWP benefits. Lessons learned are drawn for every key participant: the owner should be the responsible and the most committed subject driving the implementation process; engineering should modify the traditional way of issuing deliverables to construction by providing complete and timely EWPs; contractors should proactively participate to the planning process and take accountability for the execution of field activities.

The main limitation of present article resides in the size of the case study sample. In-depth findings have been preferred to generalizability. Another limitation can be found in the assumption that the only difference between the site with-AWP and without-AWP was the planning approach itself. Although there might be additional factors explaining the performance variance (e.g. construction crews’ skills), every interviewee linked the root cause of performance improvement to AWP implementation, providing convincing and consistent justification.

Future research developments could be oriented at increasing findings generalizability by performing additional case studies in different construction sectors, such as power or commercial. A second potential development could involve the definition of specific performance metrics to measure the “goodness” or the “maturity” of AWP implementation. The comparison between different levels of AWP implementation with different levels of project performance would represent an important contribution to further validate this relationship. Finally, the case studies highlighted that AWP implementation is a complex and resource-consuming process that involves widespread change management implications. A third research development could investigate in details the implementation challenges related to AWP.

Acknowledgements

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CII. 2012. *Performance Assessment*. The Construction Industry Institute, Austin, TX.


A SYSTEMATIC PROGRESS MODEL FOR CONSTRUCTION METHOD INNOVATION

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Abstract: The rapid development of Construction Method has posed a challenge for construction industry. This paper utilizes current Technological Innovation Method to accelerate the development of Construction Method. The Rapid Innovation Model is established based on the traditional technology innovation. This model contains four parts which can be divided into nine steps: definition of problem, fundamental reason analysis, selection of target technique, functional model analysis, scheme evaluation, experiment method, effect evaluation, summary and further application. Moreover, this paper introduces the process of SPIP Method which contains three phases: interpreting the problem according to basic reasons, seeking the answer by patent analysis and construction model and getting the solution by TRIZ and invention principle. In summary, the rapid innovation model meets both the speed and the quality requirements of Construction model development, pointing out a new way of developing construction model.

1 INTRODUCTION

The efficient and sustained, steady and rapid development of construction depends on the support of construction innovation technology. The current construction enterprise faces more challenging changes from market environment. Capability of rapid innovation in construction methods has become an important factor in determining the speed of enterprise development. Unlike other industries, the construction enterprise and its technology innovation has a strong characteristic. Construction business innovations can be classified by their functions, including engineering methods, customer service, design, construction, information technology, management, materials, occupational health and safety and ecological design and construction. Nam and Tatum(1989), based on the survey of the construction product innovation, pointed out that there were four key factors playing important roles in construction process: the owner's needs, problems, design of technical reserves, and the contractor's technology level. Dulaimi, Ling and Bajracharya(2004) discussed the possibility of construction projects to adopt innovative motivation and innovation activities interaction between participants in the organization based on two organizational theories regarding motivation and organizational relationship. Foreign scholars who specialized on the method of related studies have focused on the technical level of the specific construction methods, while the research of management mode of the method is limited. There is only a minimal amount of literature within the nation that comes from the perspective of qualitative description in connotation of methods, characteristics and significance and etc. Such literature stays in the summary of universal knowledge, and there is no further discussion of construction management in the method development process and the principle and constructive problem in the development of innovative
models. Overall, the existing research results are unable to provide guidance and examples to further support or strengthen the construction management innovation.

In the field of construction, the technology innovation is slower than other industries mainly due to the lack of innovative tools and systematic approaches. At the same time, along with the uncertainty of construction environment increasing, the innovation of construction method itself and the methods for construction method developed is needed; some new ideas are in great demand in the study of problem related to the development of engineering methods. How to develop a complex method as soon as possible has become a hot topic both in theories and practices, since the modern construction technology is no longer a traditional simple technique, but rather a complex integrated system. Based on the current situation, this paper developed a model of complex systematic engineering methods in order to rapidly develop innovative process (SPIP) for technology application. Combining with existing innovative approaches, this paper proposed a SPIP system model for rapid development of construction method.

2 CONSTRUCTION METHOD INNOVATIVE SYSTEM PROCESS MODELS

As the owners’ expectation and demands for the safety, quality and time cost of the project raised, advanced construction methods are required due to the needs of higher construction speed and quality. In this scenario, the speed of technique innovation has become as important as other business factors such as cost and quality strategy.

2.1 Traditional Construction Process Engineering Methods Developed

Method development should not only focus on building products, but also on resolving all sorts of building problems in the process of overall consideration. Therefore, the method development is a complex and innovative process, a mature product from construction enterprises accelerating their scientific and technological achievements. It is also a planned and organized activity of study, improvement and promotion of construction methods. Method management of construction enterprises includes new understanding of the power of innovation and opportunities, generation of innovative atmosphere and development of the necessary skills, providing the construction enterprises new construction technologies after testing, refinement and implementation.

Today, the implementation of the method system in China is still a novel thing. Generally, enterprise develops construction method from summaries after action, of which the main work includes: the development of construction method and establishment of management system, technical data collection, decision of development theme, novel finding in construction method theme, redacting construction method materials according to the writing code of construction technique, construction method declaration, construction method validation, engineering methods application, and summarization and improvement. The traditional development method of construction methods is a management-driven and consolidation-based development model. It recreates and formulates new construction methods through studying and refining the experiences accumulated in the past.

With the progress of technology and social development, the great uncertainty of the external and internal environment of projects lead to enormous challenges in traditional construction method development model. Construction method belongs to the category of construction enterprise standards. It is an important component of enterprise standard, which is a standardizing description of the stable and deterministic content in the project. Therefore, the precondition of the method development is the certainty and repeatability of the construction content itself. However, the fluidity of the construction process, the one-piece quality and type-diversity of the construction product and the complexity of the construction production process have determined that the construction method in construction production process is uncertain. Traditional hindsight paradigm has become insufficient to meet the increasing personalized needs of the construction, unable to bring sustainable competitive advantage for construction companies.
2.2 The Process Model of Construction Method Innovative System

The rapid-develop approaches of complex construction method include comprehensive transplantation type, development-oriented type, unearthing type, local modification type and reverse development of type. Comprehensive transplantation type means to transplant the existing soft and hard technology to create a new technology or to improve existing technology function significantly; development-oriented type is the result of the use of new technologies, new materials, new processes and new equipment; unearthing type refers to study, refine and demonstrate the experience accumulated in the past or the approaches for new situations encountered in the field, and then create a new construction methods; local modification type refers to a partial improvement of existing engineering methods in the promotion of the application shortcomings; reverse development type refers to the introduction of engineering methods to decipher analysis, combining with corporate and project circumstances absorption and transformation. Based on the common feature of all the types mentioned above, this paper extracts the process model of complex construction method innovative system (Figure 1). Complex method process model of innovation system includes four parts which can be divided into. The four parts are subject inspection method, evaluation, design, methods and diffusion method. The nine steps include the definition of method design problem, root cause analysis, target technology selection, function model analysis and correction, scheme evaluation, test, evaluation, summarize the method and application.

![Figure 1: The Systematic Process Model of Complex Construction Method Innovation](image)

3 DETERMINATION AND ASSESSMENT OF METHOD INNOVATION TOPIC SELECTION

The topic scope and differences of the construction method directly affect the development and popularization of method. Construction method topic is not only the fist step for developers to think about and prepare for the method, but also an important factor affecting the quality of construction method. Topic selection is the foundation of technique innovation. The pertinence of the topic to a certain extent
determines the success or failure of technique innovation. In the method management, it is clear that topic selection should be combined with technical research, scientific and technological achievements, promoting the transformation of scientific and technological achievements. In the actual development process, the method choice should emphasize not only advancement but also practicability. Therefore it is an important link during which decisions are difficult to make.

### 3.1 Methods Determination of Topic Selection

The purpose of construction method development is to accelerate the application of scientific and technological achievements to realistic productivity and advanced construction experience, to transform conventional technology with advanced technology, to replace the retiring method with advanced experience and to replace empirical evidence with scientific process. Therefore, we cannot use the construction method for the sake of using it; instead, we should be able to summarize and extract from the construction methods, improve construction skills and management system. Principles for theme selection of construction method include opportunity evaluation, importance evaluation and controllability evaluation. The opportunity evaluation refers to the company's business activity levels and company personnel that determine the corporate vision to explore construction methods. The importance evaluation includes innovation and practicality. According to the construction method, it must be proven by practice of the mature technology, and controllability evaluation includes two aspects: research and development strength and construction project performance.

![Figure 2: The Funnel Model of Selecting Construction Method Theme](image)

General construction method development process is divided into technical data collection, development theme determination, theme method research, construction methods writing, the examination and approval of application of method, method declaration, method application and summarization and improvement. The method filter funnel is formulated by the possibility of phase optimization in the construction method theme as the phases proceed (Figure 2). Funnel model refers to the fact that during the development process, the construction technique (also called latent construction method) is gradually transformed into the actual working model law. The model vividly describes the process and the mechanism of making choice.

In addition, for complex method, it also needs to apply value-engineering methods to determine the development of specific targets. Because it is difficult to accurately select the object of innovation in scheme design, we can use the coefficient of function evaluation as basis and select value as evaluation yardstick to develop construction method target. By means of quantitative evaluation on each constitutional element in the system, there are many levels to choose developing object of construction methods for developers, pointing out the direction for further improvement.
3.2 The Root Cause Analysis of Topic Selection Evaluation Method

For the development of construction methods, the first step is to figure out what construction question is and what is the cause of the problem. Method emphasizes the application as the guidance and chose the problem in the construction process as a starting point. There are many reasons that have caused the problems, but the root cause is the key. The problem can be solved fundamentally merely through identifying and troubleshooting the root cause.

Most difficult problems in the construction have more than one single coping method. These different solutions pose different resource requirements for the construction enterprises. Root cause analysis of the problems (Root Cause Analysis, abbreviated as RCA) is a structured problem solving approach that gradually identifies the root cause of the problem and resolves it, which includes analysis to determine the cause of the problem, solutions to problems and preventative measures to the problems.

Generally there are various causes of problems, such as physical conditions, human factors and system behavior or process factors. But the root cause, as the most fundamental cause of the problem, should be mostly concerned. RCA includes: problem identification (what), root cause analysis (why), corrective and preventive actions (any way to prevent problems from happening again).

For example, the pipeline leakage in multiple high-rise buildings will induce secondary damage to building structure and interior decoration. There are many reasons of leakage, and the establishment of RCA model is shown in Figure 3. Through it we can find out the key causes of pipeline leakage. Figure 3 shows that the root cause of pipeline leakage is "concrete crack" or "rupture". The reasons for these two fundamental factors include earthquakes, corrosion and temperature. RCA model also shows that if these two fundamental reasons are resolved, pipeline leakage can be repaired. Therefore, according to the RCA model, the possible rehabilitation program can be "concrete block gap" and "fix broken pipes."

![Figure 3: The RCA Model of Pipeline Leakage](image)

3.3 The Project Technology of the Selected Topic Selection Evaluation Method

Since the construction method has become a new method that construction techniques, new materials and new equipment are combined with, innovative ingredients in the construction method are also increasing. Patents and construction methods that were once separated are now combined, and the combination has become tighter and tighter. As a result, there has been construction method patents and patent method that are of mutual transformation trend. Therefore, analysis and patent analysis should be strengthened in the topic selection evaluation method in order to enhance innovative method.
3.3.1 Engineering Method Analysis

Construction method of science and technology novelty search has become the precondition of the construction enterprise technology development and the first step. Compared to other professional science and technology novelty search, construction method of science and technology novelty has some common characteristics as well as its unique features. Novelty searching work is based on the literature, and the method of novelty search is the same. It is retrieved from the method directory, which has been released by the nation or the province, and find out whether the same method exists. Even if the construction project is the same, as long as there is a new operation method or the construction technology, new method development can be achieved. The pioneering research of shield construction methods of Sany Group, for example, set up a professional team on the shield construction methods that include wide sets of shield construction methods and cases both at home and abroad, summarizing previous construction experience and forming a huge shield method database that contains thousands of shield construction method, construction cases, failure model and solving scheme, and etc.

During the process of construction method of science and technology novelty search, based mainly on statistical analysis of construction method, the current status, level and the future of Chinese construction method are understood. This paper, summarizing the method published by the national and provincial in decades, has extracted and refined the keywords as shown in Table 1, Table 2 and Table 3 below. From keyword density (frequency), the hotspot of construction method development comes out.

Method keyword analysis can be used in the long term. As new data added each year, it will be able to observe the changes along with time and its trends of development. Method keywords play a connecting role in information analysis work and it is the base for the analysis of construction method information. Through the construction method of comparative analysis and keyword research, we can make predictions and judgments and extract valuable information about development level, status and trend, providing a reference for the development of construction method decisions.

Table 1: The First Level Analysis: the Distribution of Construction Method Keywords

<table>
<thead>
<tr>
<th>Category name</th>
<th>The first keyword</th>
<th>Category name</th>
<th>The first keyword</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Surveying Engineering</td>
<td>Civil</td>
<td>HVAC</td>
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<tr>
<td>Engineering</td>
<td>Earthwork and foundation engineering</td>
<td>Engineering</td>
<td>Water supply and drainage engineering</td>
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<tr>
<td></td>
<td>Main structural works</td>
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<td>Steel structure engineering</td>
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<td>Bridge Engineering</td>
</tr>
<tr>
<td></td>
<td>Strengthening and Retrofitting Project</td>
<td></td>
<td>Water Resources and Hydro-power Engineering</td>
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<tr>
<td></td>
<td>Roofing construction</td>
<td></td>
<td>Municipal Engineering</td>
</tr>
<tr>
<td></td>
<td>Waterproof engineering</td>
<td></td>
<td>Tunnel engineering</td>
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<tr>
<td></td>
<td>Energy-saving insulation engineering</td>
<td></td>
<td>Geotechnical slope support engineering</td>
</tr>
<tr>
<td></td>
<td>Curtain wall project</td>
<td></td>
<td>Port and Waterway Engineering</td>
</tr>
<tr>
<td></td>
<td>Decoration Engineering</td>
<td></td>
<td>other</td>
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<td>Industrial installation engineering</td>
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</table>

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Table 2: The second level analysis: the construction method keywords of earth-rock work and foundation engineering

<table>
<thead>
<tr>
<th>The second key word</th>
<th>Provincial method number in 2007-14year</th>
<th>2007-14year National</th>
<th>Total</th>
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<tr>
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<td>Guangzhou</td>
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<td><strong>60</strong></td>
<td><strong>57</strong></td>
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Tab.3 The third level analysis: the construction method keywords of foundation excavation

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<tr>
<th>Third Keywords</th>
<th>Provincial method number in 2007-14year</th>
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<td></td>
<td>Guangdong</td>
<td>Zhejiang</td>
<td>Jiangsu</td>
<td>Hunan</td>
</tr>
<tr>
<td>Lattice</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Earthwork excavation layered disc</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reversed</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Along the edge in the inverse</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Structure center island</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Relief hole</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Large-diameter pipeline protection</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Anti-leakage</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Consolidation muck</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Large transfer beam</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3</strong></td>
<td><strong>8</strong></td>
<td><strong>0</strong></td>
<td><strong>0</strong></td>
</tr>
</tbody>
</table>

3.3.2 Patent Analysis

With the emergence of complex construction systems, the construction method that includes patents emerges in large numbers. For example, in Wuhan’s China Petroleum Building project, China Metallurgical used a "major axis diameter of 56 meters, 48 meters in diameter in the minor axis of the ellipse combination of structural support, within two oval combination of vertical structural support" construction method for the world’s first, remarkably shorting the construction period. The construction method has also resolved the deformation control, strength increase, water seepage reduction and other technical problems. A complete set of methods includes four patent technologies of China Metallurgical. If
a construction method can meet the novelty, inventive and practical features, it can be declared for patent protection. Therefore, when assessing topics in construction methods, patent analysis strengthen is needed. Since the patent has the characteristics of creativity, novelty and practicability, patent information becomes an important source for scientific research of new product and research results on the social and enterprise level. Patent analysis refers to searching the relevant patent literature, statistics, analysis and screening, and turning the patent into available information for construction method.

For example, leakage repairing of pipeline embedded in the reinforced concrete, the alternative repair plan can be "block concrete crack" and "fix a broken pipe". From existing evidence in the United States patent search, the related patents are shown in table 4.

<table>
<thead>
<tr>
<th>Patent number</th>
<th>Proprietary name</th>
<th>Publication Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>US20070249779 A1</td>
<td>Composition and method for sealing concrete cracks</td>
<td>2007</td>
</tr>
<tr>
<td>US6948716B2</td>
<td>Sealing leaks and damp improve sealing function</td>
<td>2005</td>
</tr>
<tr>
<td>US6478561B2</td>
<td>Partially foamed polyurethane prepolymer fill cracks kit</td>
<td>2002</td>
</tr>
<tr>
<td>US20010054474 A1</td>
<td>Crack filling system and foamed polyurethane prepolymer method to fill cracks</td>
<td>2001</td>
</tr>
<tr>
<td>US6309493B1</td>
<td>Methods foamed polyurethane prepolymer filling a gap in concrete structures</td>
<td>2001</td>
</tr>
<tr>
<td>US5226279</td>
<td>Sealed with Portland cement concrete methods</td>
<td>1993</td>
</tr>
<tr>
<td>US4758295</td>
<td>Stop leaking concrete structure methods</td>
<td>1988</td>
</tr>
<tr>
<td>US4744193</td>
<td>Methods to seal leaks in concrete structures</td>
<td>1988</td>
</tr>
<tr>
<td>US4360994</td>
<td>Concrete Crack Sealing Systems</td>
<td>1982</td>
</tr>
</tbody>
</table>

After studying the patent directory, Yu, Wu and Lien (2008) found that US4758295 (method to stop leakage phenomenon in concrete structures) used in foaming agent as the repair material can be an innovative option.

4 TRIZ ANALYSIS IN THE DESIGN OF CONSTRUCTION METHODS

Theory of inventive problem solving, also known as TRIZ theory, is a theory developed by the former Soviet Union inventor Altshuller GS. It is a theoretical system that builds an integrated multi-disciplinary field of methods and studies solutions of various technical issues and the methods and algorithms to achieve innovation development.

The core of construction method is the key technology in construction process, and the entire process is working around key technologies. The key technology in construction method may be advanced technology, intermediate technology, or even a junior one. The choice of construction methods topics is made from integrating a large number of existing materials, technology and techniques and extracting the key principles. The idea is established from the key technology or the expansion, divergence and construction process of key technologies structures. The basic idea of TRIZ to solve the problem of innovation is studying the basic condition deeply, combined with system evolution model to confirm the problem of ideal solution and the contradictions of system, and then find the resources available to eliminate contradictions so as to solve the problem.

4.1 Problem Description

To analyze a given problem, the first thing is transforming the practical problems into TRIZ. TRIZ theory believes that the core of the invention is to solve the problem of contradiction. In the repairing of pipe embedded in reinforced concrete structure, the problem can be defined as a technology contradiction, the parameter intending to improve is "moving object area" and the degraded parameter is "structural stability". The parameters intend to improve and degrade consist of the contradiction in the technical system. In other words, construction parameter (EP) 5 (Area of Moving Object) needs to be changed under the condition of degraded EP 21. The contradiction matrix for reference is shown in table 5.
To Help users to optimize and accelerate the process of technological innovation, a funerary wares company has developed a unique tool that effectively combines innovation process called the Goldfire Innovator™. Goldfire Innovator supports product and process innovation, and can be used to determine the need to analyze systematically the question, confirm the innovation concept and examine the innovation concept by its methods and some application examples. The conceptual solutions developed through Goldfire Innovator™’s proposed Innovative solution generator (ISG) tools include the principles of the invention (IPs): (1) IP19: "regular operation"; (2) IP10: "initial actions"; (3) IP32: "vibration characteristics change"; (4) IP18: "mechanical vibration."

4.2 The Solution

Solving the problem of the invention is the core of product innovation design. Goldfire Innovator™ offers two built-in databases (scientific impact and patent database) to generate solutions. After entering the following requirements: 1. How to stop / repair leaking water permeating into concrete; 2. How to improve liquid / fluid flow / permeability, science influence database gives four solutions: (1) increase the pressure difference between the molecular energy to improve mobile liquid; (2) derive droplets from the mixture of soda capillary water; (3) use sound to increase the diameter of bubble in water; (4) bubbles dissolve the air in the water. According to the four solutions, the model in Figure 4 obtained to modify the proposed pipeline leak method from US4758295 shown in Table 4.

4.3 The key technical scheme design

Nominal design is the way to solve conventional problem, and innovative design is the way to solve invention problem. Innovative technology is based on the conceptual solution development. Compared with traditional construction technology, engineering construction key technology should achieve...
technology innovation, technology maturation, project quality assurance, construction efficiency improvement, engineering cost reduction, remarkable achievements in energy conservation and environmental protection, and etc. The final innovation of the technology solution to fix the pipeline embedded in reinforced concrete structures is as follows: put the liquid sealing material into an open mixer; open the air compressor to provide compressed air for mixing vessel; open the ultrasonic generator vibration for mixer; under the action of air pressure and vibration, the liquid sealing material gradually flow into the crack in concrete and repair the broken pipe.

5 CONCLUSION

The current focus of competition in construction enterprises usually is not the ability to manufacture engineering products, but being capable in developing a new method meeting the project requirements, using competitive new construction method in a faster speed, lower costs and higher quality to complete the construction process. In view of the method in the demand of the rapid development for the current construction enterprise and the organic combination of the innovation of the existing methods, this paper presents a system model for rapid development of the complex construction methods. The model includes: problem definition, root cause analysis, target technology selection, functional model analysis and modification, program evaluation, laboratory testing, impact assessment, construction method application and summary. Root cause analysis (RCA) model is used to describe the problem. The solution to the problem is obtained through patent analysis and method analysis. TRIZ theory and principles of the invention are also used to generate innovative solutions. System process model can satisfy both the speed and quality requirement of the new method development, and it also points out a new way to develop method.

Since the construction method is combined with advanced technology and scientific management, the process and pattern of construction method development is different from the general technological innovation. Due to limited time and data, this paper was not thorough enough in practical studies of construction method. Further research can be implemented by choosing some representative enterprises, tracking their construction method development process to obtain appropriate data and analyze the development process of construction methods. The understanding of meaning and significance of the rapid development of construction method will be more clearly.

References

A MODEL TO EVALUATE THE MATURITY OF CONSTRUCTION ORGANIZATIONS’ DISABILITY MANAGEMENT PRACTICES

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\textsuperscript{2} quaigrra@myumanitoba.ca

Abstract: Evidence exists as to what constitutes successful disability management (DM), with many describing recent upsurge in the area as a major paradigm shift. Despite the benefits of return-to-work (RTW) programs in reducing costs and improving workplace morale, many workplaces appear unwilling or unable to develop and implement successful RTW programs. A review of the literature reveals a lack of coherent theoretical frameworks for implementing DM. This paper presents a model developed to assess the maturity of DM practices in construction organizations. The model is part of an overall research project aiming to evaluate DM in the Manitoban construction industry and its relation to health and safety performance. This project is conducted by the University of Manitoba Construction Engineering and Management Group and funded by the Workers’ Compensation Board of Manitoba. The proposed model is based on existing construction industry maturity models and the concept of process improvement and relies on leading and lagging indicators of performance at the organizational level, thus enabling a thorough evaluation of it. Once validated, the model should help construction organizations evaluate their DM practices against best practices, identify and address areas where improvements are needed, and assess and benchmark DM performance on a regular basis, thus providing a framework to guide the advancement of DM. Similarly, the model can be used by Worker’s Compensation Boards, safety associations and other regulatory bodies across Canada and elsewhere for auditing purposes.

1 INTRODUCTION

Disability management (DM) performance has traditionally been at odds with project and organizational performance. Research in the field (Amick et al. 2000; Rosenthal, 2003; Shrey, 1995; Millington and Strauser, 1998; Ngai et al. 2013) has traditionally argued that disability management (DM) practices used up organizational resources and weakened organizations’ competitiveness. With the advancement of knowledge in the field, researchers have begun to realize the benefits of DM practices (Reynolds et al. 2006). A study by Geisen et al. (2008) on workplace DM shows not only economic incentives but also corporate culture and external incentives for establishing in-house DM. With proactive DM practices, companies are able to generate additional business opportunities, and reduce DM costs (Amick et al. 2000; Ngai et al. 2013). Despite the advancement of knowledge in the field, DM in the construction industry receives limited research attention (Lingard and Saunders, 2004: Omerald and Newton, 2013). A review of the literature shows a lack of clear and coherent frameworks for managing disability management, especially in the construction industry (Lucas, 2010). There is in particular a lack of frameworks for the implementation, monitoring and evaluation of DM practices (Tshobotlwane, 2005). This makes it difficult for construction organizations to evaluate the maturity of their DM programs and by
extension improve them; leading to a situation wherein the potential benefits of FM cannot be fully realized in the construction workplace.

This research, currently in progress aims to develop and validate a disability management maturity model called the Construction Disability Management Maturity Model (CDM3) for use in the construction industry. The model has two major functions. First, CDM3 provides an assessment framework with five maturity levels for analyzing construction organizations’ DM maturity. Second, it provides a progressive framework to guide organizational advancement in the field.

This paper reports on the work that has been done so far by the Construction Engineering and Management (CEM) Group at the University of Manitoba and funded by the Workers Compensation Board of Manitoba as part of this research. This work aims to: 1) review the use of maturity modeling in construction, 2) present an overview of the CDM3, its features and theoretical underpinnings, and 3) describe its proposed implementation. The paper concludes by highlighting the strengths of the CDM3, and future work associated with it. Construction organizations should be able to use the tool/paper as a basis to assess their performance and address issues regarding their DM performance. The tool will be flexible enough to allow for its modification to accommodate changing guidance in the future and thus allow for a more accurate evaluation of existing practices against those changing best practices. The paper additionally provides a foundation from which further investigations can be impelled.

2 LITERATURE REVIEW

This section includes a review of the concept of maturity modelling in general, and as it applies to the construction industry in particular.

2.1 Disability Management

Disability Management originated from the concept of older vocational rehabilitation programs for injured workers and gradually evolved to incorporate the return to work (RTW) model. It incorporates three key domains: prevention, early intervention and proactive RTW interventions to reduce the impact of injury and disability and to accommodate those experiencing functional work limitations (Quaigrain and Issa, 2014). DM a model integrates protection from work hazards and promotes improvement in personal health behaviours (Angeloni, 2013); however this aspect is hardly harmonized and considered in implementing DM in workplaces. Despite the benefits of RTW programs in reducing costs and improving workplace morale (Shrey and Hursh, 1999), many workplaces appear unwilling or unable to implement and sustain successful RTW programs (Brooker et al, 2012). A systematic literature review of evaluative studies of modified work (Krauset al. 1998) noted little documentation of program implementation or the strengths and weaknesses of RTW programs. According to Tshobotlwane (2005) employers have frequently overstated the cost of adjustments in respect to accommodating disabled persons in their workplaces as an excuse to discreetly discriminate in the workplace. A comprehensive DM program enables early preventative actions and intervention, helping to alleviate many of the concerns experienced by injured or ill employees. Most employees want to be able to return to work, whether or not they would is dependent on the comprehensiveness of the DM program (Quaigrain and Issa, 2014).

2.2 Conceptualization

Maturity modeling emanated from the software manufacturing industry (Finnemore et al, 2000) in response to the poor performance of software manufacturers working on US Department of Defense Projects (Pauluk et al. 1995). It is based on the earlier concepts of process improvements such as Philip Crosby's quality management maturity grid describing "five evolutionary stages in adopting quality practices" (Crosby, 1979) and the Shewhart plan-do-check-act cycle (Pauluk et al. 1995). Process maturity modeling consists of various stages of progression which, when adhered to increases the effectiveness of a process. One of the earlier models is the Capability Maturity Model (CMM) developed by researchers at Carnegie Mellon University (Pauluk et al. 1995). CMM uses the original framework of maturity modeling and defines five thresholds or levels of maturity for a given process (Pauluk et al. 1995). At the first level, a process is primarily chaotic or ad-hoc. It is made repeatable at the second level, after which it becomes
defined or standardized. At the fourth level, a process is usually measured or controlled, before it is optimized at its highest level by subjecting it to continuous improvement and feedback cycles.

Assessing the maturity of a process involves investigating the degree to which the process is defined, managed, measured and controlled (Dorfman and Thayer, 1997). This is usually accomplished by analyzing the policies and practices existing within the process (Paulk et al. 1995). Process maturity modelling was found to reduce the overall software development cycle in the field of software development (Harter et al. 2000) and improve project performance in the field of project management (Ibbs and Kwak 2000). It also improves the forecasting and meeting of goals, costs and performance (Lockamy and McCormack, 2004).

2.3 Maturity Modelling in Construction

In construction, the concept has been applied to develop maturity models such as the Standardized Process Improvement for Construction Enterprises Model (Sarshar et al. 1998), the Construction Supply Chain Maturity Model (Vaidyanathan and Howell, 2007) and the Construction Industry Macro Maturity Model (CIM3) (Willis and Rankin, 2011). A number of maturity models have been developed for project management specifically, with the Project Management Maturity Model being the most notable of all (PMI, 2005) and the Fuzzy Industry Maturity Grid being the most used at the macro level. Only one model has so far been developed for health and safety in construction: the Health and safety Maturity Model (Goggin and Rankin, 2009). The DM model currently being developed builds on these five existing models which are reviewed below. It should be noted that although five models are reviewed in the paper, the model (CDM3) still being developed will incorporate other relevant maturity models not outlined in this paper.

CMM integration (CMMI) is an extension of CMM composed of a collection of the best practices in the areas of product and service development; service establishment, management, and delivery; and product and service acquisition (Ngai et al, 2013). CMMI provides guidance for continuous organizational improvement by integrating inter-organizational functions, setting process improvement goals and priorities, providing guidelines for quality processes, and establishing a reference point for appraising current processes (Mani et al., 2010). CMMI has two different representations of maturity, namely, staged representation and continuous representation. CMMI representation uses six capability levels ("incomplete," "performed," "managed," "defined," "quantitatively managed," and "optimizing") which enable organizations to track, evaluate, and demonstrate organizational improvement within process areas (Ngai et al, 2013). Staged representation is a more appropriate reference framework for CDM3 because it provides a highly generic measurement of the maturity of DM practices as a whole and not according to the maturity level of each specific process area (Mani et al., 2010).

The Standardized Process Improvement for Construction Enterprises (SPICE) Maturity Model was developed by researchers at Salford University to improve the management of construction processes, as called for in the Latham report on the performance of the UK construction industry (Sharshar et al., 1998). The framework consists of five maturity levels. It involves testing an organization’s key processes against five process enablers (Finnemore et al. 2000). They applied the SPICE maturity model to four construction organizations, while Amaratunga et al. (2002) tested it on a facilities management organization. Both studies found its assessment to be based on facts rather than perceptions. They also found that the model identified process strengths as well as weaknesses, and enabled the development of improvement and implementation plans. Its main limitation is that it does not account for the multi-organizational nature of construction work (Vaidyanathan and Howell, 2007).

The Construction Supply Chain Maturity Model (CSCMM) is based on the concept of process maturity as used in the CMM and consists of four levels of maturity. The CSCMM assumes that for a construction firm to grow with respect to supply chain maturity it must do so along three dimensions: functional, project and firm. The model was proposed with the objective to offer a roadmap for supply chain members to improve performance through operation excellence of process, technology, strategy, and value (Vaidyanathan and Howell, 2007). Although model does address multi-enterprise supply chain aspect of construction, but it does not handle the maturity of other aspects such as BMI and hence cannot be directly applied.
The Construction Industry Macro Maturity Model (CIM3) is based on an adaptation of the concept of process improvement as used in the CMM. The CIM3 assesses the maturity of the construction industry at the macro level and provides leading indicators of project performance. There are three possible maturity levels associated with each key practice. The evaluation of each key practice is based on the presence of specific outcomes/indicators. It utilizes the analytical hierarchy process (AHP) and questionnaires to conduct the assessment. The utilized detailed levels of maturity adopted may be appropriate for use at the macro level given the characteristics of the industry, however from the organizational level perspective may be deemed inadequate and over simplification of the growth process (Willis and Rankin, 2011).

Finally, the Health and Safety maturity model (Goggin and Rankin, 2010) assesses maturity partly through AHP and questionnaires based on six key safety factors. Its scale is restricted to three maturity levels to simplify the data collection and analysis process. The model however inadequately takes into covers injury management and preventive practices.

A specific comparison can be made of the differences in cumulativeness of the models. In general, a specific trait of maturity models is that levels are assumed to be cumulative. That is, achieving level z implies that level z1 is also fulfilled. Interestingly, although existing construction maturity models provide leading indicators of construction industry performance both at the macro levels and organisational levels, none of them provides a context in which to interpret the performance of the construction industry in relation to its DM practices and subsequently correlated it to its overall health and safety performance. The development of the CDM3 is based on adapting and combining various aspects from the methodologies of the five aforementioned maturity models, although not entirely limited to them. Such aspects include the CIM3 and the safety model’s use of AHP as well as SPICE’s definition of progressive thresholds or levels of maturity and its five maturity levels. Based on the five specific models reviewed, we are currently developing an integrated framework. This framework incorporates contents of many models as well as our specific findings with respect to model scope, domain focus, and the number of levels.

3 METHODOLOGY

This section provides an overview of the CDM3, its assessment indicators at the individual and organizational levels.

3.1 Model Overview

The CDM3 reflects the perspectives of the DM or Case manager's practical work context. The CDM3 adapts the concept of process improvement epitomized in the process maturity framework, taking into account key DM practices identified in existing DM guidance. It enables the identification of the DM activities currently in place within an organization and the development of a process of iterative improvement for those activities. The goal of the model is to benchmark an organization’s existing DM practices against best practices. Its objectives are to:

- Define key DM best practices.
- Evaluate the maturity of construction organizations’ DM practices using leading indicators of performance.
- Provide guidance and make recommendations on improving construction organizations’ management of DM.

3.2 Assessment Indicators

Assessment indicators represent clusters of related activities and regulations, which when performed and adhered to enable the achievement of performance goals. They also identify areas of concern that need to be addressed to achieve these goals. Many of the indicators of DM in construction are related to the parameters of project performance as well as construction project management knowledge areas. They cover employer-based strategies aimed at preventing and managing injuries and represent leading
indicators of performance. They are divided to two main categories based on their level of implementation and applicability.

3.2.1 Individual Level Indicators

Communication practices: Related practices cover information provided to all employees about the organisation’s strategy with respect to DM, and accommodations provided at all levels in support of those with disabilities.

Case management practices: These practices deal with the individual employee once an injury occurs with the aim of managing the injury and rehabilitating the employee. Case management is a term used to describe a variety of strategies aiming to manage the health and social services provided to injured employees and their families (Brooker et al, 2012).

Return to work and accommodation practices: These practices involve the completion of a job needs assessment to determine how the DM program can best meet the needs of employees with disabilities and bring them back to work. A comprehensive analysis of employees' skills is conducted to modify their original jobs or identify alternate jobs for which they would be more suited.

Claims management practices: Related practices deal with managing claims related to occupational and non-occupational injuries or illnesses that may entitle the individual employee to long-term disability (LTD) benefits.

3.2.2 Organizational Level Indicators

Disability and injury prevention practices: These practices cover the preventative aspects of DM programs, which have matured considerably in recent years and are critical to the overall performance of these programs and to controlling related costs. DM programs should educate employees on these aspects before the occurrence of disabling injuries.

Transitional program management practices: These practices cover the development of a generic DM program for injured employees, which can be customized to the individual employee during the individualized case management.
Physical accessibility management practices: These practices aim to improve the physical accessibility of construction workplaces to people with disabilities and as such cover physical workplace accessibility requirements.

Senior Management and leadership support practices: These practices involve getting continuous and consistent support at the senior management level to ensure the effective implementation of DM programs.

Program evaluation practices: These practices encompass the continuous evaluation of DM programs, customized individual RTW programs and injury and illness statistics to identify necessary program modifications and improvements and justify these programs’ costs and benefits as well.

Regulatory and compliance policies: These practices cover existing policies both at the federal and provincial levels. Additionally it delves into specific policies developed by the organization in relation to accommodating injured and disabled workers. Policies can cover issues as salary replacement, job accommodation, transitional employment, budgetary responsibility and vocational training when necessary.

Recruitment and retention policies: Practices cover the recruitment process of employees in the construction workplace as well the procedures undertaken to ensure the retention of injured workers. The principle of non-discrimination should be respected throughout the process, to ensure maximal benefit to the employer and equitable opportunities to candidates with and without disabilities.

Ergonomic practices: Related practices should ensure the design of work processes and spaces that minimize injuries, complaints, staff turnover and work absenteeism; meet employers’ social and legal obligations and improve employees’ health and safety.

3.3 Measurement and Scale

An assessment tool was developed to enable organizations to determine the maturity of a comprehensive range of DM practices under twelve different categories. Responding organizations are expected to rate their level of implementation of these practices using a five-point Likert scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The tool enables respondents to add additional practices to the ones existing as part of the model and rate them accordingly.

3.3.1 Scaling Framework

This study uses the CMMI and SPICE as reference frameworks for the development of the maturity scale for the CDM3. Similar to the CMMI and SPICE, the CDM3 has five well-defined maturity levels that enable continuous monitoring and improvement with the aim of approaching the highest level of process maturity. The rationale for opting for five levels instead of three or four is to provide a more comprehensive breakdown of the growth process, and avoid overlaps and oversimplification of it. Each maturity level represents a well-defined stage that institutionalizes new process areas for disability management process maturation. The characteristics of each stage are described below.
At maturity level 1, organizational processes are usually ad hoc and chaotic (CMMI Product Team, 2002). No procedures or policies are defined or performed. Organizations’ DM performance usually depends on the competence of organizational members rather than the application of specific DM practices.

At maturity level 2, processes are planned, performed, measured, and controlled. This level implies that DM requirements and programs as well as monitoring, control, and measurement mechanisms are managed, with DM practices and results visible to management.

At maturity level 3, a set of standard organizational DM procedures and processes are defined, implemented, managed and used to establish consistency across the organization.

At maturity level 4, organizations perform DM processes accurately and efficiently, practicing standard quality and performance measurement control. Human resource management performance data are collected and evaluated against internal and external benchmarks to identify causes of process variation.

At maturity level 5, organizational DM processes are continually enhanced through technological improvement and the establishment of quantitative objectives and targets.

### 3.3.2 AHP Implementation

Disability Management (DM) performance measurement will be partly determined using the concept of absolute comparison in analytical hierarchy process (AHP) (Islam and Rasad, 2006; Saaty, 1987). The AHP will provide a controlled and systematic way for determining the weights of importance of the construction industry’s indicators for DM and determining the accuracy and reliability of these weights. It is an analytic decision making method used to select the best alternative from a number of alternatives using several criteria.

The indicators will be prioritised by determining the relative weights of the twelve primary indicators using pairwise comparison. A focus group encompassing a minimum of four experts will be set up to determine the indicators weights for the twelve defined leading indicators. The comparisons will be performed using the fundamental scale for pairwise comparison developed by Saaty (1987). A minimum of four such pairwise comparisons will be completed for each indicator and aggregated using geometric means (Yee-Ching and Elea, 1991). The comparisons of indicators will be done using a nine point fundamental scale of values instead of an abbreviated five point scale to reduce the level of fuzziness associated with the pairwise comparison judgements made by the experts. In its use of AHP, the CDM3 considers the indicators (practice areas) as being the decision alternatives that are being compared, with the criteria for comparison being the relative importance of an indicator relative to another to the performance of DM.
The aggregated pairwise comparison values will be normalized by dividing each column value (each indicator) by the sum of column values such that the sum of each column’s values will be 1. A consistency check will be conducted to test the consistency of the rating of the various indicators (Saaty, 1987). The pairwise comparison will be repeated if the consistency ratio is greater than or equal to 0.1.

Each construction expert will assess the primary parameters as shown in figure 1 with respect to the methods described in table 1. When comparing the indicators, each expert will ask himself or herself which indicator is more important to the overall performance of the DM. All will be rated on a nine point scale from “Strongly Disagree” (1) to “Strongly Agree” (9). These subjective ratings will be quantified using the same pairwise comparison procedure that is, the same AHP process explained above to determine parameter weights to obtain quantified subjective ratings.

For each indicator, the pairwise comparisons conducted by an expert produce a matrix referred to as a pairwise comparison matrix (Yee-Ching and Elea, 1991). The values of the pairwise comparison matrix are known as pairwise comparison judgments and reflect the relative importance of the indicators as perceived by an expert (Saaty, 1987). The study adopts the scale developed by Saaty (1987) instead of developing its own scale because Saaty’s (1987) scale has been adopted and validated by many studies, and was found to produce consistent and uniform results in each. The pairwise comparison judgments which comprise the pairwise comparison matrix are normalized, producing ratio scales in the form of principal eigenvectors or Eigen functions (Saaty, 1987). These eigenvectors or Eigen functions represent the weights of importance of the various assessment indicators.

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>Two indicators contribute equally to the objective/goal</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>Experience and judgment slightly favor one indicator over another</td>
</tr>
<tr>
<td>5</td>
<td>Essential or strong importance</td>
<td>Experience and judgment strongly favor one indicator over another</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
<td>An indicator strongly favored over another and its dominance demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>The evidence favoring one indicator over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values between adjacent judgments</td>
<td>When compromise is needed</td>
</tr>
<tr>
<td>Reciprocal</td>
<td>If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i</td>
<td></td>
</tr>
</tbody>
</table>

The second part of implementing the CDM3: the assessment worksheet is based on a set of close ended questions which require a rating ranging from “Disagree” to “Strongly Agree” response, and which represent specific practice areas under each indicator. This technique is the central technique for implementing maturity modelling. It has been validated for use in a number of maturity models and was therefore adopted for the study. Scoring an organization using the assessment worksheet is straightforward. After answering the questions, evaluate the answer column to determine the maturity level. It is indicated by affirmative answers on all questions above the markers to the right of the answer column. The questions seek to determine the existence of specific outcomes/indicators within the organization and thus the implementation of specific practices. The CDM3 requires that the assessment
worksheet be administered to the relevant members of the organization by the researchers. As a check on the accuracy of the responses, the CDM3 requires that random verification be conducted to increase the rigour and validity of the assessment through a review of project and organizational documents, as well as through direct observations and follow up interviews. After completion of the assessment worksheets, additional audit work will be performed to check the organization to ensure the activities prescribed by each practice are in place.

4 CONCLUSION

The paper outlines the development and theoretical underpinnings of the Construction Disability Management Maturity Model or CDM3 and describes its proposed implementation. The primary purpose of the CDM3 is to provide a framework for benchmarking the disability management (DM) performance of the construction industry over time and across countries and regions. Empirical studies on the use of the CDM3 as a tool for continuous improvements should contribute to the development of a better understanding of the problems associated with the implementation of DM programs.

The research, once complete should have research and practical contributions. Theoretically, this research extends the application of CMMI to DM in the construction industry. Furthermore, it develops a progressive framework that defines the advancement of the process of DM from one maturity level to another, thereby helping researchers advance knowledge in the field and helping practitioners implement DM successfully in practice. Once complete, the model will be implemented in practice by applying it to ten construction organizations with the aim of validating it.

Acknowledgements

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References


ASSESSING THE MANAGEMENT PRACTICES FOR SMALL TO MEDIUM Sized CANADIAN GENERAL CONTRACTOR ORGANIZATIONS

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Abstract: This paper describes a research study entitled Enhancing the Performance and Productivity of the Canadian Construction Industry through Appropriate Digital Technology Adoption. The study was completed by researchers from four regions across Canada over the period of August 2013 to March 2014. The underlying purpose of the study was to assist in the development of decision-making tools to support the construction industry in the successfully adoption and implementation of new technologies. The study was accomplished by completion of the following steps: (1) an existing framework for the assessment of management practices at the project level for general contractors in the construction industry was refined and extended; (2) a standard assessment tool was developed and administered to 25 small to medium sized commercial/institutional building general contractor organizations, resulting in the identification of potential opportunities for improvement; (3) opportunities for improvement were validated with organizations; and (4) the assessment results were aggregated to provide an initial benchmark of the level of implementation of management practices. The assessment included 117 practices, across nine practice areas, and grouped as planning and control. The aggregated assessment results are indicating that at an industry level, the management practices in need of improvement that relate more directly to digital technologies are becoming clearer and include: Time - better utilization of the capabilities of existing scheduling software; Cost - improve the integration between time management and cost management software; Scope - improve the capture of as-built information and the management of warranty and operation and maintenance information; Quality - capture and categorize rework and non-conforming work; Materials - implement materials tracking and on-site management; and Information and Communication - implement processes to assess the performance of information and communication processes and use structured forms for information capture. The study built on previous work and extended it with respect to gaining insight on practices from the perspectives of the level of implementation and the consistency with which a practice is employed. To further extend this work, partnerships are being developed with national industry organizations to broaden the application of the assessment framework, thereby expanding the benchmarking dataset.
INTRODUCTION

Impediments to increasing the rate of innovation and improving productivity in the Canadian Construction Industry are related to accessing knowledge in the appropriate form to support decision making, and realizing the necessary capacity to successfully adopt and implement new technologies (or methodologies). This research project continues efforts to provide solutions to overcoming these barriers in support of digital technologies adoption. The project was undertaken with the support of the Digital Technologies Adoption Pilot Program administered by National Research Council Canada’s Industrial Research Assistance Program (NRC IRAP). This paper also represents an abbreviated version of the final results of this project (UNB CEM 2014).

The project builds on a method for a comprehensive assessment of construction companies’ operational processes and identifies areas with the potential to improve performance and productivity through successful adoption. The enhanced methodology is applied in a series of diagnostic projects with construction companies in four geographical regions (the Canadian Provinces of British Columbia, Manitoba, Ontario, and Nova Scotia) with the intention of: 1) identifying candidates for technology adoption projects, and 2) adding to an existing benchmarking dataset of management practices for the construction industry.

The project was accomplished by completion of the following objectives:

1. Critique and further refinement of an existing framework for conducting a diagnostic assessment of digital technologies in the construction industry at an organization level.
2. Identify regions for application and willing companies that will form a representative group in the construction industry.
3. Assess each individual representative company to determine both current capabilities and opportunities for improvement (identifying practices and processes that are lacking, and those that could be enhanced through digital technology adoption).
4. Aggregate the analysis of the individual assessment to an industry level to identify current capabilities and trends in management practices.

The intended audience for this paper is practitioners that are considering a benchmarking of their construction management practices and, more broadly, those attempting efforts in establishing benchmarking programs within the construction industry.

1.1 Refinements to Framework for Diagnostics Assessment

The first step in the research project was to complete a critique and refine the existing framework from a previous study (UNB CEM 2013) for conducting a diagnostic assessment of digital technologies in the construction industry at an organization level. The existing framework was developed based on the foundation provided by previous work in the assessment of organizational management practices within the construction industry. In summary, the following efforts were used to support the development of the framework:

2. The Nova Scotia Construction Sector Council’s Functional Information Technology Project (Rankin 2010).
3. The researchers’ previous research in assessing management practice maturity (Goggin et al. 2010, Willis and Rankin 2012).
The result was the adoption of nine management practice areas. Each area of management practices is a synthesis of numerous sources of commonly employed best practices within the construction industry. The following notes describe the scope and context of the practices:

1. Practices are intended within the scope of a design-bid-build type project versus any form of design-build-operation project (e.g., less emphasis on financial management).

2. Practices being examined are common to general contractors in commercial, institutional and infrastructure projects (e.g., equipment management is excluded as it is considered heavy-civil specific).

3. Although some practices are normally performed in a home-office scenario (i.e., planning practices), the emphasis is project (site)-level practices.

With this as a starting point, a broader search on assessment methodologies in the context of digital technologies and organizational management practices was completed at each research location. Materials reviewed included existing international standards for organizational project management practices and techniques for their application to an assessment framework:

1. PMI’s Construction Extension to the Project Management Body of Knowledge (PMI 2003).

2. UK’s PRINCE2, PRojects IN Controlled Environments, Version 2 (OGC 2002).


The results were used as the basis of identifying opportunities to improve the existing framework. The following summarizes the areas for improvement and actions undertaken to complete the refinement.

1. The scope of management areas, and project practices.
   - The existing framework is based on practices derived from PMI PMBOK and its management processes where some areas (e.g., integrated, risk, procurement) have been incorporated into others (e.g., cost, scope). This is a reasonable structure to continue with and can be cross-referenced with other standards if required for comparisons.
   - It is anticipated that the structure will work in the future as additional practices emerge.
   - There is consensus that the area of information practices needs to be improved.
   - There is consensus that direct assessment of project performance should remain outside the scope of the framework.

2. The capture of the level of maturity of a practice and the influence of the complexity of a project.
   - Modifications were made in order to gain more insight in the level of implementation of practices with respect to the concept of the “maturity of practice” (e.g., how formal it is) and the influence of the complexity of an application (e.g., size of project). A project complexity metric is proposed for use with each company to establish a type of best-typical-worst scale and then collect these for each practice.
   - Using multiple participants in the same company for the assessment will provide more insight on opportunities and increase the validity of the results.
   - If there are instances where it makes sense from a company perspective to collect data from multiple participants, consideration will be given to collect these separately and then reconcile these multiple responses in a group setting.

3. Capturing the motivation behind the use or non-use of a practice.
• A categorization of practices based on their source of motivation (e.g., voluntary, owner driven, legislated) was considered as an addition to the survey questionnaire.

1.2 Project Complexity

Project management practices vary with the complexity of an organization’s projects. Project complexity is measured by comparing it to other projects within the same industry sector. This study adopts the project complexity definitions used by the Construction Industry Institute (CII)’s Benchmarking and Metrics Program (CII 2008), which measures project complexity on a scale of 1 to 7 (low to high) by asking companies to rate their projects’ complexity compared to other typical projects within the same industry sector (e.g. commercial, institutional, infrastructure, etc.). The level of complexity for typical projects undertaken by a company is assessed with the following definitions:

1. Low complexity: projects are categorized by the use of well-established, proven technology, a relatively small number of process steps, a relatively small facility size or process capacity, a facility configuration or geometry that your company has used before, and well-established, proven construction methods.

2. Average complexity: projects are categorized by the use of established technology, a moderate number of process steps, a moderate facility size or process capacity, a facility configuration or geometry that your company has used before, and established, proven construction methods.

3. High complexity: projects are categorized by the use of new, “unproven” technology, an unusually large number of process steps, large facility size or process capacity, new facility configuration or geometry, and new construction methods.

2 PRACTICES

Table 1 is a summary of the nine practice areas and the grouping of practices under the basic management categories of planning and controlling. Each grouping contains multiple practices.

Table 1: Practices by management area with groupings.

<table>
<thead>
<tr>
<th>Management Area</th>
<th>Practices Grouping</th>
<th>Planning</th>
<th>Controlling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time</td>
<td>Schedule development; Resource management; Schedule analysis</td>
<td>Schedule control</td>
<td></td>
</tr>
<tr>
<td>2. Cost</td>
<td>Cost estimating; Estimate analysis</td>
<td>Cost control</td>
<td></td>
</tr>
<tr>
<td>3. Quality</td>
<td>Quality planning; Quality assurance</td>
<td>Quality control; Quality assurance</td>
<td></td>
</tr>
<tr>
<td>4. Scope</td>
<td>Scope planning; Risk management</td>
<td>Scope control; Contract closeout</td>
<td></td>
</tr>
<tr>
<td>5. Safety</td>
<td>Health and safety planning; Safety equipment; Hazard management</td>
<td>Safety equipment; Hazard management</td>
<td></td>
</tr>
<tr>
<td>6. Human Resources</td>
<td>Human resource planning</td>
<td>Human resource analysis</td>
<td></td>
</tr>
<tr>
<td>7. Materials</td>
<td>Materials planning; Materials coordination</td>
<td>Materials control; Materials coordination; Materials inspection and maintenance</td>
<td></td>
</tr>
<tr>
<td>8. Information and Communication</td>
<td>Information and communication planning</td>
<td>Information and communication analysis; Information and communication control</td>
<td></td>
</tr>
<tr>
<td>9. Environmental and Waste</td>
<td>Environmental and waste planning; Environmental and waste analysis</td>
<td>Environmental and waste control</td>
<td></td>
</tr>
</tbody>
</table>
2.1 Protocols for Data Collection

Within the management areas, each practice is assessed for two factors:

1. The level of implementation (how often is the process used?) for a typical project performed by your organization, on a scale of: never; rarely; sometimes; often; or always.

2. The level of consistency (how formally is the process defined and managed?) for a typical project performed by your organization in which the practice is applied, on the scale of: ad-hoc (the process is determined as needed); repeatable (the process is carried out consistently from one occurrence to the next); defined (the process is formally defined and documented); standard (the process is formally standardized throughout the company); or improving (the process undergoes formal review and ongoing improvement).

Additionally, open-ended questions invite information about additional management practices within each area, and situations where there are significant exceptions to the implementation or consistency of a typical practice.

The practices were then converted to a survey format to serve as a script for face-to-face interviews for data collection. Table 2 summarizes the format of the survey and provides examples of the questions.

Table 2: Overview of survey questions for initial data collection.

For the following statements of management practices, please indicate the level of implementation (how often is the process used?) and the level of consistency (how formally is the process defined and managed?) for a typical project performed by your organization.

Schedule development

1. A standard work breakdown structure (e.g., CSI MasterFormat) is used to define the activities/tasks for project schedules.

<table>
<thead>
<tr>
<th>implementation</th>
<th>□ never □ rarely □ sometimes □ often □ always</th>
</tr>
</thead>
<tbody>
<tr>
<td>consistency</td>
<td>□ ad-hoc □ repeatable □ defined □ standard □ improving</td>
</tr>
</tbody>
</table>

The data collection protocols (i.e., basis of the study, method of data collection, and survey questions) were reviewed and approved by the UNB Research Ethics Board, per the Canadian Tri-Council (CIHR, NSERC, SSHRC) policies for research involving humans.

3 INITIAL ASSESSMENT

At each geographical location an initial list of general contractors was identified as potential participants for assessment. In most cases, the cooperation of local construction associations was solicited to assist in developing these lists. Upon first contact with each organization the general intent of the project was explained and survey/interview respondents identified. This was sometimes followed by a face-to-face meeting to further describe the study but in most cases the next step was administering the scripted interview for initial data collection on practices. All participants in the interview were senior managers in the organization with direct experience in the execution of all management practices at the project level. Each scripted interview session lasted between three to four hours and was conducted by the same researcher (either face-to-face or by phone) in each geographical location for consistency. To protect the confidentiality of participating organizations, none are directly or indirectly identified. A total of 25 companies were assessed.

3.1 Overall Assessment

Subsequent to the completion of the initial data collection a summary analysis was provided to each participant in the form of a “box and whisker” diagram. The results provided are an aggregation of scores...
based on the initial assessment of all organizations. The results in Figure 1 are summarized by
management areas to give a general overview of the average level of implementation. Each practice is
weighted equally with a maximum score of 5 corresponding with the highest level of implementation and a
score of 1 corresponding to the lowest level of implementation. The maximum and minimum scores
correspond to practices within each area and the boxes indicate the variance across companies within
each management area. Figure 2 provides additional insight with a breakdown of the management step
within each area.

In general, the traditional management areas of time, cost, and scope, are performed at a higher level. As
expected, safety is at the highest level of implementation. Next are quality, human resources, and
information and communication. The lower levels of implementation are practices in materials, and
environmental and waste. As depicted in Figure 3, planning practices are implemented at a higher level.
However, this is not the case for both scope and quality (with higher scores of implementation for control
practices).

Figure 1: Aggregated implementation score for practices by nine management areas.

Figure 2: Aggregated implementation for all practices by management area and step.
3.2 Individual First Stage Analysis

At the same time the overall summary of practices was provided, each company also received an overview of their scores at the management area level and a more detailed description of where opportunities for improvement were identified. This was captured in a single page, which contained a radar chart (Figure 4) that measured the company against the average of all companies and a summary of opportunities for improvement. These results were used to further engage each company on their practices and to validate the opportunities for improvement.

The opportunities for improvement were aggregated under each management area with the frequency of common opportunities also indicated. The most frequently identified opportunities in each management area are summarized as follows:

1. **Time**: incorporate uncertainty in project schedules during planning; use short-term look ahead scheduling during project execution; communicate the project schedule to all project participants; better utilize the capabilities of existing scheduling software.

2. **Cost**: improve the integration between time management and cost management software; improve internal reviews of estimates; improve the use of expertise in the development of estimates.

3. **Scope**: improve project risk identification and management; improve the capture of as-built information and the management of warranty and operation and maintenance information.

4. **Quality**: capture and categorize rework and non-conforming work; perform internal analyses of common work processes for improvement.

5. **Safety**: improve the hazard planning and inspection planning processes; improve the management of safety equipment, materials and resources management.

6. **Human Resources**: implement team building practices on projects; implement performance assessment on a project basis.

7. **Materials**: implement materials tracking and on-site management; integrate procurement of materials with project scheduling.

8. **Information and Communication**: implement processes to assess the performance of information and communication processes; use structured forms for information capture.
9. *Environmental and waste*: overall the practices in this area are the least mature; therefore in general, consideration should be given to the overall management approach.

![Radar Chart of Initial Assessment](image)

**Figure 4: Example of radar chart of initial assessment.**

### 3.3 Validation and Final Analysis

Validation of the results and opportunities for improvement identified was completed by either a face-to-face meeting or phone call, at which the overall results were reviewed and additional insights provided, followed by a discussion of each individual opportunity. Each validation meeting was completed in a single session of one to two hours.

In general, for each company, the initial opportunities were classified into three groups:

- identified as an opportunity and ready to pursue
- identified as an opportunity but not ready to pursue
- at this point not able to rationalize the investment to improve in the area identified
- currently satisfied with practices in the management area identified

Of the 25 organizations that completed the initial assessment, twelve were available to further validate the results and opportunities for improvement identified.

### 4 AGGREGATION AS A BENCHMARK

As noted, Figures 1 and 2 summarize the average score for an aggregation of practices in each management area. This was used for the purpose of validating opportunities for improvement. These commonly used descriptive statistics in benchmarking can provide additional insight with respect to the practices assessed. It should be noted that at this point the results are not considered statistically significant due to the current sample size.

Figure 3 provides the aggregated practices per a management step classification of practices (i.e., planning and controlling). At this aggregated level, the assessment indicates that overall there are higher scores for the level of implementation for planning practices and conversely overall more variance in the scores for level of implementation of controlling practices.
The assessment of management practices reported at an aggregate level for each management area is provided in Figure 4. Apart from the observations noted earlier on the average values for each management area, general observations on the variance of the resulting scores is offered. Management areas with lower variance in the scoring of their level of implementation include scope and safety, groupings of management areas with higher variance include quality, human resources, and materials. Although not depicted in this paper, general observations for planning practices are that there are higher variances in the scoring of level of implementation for quality and materials. Whereas for the controlling practices, there are a number of management areas with higher variance in the scoring of level of implementation including: cost, quality, materials, and human resources. As part of the final analysis, each individual organization was also provided with a more detailed comparison of their practices against the aggregated group. Figure 5 depicts an example of this comparison.

![Box plot of Company A](image)

**Figure 5:** Descriptive statistics example indicating an individual organization.

### 5 CONCLUSIONS AND FURTHER STEPS

The project resulted in knowledge in a form that is usable to the potential adopter (industry practitioners) for decision making purposes. When aggregated with a previous project, we now have assessment results from 33 (8 from the previous study and 25 from this most recent one) small-to-medium sized general contractors in five geographical regions. The results demonstrate evidence of the common issues that need to be addressed at an industry level.

Also to note is the challenge presented in developing a mechanism of assessment with a common structure while also providing enough depth to be useful for each organization. One of the more positive aspects of the research project was the reaction of members of the construction industry to the research project. Although there were some challenges due to timing, all participants were quite willing to participate and saw the value in having an independent review of their practices, as well as an opportunity to consider exploiting technological solutions to address their needs.
5.1 Next Steps

The refined assessment framework and subsequent data collected and aggregated, serve as an initial benchmarking mechanism for industry management practices at the project level. Results are now available to move forward with a broader dissemination of the framework and its potential to assist in the identification of opportunities for organizational improvements. It is the researchers’ intent to further the application of the framework by adding additional participants on a regional basis, as well as exploring its application in other regions.

Dissemination of the current results is being pursued through partnerships with local and regional construction associations in the form of industry briefs and presentations. In addition, further application of the framework is being explored through partnerships with national level construction industry organizations (e.g., BuildForce).

References

As noted, the following reference materials were used primarily in the development and refinement of the construction project management practices assessment framework.

UNB CEM, 2014. Enhancing the Performance and Productivity of the Canadian Construction Industry through Appropriate Digital Technology Adoption. A technical report funded by NRC IRAP under DTAPP, April, 40 pages.
UNB CEM, 2013. Enhancing the Performance and Productivity of the New Brunswick Construction Industry through Appropriate Digital Technology Adoption. A technical report funded by NRC IRAP under DTAPP, April, 36 pages.
IDENTIFYING FACTORS AFFECTING MOTIVATION OF CONSTRUCTION CREW WORKERS

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Abstract: Motivation is a critical factor affecting construction crew performance. Motivation arises from various internal and external factors such as self-efficacy, assigned goals, and other sources. On construction and industrial projects, workers usually work in crews; thus, performance factors such as productivity are mostly measurable at the crew level. Crew motivation is one factor impacting crew performance. However, it is difficult to define and measure crew motivation in construction, due to the uniqueness and dynamism of the construction environment. Additionally, motivational factors may be described in the form of subjective or objective data. Therefore, a method of measurement is required to systematically and explicitly measure each factor affecting crew motivation and therefore performance. This paper reviews theories and models of motivation that have been developed in research domains other than construction. Next, it overviews motivation literature within the construction domain, and discusses shortcomings of these current approaches. From the literature review, the key factors affecting crew motivation are identified. Finally, the paper proposes a method of measuring crew motivation. The findings and methods presented in this paper will help to define and measure construction crew motivation which will contribute to better predictions of performance.

1 INTRODUCTION AND PROBLEM STATEMENT

There are different definitions of the term “motivation” in existing literature. Colquitt et al. (2013) trace the word to its Latin roots: “motivation” derives from the Latin word for movement, movere. Motivated people usually move or work faster and for longer periods of time than unmotivated people, which makes this Latin root particularly representative of the concept of motivation (Colquitt et al. 2013). Based on Latham and Pinder’s (2005) definition, for an employee, motivation is a set of internal and external energetic forces. Motivation triggers the effort to perform a task. Motivation also determines the three characteristics of such effort: direction, intensity, and persistence (Latham and Pinder 2005). Campbell (1970) defined motivation as “the extent to which persistent effort is directed toward a goal".
Motivation is a critical factor affecting construction crew performance. An effective job performance often requires high levels of both ability and motivation; therefore, motivation is a critical consideration (Maier 1955). However, there is a lack of research on factors affecting motivation in the construction area. Motivation is a major area of research in domains other than construction. Much research has been done in business, management, psychology, industrial psychology, and organizational behavior. In this paper, research in these domains is reviewed. There are some gaps and shortcomings in the research done on motivation; most theories of motivation consider motivation on an individual level. Some theories, like equity theory, recognize that the individual may compare himself or herself to others (e.g., to another group member or another company personnel). As workers mostly work in crews on construction sites, there is a need to evaluate the motivation of workers at the crew level.

Research on motivation in the construction domain suffers from many gaps and shortcomings. The objective of this paper is to define a method to measure crew motivation based on factors that have been derived from literature in both non-construction and construction domains. This paper is organized as follows: First, a comprehensive review of past research is presented on theories of motivation in general domains (e.g. general management, social psychology, applied psychology, personnel psychology, occupational and organizational psychology, and organizational behavior). Secondly, the paper provides a review of motivation literature specifically in the construction domain. Factors that affect construction crew motivation are identified from the reviewed literature. A model of crew motivation is then proposed based on the factors that have been derived from the literature in both non-construction and construction domains. Lastly, a method is proposed to measure the factors affecting construction crew motivation and to measure the overall crew motivation. The findings of this paper will help to define and measure construction crew motivation, which will contribute to better prediction and management of construction labour productivity and project performance. The findings of this paper also provide a basis for future research on construction crew motivation.

2 REVIEW OF MOTIVATION THEORIES IN NON-CONSTRUCTION DOMAINS

Theories of work motivation can be categorized broadly into two groups: (1) content (need) theories of work motivation and (2) process theories of work motivation. Content theories focus on human needs as the main source of motivation and specify the types of needs people have. Psychologists have spent several decades studying types of human needs and have proposed different need structures. Three prominent need theories of motivation are Maslow's hierarchy of needs, Alderfer's ERG theory, and McClelland's need theory. Process theories provide information about how motivation occurs by presenting the factors that affect the motivation and describing the causal relationship between such factors and motivation. Process theories and need theories are not contradictory but complementary (Johns and Saks 2011). However, since this paper ultimately proposes metrics for construction crew motivation and the factors that contribute to it (i.e., it focuses on causal relationships between motivational factors and motivation), it relates most directly to process theories of motivation, the most prominent of which are summarized here. In 1964, psychologist Victor Vroom introduced the first complete version of expectancy theory. Based on the expectancy theory, motivation is determined by the outcomes that people expect to occur as a result of their actions on the job (Vroom 1964). Equity theory was introduced by Adams in 1965. Unlike expectancy theory, equity theory poses that motivation does not depend only on employee beliefs about himself or herself and on personal circumstances, but also on employee beliefs about other people. Bandura (1986) defined perceived self-efficacy as "people’s judgment of their capabilities to organize and execute courses of action required to attain designated type of performance". Bandura proposes that perceived self-efficacy works as the motivational force to take an action. In goal-setting theory, goals are viewed as the primary drivers of an effort (Locke 1968). Goal-setting theory suggests that assigning specific and difficult goals to employees will result in higher levels of performance compared to assigning no goals or easy goals (Locke and Latham 1990). In 1991, Ajzen proposed the theory of planned behaviour. This theory suggests that “intentions to perform behaviour of different kinds can be predicted with high accuracy from attitude toward behaviour, subjective norms, and perceived behavioral control” (Ajzen 1991). Self-determination theory (SDT) suggests that people are motivated to pursue behaviours that lead to the satisfaction of three innate psychological needs: competence, autonomy, and relatedness. According to SDT, the nature of one’s motivational experience
varies along a continuum of internal versus external control (Ryan and Deci 2000). In primary models of goal setting, the focus was on the effect of an assigned goal on personal goals and also the effect of personal goals on performance (Locke 1968; Locke and Latham 1990). More recently, Mitchell et al. (2000) proposed an integrative model of the effect of goals on performance, in which self-efficacy and personal goals are determinants of performance in addition to ability and other factors. In 2001, Locke proposed an integrative model of motivation around the concept of the motivation hub. The motivation hub model consolidates two previously described models: goal-setting theory (Locke 1968; Locke and Latham 1990) and social cognitive theory (Locke 2001). Johns and Saks (2011) proposed another integrative model of motivation that considers expectancy theory (Vroom 1964), goal-setting theory, equity theory (Adams 1965), and need theories.

The above review conveys how different theories and models of motivation in the general domain have developed over time. It also shows which motivational factors have been considered by psychologists and other experts in domains other than construction. Comparing the motivation literature in the general domain to that which exists in construction will help identify the gaps in and shortcomings of motivation research in the construction domain. Thus, the next step is to review the motivation literature in construction in order to understand which motivational factors and motivation theories have not been considered in this area so that the factors affecting crew motivation can be better defined.

3 REVIEW OF MOTIVATION LITERATURE IN THE CONSTRUCTION DOMAIN

Early research on motivation in the construction domain was mostly related to the definition of motivation, with a focus on expectancy theory. Maloney (1981) reviewed studies about construction worker motivation and discovered a lack of empirical research. Soon after, use of the expectancy theory of motivation and performance was proposed in the construction area following the surveys administered to construction workers on the importance and satisfaction of various job-related factors. This research introduced three worker motivational factors: work, supervisor or leader behavior, and incentives (Maloney and McFillen 1986). Questionnaire responses and data collected from different trades were analyzed in order to determine the impact of the work crew on individual worker motivation; this analysis resulted in the conclusion that contractors must manage their work crews in terms of planning, organizing, staffing, directing, and controlling in order to increase worker performance and satisfaction (Maloney 1987). Overall, these early research efforts lacked clarity and rigour in selecting factors, used a limited number of factors, or, in some cases, demonstrated a misunderstanding of motivation theories and concepts. In the following years, researchers expanded on the identification of motivational factors in construction, although such research varied in terms of rigour and comprehensiveness. Carrier (1992) briefly introduced general motivational factors in the workplace. Khan (1993), after reviewing popular motivation theories, concluded that “each theory deals with selected aspects of human behavior that, if managed carefully, motivate people and thus improve productivity” (Khan 1993). Shoura and Singh (1999) used a questionnaire to quantitatively assess motivational parameters of engineering managers. These studies defined motivational factors very generally and based their definitions on the suggestions of previous authors without providing original data analysis. Recently, researchers investigated motivational factors relating to specific types of employees in the construction industry. For example, Cox et al. (2006) identified factors that promote positive motivational behavior in construction subcontractor crews. Šajeva (2007) summarized research done in defining knowledge workers and identifying factors affecting their motivation and loyalty. She identified five motivator categories: work, personal growth and continuous learning, autonomy and personal freedom, status and recognition, and monetary motivators. Siriwardana and Ruwanpura (2012) specified motivational factors as one category of factors affecting productivity in addition to management, supervisor’s assessment, and technical skills. However, their study includes a limited number of factors, provides no ranking between the different factor categories, and is not based on job-site data collection.

In summary, this review of motivation literature in construction shows that there are major shortcomings in this research area: studies largely relied on expectancy theory without integrating other and more recent motivation theories, lacked data analysis and therefore based recommendations only on authors' personal perceptions, and were performed based on questionnaires with no job-site (field) data collection. Comparing the Section 3 review of motivation literature in construction with the Section 2 review of
motivation literature in general reveals many gaps in construction motivation research that should be addressed. One such gap is defining all factors affecting crew motivation in construction. These factors should be identified from developed theories and models of motivation in the general domain. While previous studies have identified some motivational factors in construction, researchers have yet to produce a comprehensive list of factors that adequately addresses all possible sources of motivation. Section 4 addresses this gap by defining a list of motivational factors affecting crew motivation.

4 IDENTIFICATION OF KEY FACTORS AFFECTING CREW MOTIVATION

In this section, factors affecting crew motivation are identified from the motivation literature in both construction and non-construction domains. To accomplish this task, two major issues must be kept in mind. One issue is that theories of motivation have developed and evolved over the last 80 years. Some theories dominated for a period of time before declining in prominence at the arrival of new theories. However, recent literature published in the last decade has tended to integrate numerous earlier theories to propose more comprehensive meta-theories of motivation that overcome the limitations of any of their component approaches alone. Another issue is that existing motivation theories are concerned with the motivation of individuals. However, in construction, individuals usually work in a crew whose performance (e.g., productivity) can only be measured as an aggregate of the individuals' performances (i.e., at the crew level). Therefore, factors affecting motivation in the construction context should also be measurable at the crew level and should include factors affecting crew motivation as a result of peer influence.

Among motivation theories, expectancy theory and self-determination theory are more related to individual motivation, while goal-setting theory and equity theory are more related to team or crew motivation. As the motivation of a worker who is working in a crew results from a combination of different factors related to both the individual and the group, it is important to consider all possible sources of motivation in developing a base model of motivation for the construction domain. For example, a worker may be motivated by goals assigned by the foreman; at the same time, the worker may be motivated by the perception that the ratio of his or her output (e.g., income) to input (e.g., time spent on tasks) compares favourably to co-workers. The recent, integrative theories of motivation (e.g., Johns and Saks 2011) are useful in accounting for these multiple, distinct, interacting motivational factors. In this paper, we group factors affecting crew motivation into five different categories: individual factors, crew factors, project factors, industry factors, and context factors. In each category, we identify factors affecting crew motivation from the motivation theories discussed in previous sections.

4.1 Individual Factors

Factors affecting crew motivation at the level of the individual are those which concern individual workers' self-efficacy and self-set goals. We use the motivation hub model (Locke 2001) to identify factors affecting crew motivation in this category. Based on the motivation hub model, self-set goals (i.e., personal goals or intentions) and self-efficacy (i.e., task-specific self-confidence) are two factors affecting motivation. Although these factors are measured at the individual level, in our model they are grouped together and evaluated at the crew level so that they can be used to assess crew performance.

4.2 Crew Factors

Factors affecting crew motivation at the level of the crew are those which concern the effects of working in a group. We use equity theory (Adams 1965) and the theory of planned behaviour (Ajzen 1991) to identify factors affecting crew motivation this category. Equity theory deals with peer influence by recognizing that employees compare themselves to other referent persons. These referent persons may be in the group, in the company, or outside. Employees compare their own work inputs and resulting outcomes to the perceived inputs and outcomes of their referent persons—their peers—and they adjust their ratio of inputs to outcomes (performance) so that it equals that which they perceive of their peers. Based on this theory, equity perception is a factor that affects worker motivation and therefore crew motivation. According to the theory of planned behaviour, attitude (personality), subjective norms (e.g., social pressures), and perceived behavioural control (perceived ability) are factors that define motivation. While working in a crew a worker may feel social pressure from other crew members. This felt social
pressure (subjective norms among crew members) affects the worker’s motivation. In other words, based on the theory of planned behaviour, crew norms are another factor affecting crew motivation. To identify factors affecting motivation in this category, in addition to using theories and models of motivation, the influence of group processes (i.e., the effect of working in a group on an individual in the group) must also be considered. Our model therefore considers crew characteristics (e.g., crew size) and crew similarity (e.g., the extent to which workers’ ethnicities are similar) as factors affecting crew motivation.

4.3 Project Factors

Factors affecting crew motivation at the project level are those which concern the effect of working on a project or for a company. Our model considers equity theory (Adams 1965), the theory of planned behaviour (Ajzen 1991), and self-determination theory (Ryan and Deci 2000) in identifying project factors affecting crew motivation. Based on equity theory, the equity perception of a worker in relation to other company employees is a factor that affects crew motivation. Based on the theory of planned behaviour, a worker may feel social pressure (company norms) from other company members. Therefore, company norms are another factor affecting crew motivation. Based of self-determination theory, motivation types vary according to regulatory styles (i.e., different methods of control) that exist in a company.

4.4 Industry Factors

Factors affecting crew motivation at the industry level are those which concern the effect of working in an industry sector, as a member of a labour group, or in a regional economy (e.g., as a member of a union or in a specific provincial economy). Our model considers equity theory (Adams 1965) and the theory of planned behaviour (Ajzen 1991) in identifying factors affecting crew motivation in this category.

4.5 Context Factors

Factors affecting crew motivation at the context level are those which derive from the context in which the work is being done. For example, market conditions are a context factor that may affect crew motivation. Table 1 summarizes key factors affecting crew motivation in these categories.

Table 1: Key factors affecting crew motivation

<table>
<thead>
<tr>
<th>Factor Category</th>
<th>Key Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual</td>
<td>Self-set goals (goal commitment), self-efficacy</td>
</tr>
<tr>
<td>Crew</td>
<td>Perceived equity to other crew members, crew norms, crew characteristics, crew similarity</td>
</tr>
<tr>
<td>Project</td>
<td>Perceived equity to other company employees, company norms, company culture, regulatory style</td>
</tr>
<tr>
<td>Industry</td>
<td>Perceived equity to others outside company, industry norms</td>
</tr>
<tr>
<td>Context</td>
<td>Market conditions</td>
</tr>
</tbody>
</table>

5 PROPOSED MODEL FOR PREDICTING CREW METRICS FROM CREW MOTIVATIONAL FACTORS

Based on the identified factors affecting crew motivation, we propose a model for predicting crew metrics from crew motivational factors in Figure 1. As shown in the model, factors affecting crew motivation in the different categories (individual, crew, project, industry, and context) are organized in a hierarchical structure. These factors are defined and discussed in Section 4. In the proposed model, crew metrics include: crew overall performance, turnover, absenteeism, and safety (e.g., incidents). Crew overall performance is further divided into three categories: task performance (e.g., productivity, rework), contextual performance (i.e., organizational citizenship behaviour [OCB], either interpersonal or organizational, such as helping others or following rules), and counterproductive behaviour of an interpersonal or organizational nature (e.g., gossiping, wasting resources).
Figure 1: Model for Predicting Crew Metrics from Crew Motivational Factors
These metrics (i.e., crew overall performance, turnover, absenteeism, and crew safety) are included in the model because each is affected by crew motivation. In addition to the identified factors affecting crew motivation, the model also includes other factors affecting crew metrics: ability, work-setting conditions (e.g., factors such as distance to lunchroom, access to tools and equipment, and noise level in working area), environmental factors, and resource availability. Since performance in construction is usually measured at the crew level, motivational factors affecting crew performance should also be measurable at the crew level. Measurement of motivational factors and crew motivation are discussed in the next section. However, this paper only focuses on defining and measuring motivational factors and crew motivation; crew metrics will be defined in future research.

6 METHOD OF MEASURING MOTIVATIONAL FACTORS AND CREW MOTIVATION

This section describes how to measure both the motivational factors and the crew motivation. According to our model, the first concepts to be measured are factors affecting crew motivation. Measurement should be designed for each factor in order to appropriately quantify that factor. Factors may be in the form of quantitative data (e.g., crew size is three workers) or qualitative data (e.g., crew similarity is high). Therefore, both quantitative and qualitative types of data should be collected. The second concept to be measured is crew motivation; an overall measure for crew motivation should be defined. In the following sections we describe the measurement of these two concepts (motivational factors and crew motivation).

6.1 Identifying and Selecting Measures of Motivational Factors

Identification of measures in this research depends on the type of data that is to be collected. The data type may be quantitative (e.g., an objective attribute such as crew size or weather conditions) or qualitative (e.g., a subjective attribute such as crew similarity and company norms). As our model includes both subjective and objective variables, we need to collect both qualitative and quantitative data. Weather conditions, as an objective input variable, can be measured by objective attribute values (e.g., temperature: 28°C, humidity: 52% humidity, wind speed: 10 km/hr). Crew similarity, as a subjective input variable, can be measured by subjective terms of its attributes (e.g., high similarity in crew members’ ethnicity, medium similarity in number of languages spoken in crew, very low similarity among crew members in years of experience). Subjective terms like “very low”, “low”, “medium”, “high”, and “very high” can be used as linguistic descriptors in a predetermined rating scale. The advantage of using predetermined rating scales is that they provide better definitions for factors and thus lead to more consistency in the collected data. Our model requires the collection of both subjective and objective data. However, we define and use predetermined rating scales for the subjective data. Table 2 shows an example of how measures for one factor—crew similarity—are identified and selected.

For measuring motivational factors, different types of data collection tools and techniques may be used such as company (project) databases and documents, questionnaire surveys (self-reports), interview surveys, and work sampling. Depending on the project under study, the availability and suitability of a potential source of information should be investigated. For example, factors such as company norms (e.g., having a good attitude toward colleagues is mandatory; following manager-imposed rules and disciplines is mandatory) may be available in the company or project database. However, many of the factors that affect worker motivation are based on individual perception. For example, self-efficacy is a worker’s perception of his or her ability to do a job. Similarly, perceived equity to other members of the crew is a factor that relates to a worker’s own perception. For these types of factors, there is a need to obtain the opinions of workers through questionnaire surveys or interview surveys. An advantage of interview surveys is that this method of data collection provides a better understanding of the research situations for the respondents and probably more accurate and useful responses as compared to self-reports. Therefore, structured interview surveys are the most suitable method for collecting motivational factors because they allow researchers to capture the advantages of both face-to-face interviews and structured survey questionnaires.
### Table 2: Identification and selection of measures: Crew similarity

<table>
<thead>
<tr>
<th>Key Factor</th>
<th>Factor Attributes</th>
<th>Data Type</th>
<th>Scale of Measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew similarity</td>
<td>Similarity in crew members’ ethnicity</td>
<td>Qualitative</td>
<td>1–5 predetermined rating</td>
<td>1-Very diverse ethnicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2-Diverse ethnicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3-Somewhat diverse ethnicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4-Similar ethnicity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5-Very similar ethnicity</td>
</tr>
<tr>
<td>Number of languages spoken</td>
<td></td>
<td>Numerical</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>Similarity among crew member experience</td>
<td>Qualitative</td>
<td>1–5 predetermined rating</td>
<td>1-Very diverse abilities, very diverse problem-solving techniques, very diverse backgrounds</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2-Diverse abilities, diverse problem-solving techniques, diverse backgrounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3-Somewhat similar abilities, somewhat similar problem-solving techniques, somewhat similar backgrounds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4-Similar abilities, similar problem-solving techniques Similar background</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5-Very similar abilities, very similar problem-solving techniques, very similar backgrounds</td>
</tr>
</tbody>
</table>

### 6.2 Measurement of Crew Motivation

Once the factors affecting crew motivation have been measured, the overall motivation level of the crew must be measured so that it can be related to the factors affecting crew motivation for model development (as shown in Figure 1). When attempting to measure crew motivation, experts often find it difficult to express a score using exact numbers because of inherent uncertainty. For this reason, the use of linguistic terms makes expert judgments more reliable and informative, which is why we have chosen to express crew motivation scores in this way. The first step in measuring overall crew motivation is to define evaluation criteria for crew motivation. As mentioned in Section 1, motivation is concerned with the intensity, persistence, and direction of effort (Johns and Saks 2011). Accordingly, in our model, these three attributes are evaluated and measured on a rating scale in order to define crew motivation. The second step is to measure crew motivation based on the defined measurement criteria. The available sources of this measurement data are the crew workers themselves, the foreman, and direct supervisors. It is possible to ask the workers, foreman, and supervisor about the crew motivation in form of a survey; however, this method poses some challenges for aggregating the respondents’ opinions. As some of the crew metrics attributes (e.g., crew productivity) are measureable only at the crew level, it is important that in these cases the relevant measurement is also taken at the crew level. In other words, all motivation attributes should be measured for the crew as a whole (e.g., How intense is the effort of crew workers? How persistent is the effort of crew workers? To what extent did the crew direct their effort toward their tasks?). The challenge here is related to aggregation of different expert opinions about crew motivation.

The aggregation of individual judgments into a group opinion requires a measured level of consensus. Omar and Robinson (2014) proposed a framework for measuring competencies for construction projects. In their work they used OWA (Ordered Weighted Averaging) to aggregate different expert opinions. Ben-Arie and Chen (2006) introduced a new linguistic-labels aggregation operation for handling an autocratic group decision-making process under linguistic assessments. They proposed a FLOWA (Fuzzy Linguistic OWA) algorithm. The methodology they presented has two outcomes: a group-based recommendation and a score for each expert reflecting the expert’s contribution towards the group recommendation (Ben-Arie and Chen 2006). Both methods (OWA and FLOWA) can be implemented here to define a score for
crew motivation. The difference is that OWA provides a point score as representative of each expert judgment of crew motivation while FLOWA provides a fuzzy set for each expert judgment of crew motivation. After implementing either OWA or FLOWA, all scores experts assigned for various crew motivation attributes are aggregated to define the crew’s motivation. Ben-Arieh and Chen (2006) considered applying the classic aggregation method, in which each expert’s importance is multiplied by their expert opinion score. Following this method, a crew motivation score is defined including a combination of different opinions of crew motivation.

Measuring crew motivation and the factors affecting it will help in modeling and identifying the most critical factors that affect crew motivation. By determining the strength of the links between motivational factors and crew motivation, a model for predicting and improving crew motivation can be developed. Future work on assessing and measuring crew metrics will be done to complete the proposed model shown in Figure 1. The model will be validated with actual data and used to determine crew performance based on motivational and other factors affecting crew performance. Agent-based modeling will be used to further implement the concepts in order to show the relationships between the individuals on the crew and crew performance, and to thus gain a better understanding of the dynamics of the crew as they relate to motivation.

7 CONCLUSIONS AND FUTURE RESEARCH

The first contribution of this paper is in providing a comprehensive review of motivation literature in both the construction and non-construction domains, identifying the shortcomings of construction literature about motivation, and identifying factors affecting crew motivation in construction. Identifying these motivational factors enables their effects on crew motivation to be analysed, which in turn leads to better prediction of crew performance. We reviewed past research on motivation in the general domain followed by a review of motivation literature in construction. We then provided a list of key factors that affect crew motivation based on the reviewed literature. Previous research in construction failed to provide a comprehensive review of motivational factors affecting crew workers even though the need for such a consideration has only been increasing in order to better predict crew performance. The second contribution of this paper is the presentation of a method for measuring crew motivation. We illustrate how it is possible to measure both motivational factors and crew motivation quantitatively. Quantifying crew motivation will help in analysing and evaluating crew motivation models, such as models for understanding the relationship between motivational factors, crew motivation, and crew performance.

This paper is part of a broader research study that intends to understand the effect of motivational factors on crew metrics. In future, the research presented here will be extended to develop crew metrics including not only crew performance indicators (e.g. productivity) but also other crew behavioral outputs (e.g. turnover, absenteeism, and safety [incidents]). Through our study, we will try to find the relationship between crew motivation and other crew performance metrics. A model of such relationships is presented in this paper. Future research will also focus on further analysing the relationships between motivational factors, crew motivation, and crew metrics by developing suitable theoretical models such as fuzzy agent-based models. Agent-based modeling and simulation (ABMS) is a powerful technique when dealing with attributes like human behaviour. On the other hand, fuzzy techniques are powerful when dealing with subjective data. Thus, future research will examine the possibility of developing fuzzy agent-based models to model the relationships between motivational factors, crew motivation, and crew metrics. Such models will allow the construction industry to achieve better predictions of crew performance.

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COMPARISON OF CONSTRUCTION EQUIPMENT EMISSIONS FOR SEVEN CONSTRUCTION PROJECTS

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Abstract: This paper reports on the results of field studies of seven transportation infrastructure projects. The results of two road projects are compared to four street and utility projects and to a commercial building project. The study results show that road construction emits a much higher quantity of emissions than building construction; that the emissions calculated with published data are higher than those from field data; and that backhoes, motor graders, and bulldozers produce the highest total emissions. This paper adds to our understanding of emissions estimates from multiple project types and data sources.

1 INTRODUCTION

Typically, an infrastructure project is studied from different perspectives during planning and design phases to assess the impact the project will have on the community, the existing infrastructure system, and the environment. Such analysis is particularly intense during the development of highly visible transportation projects, especially highway projects. The impacts of these types of projects are visible and obvious to the general public.

Air pollution emissions are one of the effects that are of special interest because of the dangers they pose to health. The impact of future emissions from passenger cars, heavy-duty trucks, and other vehicles that use transportation infrastructure is an important area of study during the early phases of a project. However, such study does not typically include construction equipment emissions assessments, leaving a full understanding of the emissions produced during the infrastructure development processes as a void in the body of knowledge.

This paper addresses that knowledge void. Seven actual construction projects located in central North Carolina were studied in numerous ways to assess their emissions generation. This paper compares those projects, reports some of the key findings of these studies, and makes observations about their significance.

The research question addressed in this particular paper is, “to what extent, if any, do different project types vary in their emissions during construction?” To answer this question we compared emissions forecasts from two road projects, to four street and utility construction projects, and to a building construction project.
Results from the different types of projects can be used to understand how the emissions profiles change, not only between projects but also between different activities and schedules, over time. These comparisons begin to reveal general emissions patterns and rates. This enables us to calculate emissions factors per dollar or per productivity unit and these factors can then be used to forecast emissions for numerous other projects during their early planning stages, thus improving design alternative selection. At this point the research question “are there metrics by which emissions forecasts can be compared across various project sizes and types?” is addressed.

1.1 Scope

This paper focuses on forecasting emissions from the exhaust system of nonroad construction equipment during the construction process. The six pollutants studied are hydrocarbons (HC), nitrogen oxide (NO\textsubscript{x}), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO\textsubscript{2}), and carbon dioxide (CO\textsubscript{2}). Emissions from other parts of the equipment such as the braking system are not included. This paper also does not include other air pollution produced during the construction project such as fugitive dust.

The equipment used for the calculations in this paper was categorized using the tier system derived from the US Environmental Protection Agency (EPA) regulations. Engine tier is a categorization of equipment by age and by regulated emissions quantities for that age. Engines can be identified by the emissions levels that were in place for that model year with each subsequent tier being more restrictive with respect to allowable emissions quantities [EPA 2010].

2 LITERATURE REVIEW

One interesting recent study focused on greenhouse gas (GHG) emissions during the construction of transportation projects in Korea [Kim et al. 2012]. The paper focused on CO\textsubscript{2}, methane, and nitrous oxide emissions presented as CO\textsubscript{2} equivalent. The paper presented an estimation of GHG emissions for two highway projects. The key finding was that earthwork activities consumed more fuel than any other activity and that dump trucks (on-road equipment) are the highest emitters of pollutants. Using these results, the authors calculated emissions during earthwork activities. The optimal equipment fleet for each activity was determined using typical equipment combinations. The activities and emissions quantities were determined using the design documents for each project. Thus, the estimates produced by the authors are based on published data.

Cui and Zhu [2011] surveyed the use of green contracting strategies by state DOTs. The survey was completed by 39 states of which 25 reported using some type of green strategy. The findings indicated that New York, California, Washington, Oregon, and Illinois have green strategy programs that are enforced either by the state government or by DOT. This paper also mentioned that EPA recommends the use of the Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) to calculate the economic and environmental effects of an existing, proposed, or hypothetical highway construction projects. The output of the tool includes the energy use and emissions produced during the construction and maintenance phases of a project, including material transportation. However, PaLATE is currently only applicable to roadway construction, it only operates at the project level, and it does not assess the impact of individual construction project activities, which is a critical element addressed herein.

A paper by Avetisyan et al. [2012] presented a decision model to select construction equipment for transportation projects. The authors assert that the model can be used for any type, location, and conditions of construction projects. The inputs for the model are derived from information provided by the contractor and included the amount of work and time available for each activity, details about equipment capacity and compatibility, operational and maintenance cost, engine tier specifications, and emissions rates. The model can be used to optimize equipment selection by cost and emissions production. The result of the model is a list of equipment that should be used for the project and the tier for each item of equipment. However, it is not clear from the paper which factors were used to determine the equipment fleet and which equipment characteristics were studied. Only one case study was used to test the model. Finally, there is no way to benchmark their model.
In summary, research has been conducted in auto emissions, other on road vehicle emissions, life cycle emissions, standards development, emissions regulations, sustainability, and green infrastructure. However, other than previous work examining four street and utility projects [Arocho et al. 2014] and the project by Kim et al. (2012) (that looked at GHG emissions during the earthwork activities of highway construction projects) little has been done in measuring and benchmarking emissions from nonroad construction equipment performing actual highway construction work. This paper makes a contribution toward filling a part of that void. Furthermore, it is worth noting that life cycle analyses estimate the quantity of emissions produced during the construction process. The work described herein provides quantification for the construction process to fill that void (replace the estimate) in existing life cycle models.

3 PROJECT DESCRIPTIONS

This section presents brief descriptions of the two highway, the four street and utility, and the building projects analyzed herein. Table 1 shows the basic characteristics of these seven projects. The first four projects are the street and utility projects. Apex and Wake Forest are the two road construction projects. The Building project was a 13,400 square foot commercial building that included parking and site work.

<table>
<thead>
<tr>
<th>Project</th>
<th>Total Cost ($)</th>
<th>Year Built</th>
<th>Construction Duration (days)</th>
<th>Length (ft)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little Street Roadway</td>
<td>$179,000</td>
<td>2011</td>
<td>65</td>
<td>600</td>
<td>Street and utility improvement</td>
</tr>
<tr>
<td>W. Burkhead Street</td>
<td>$103,860</td>
<td>2012</td>
<td>9</td>
<td>500</td>
<td>Street and utility improvement</td>
</tr>
<tr>
<td>Sutton Place Phase 1</td>
<td>$219,540</td>
<td>2009</td>
<td>49</td>
<td>930</td>
<td>New development</td>
</tr>
<tr>
<td>Sutton Place Phase 2</td>
<td>$622,660</td>
<td>2009</td>
<td>101</td>
<td>2,813</td>
<td>New development</td>
</tr>
<tr>
<td>Apex</td>
<td>$862,881</td>
<td>2012</td>
<td>124</td>
<td>2,600</td>
<td>Relocation</td>
</tr>
<tr>
<td>Wake Forest</td>
<td>$203,000</td>
<td>2013</td>
<td>13</td>
<td>1,300</td>
<td>Widening</td>
</tr>
<tr>
<td>Building</td>
<td>$1,454,720</td>
<td>2009</td>
<td>125</td>
<td>NA</td>
<td>Commercial Building</td>
</tr>
</tbody>
</table>

Table 2 shows the construction activities associated with the transportation projects. The building project was not added to Table 2 because the activities needed for it (e.g., earth movement and excavation for the utility connection and foundation, and grading and paving needed for the landscaping and parking area) do not correspond well with the activities for the transportation projects.

4 RESULTS

In this section the paper compares the emissions from the three distinct project types (road, street and utility, and building) for all of the seven projects.

4.1 Project Type Comparison with Tier 3 Equipment

This section shows the emissions results using Tier 3 as the reference for all equipment used. In Table 3 the average daily emissions for the four street and utility projects are lower than the average daily emissions for the building project. The emissions for the two road projects (calculated using the field data) are almost double the emissions for the street and utility and building projects for all the pollutants. The emissions estimates for the road projects using published data (RS Means) are even higher than those using field data (with the exception of PM).
Table 2. Project Construction Activities

<table>
<thead>
<tr>
<th>Construction Activities</th>
<th>Little Street</th>
<th>West Burkhead</th>
<th>Sutton Place Phase 1</th>
<th>Sutton Place Phase 2</th>
<th>Apex</th>
<th>Wake Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobilization</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Staking and layout</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Clearing and grubbing</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demolition and removal of existing asphalt</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Erosion control measures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earthwork and grading</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Demolition: sewer, storm, and water systems</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial grading and excavation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation of new sanitary sewer system</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Abandon existing sewer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation of water distribution system</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation of storm sewer</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remove and replace curb on adjacent streets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curb installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Prepare subgrade</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Paving</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Traffic signals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final clean up, punch list, and demobilization</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Average Grams per Day for Tier 3 Equipment

<table>
<thead>
<tr>
<th>Project Type</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Building</td>
<td>538</td>
</tr>
<tr>
<td>Average Street with Utilities (4 Projects)</td>
<td>467</td>
</tr>
<tr>
<td>Average Field Roads (2 Projects)</td>
<td>1,010</td>
</tr>
<tr>
<td>Average RS Means Roads (2 Projects)</td>
<td>1,660</td>
</tr>
</tbody>
</table>

Table 4. Grams per Square Foot of Pavement for Street and Road Projects for Tier 3 Equipment

<table>
<thead>
<tr>
<th>Project Types</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Average Street with Utilities (4 Projects) (Field and RS Means combination)</td>
<td>0.73</td>
</tr>
<tr>
<td>Average Field Roads (2 Projects)</td>
<td>1.51</td>
</tr>
<tr>
<td>Average RS Means Roads (2 Projects)</td>
<td>1.75</td>
</tr>
</tbody>
</table>

4.2 Comparison Between Field and RS Means Results

To better understand the differences between field and published data the total emissions calculated using field data were compared to those calculated using RS Means data for the Apex and Wake Forest projects. We found that the difference in the equipment fleet between the two data sources is the largest contributor to the total emissions difference shown in Tables 3 and 4. To illustrate this finding Table 5 shows the field and RS Means fleets for the Apex project and clearly shows the difference in equipment used.
Table 5. Comparison of Equipment Fleet for the Apex Project

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
<th>Equipment Type</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Compressor</td>
<td>117</td>
<td>Front End Loader</td>
<td>200</td>
<td>Aggregate Spreader</td>
<td>203</td>
</tr>
<tr>
<td>Asphalt Distributor</td>
<td>5.5</td>
<td>Grader 1</td>
<td>135</td>
<td>Paver</td>
<td>130</td>
</tr>
<tr>
<td>Backhoe</td>
<td>100</td>
<td>Grader 2</td>
<td>135</td>
<td>Backhoe</td>
<td>48</td>
</tr>
<tr>
<td>Brush Chipper</td>
<td>85</td>
<td>Loader</td>
<td>128</td>
<td>Brush Chipper</td>
<td>130</td>
</tr>
<tr>
<td>Bulldozer 1</td>
<td>130</td>
<td>Milling Machine</td>
<td>140</td>
<td>Concrete Pump</td>
<td>77</td>
</tr>
<tr>
<td>Bulldozer 2</td>
<td>121</td>
<td>Mini Excavator</td>
<td>39.4</td>
<td>Concrete Saw</td>
<td>44</td>
</tr>
<tr>
<td>Bulldozer 3</td>
<td>140</td>
<td>Mixer</td>
<td>25</td>
<td>Crawler Crane</td>
<td>173</td>
</tr>
<tr>
<td>Bulldozer 4</td>
<td>90</td>
<td>Mulch Blower</td>
<td>33.5</td>
<td>Crawler Loader</td>
<td>189</td>
</tr>
<tr>
<td>Bulldozer 5</td>
<td>90</td>
<td>Paver</td>
<td>174</td>
<td>Curb Machine</td>
<td>99</td>
</tr>
<tr>
<td>Bulldozer 6</td>
<td>121</td>
<td>Pneumatic Roller</td>
<td>80</td>
<td>Dozer</td>
<td>200</td>
</tr>
<tr>
<td>Bulldozer 7</td>
<td>90</td>
<td>Roller 1</td>
<td>145</td>
<td>FE Loader Wheel 1</td>
<td>96</td>
</tr>
<tr>
<td>Compact Track Loader</td>
<td>84</td>
<td>Roller 2</td>
<td>99</td>
<td>FE Loader Wheel 2</td>
<td>196</td>
</tr>
<tr>
<td>Curb Machine</td>
<td>130</td>
<td>Roller 3</td>
<td>33</td>
<td>Grader</td>
<td>158</td>
</tr>
<tr>
<td>Excavator 1</td>
<td>100</td>
<td>Roller 4</td>
<td>99</td>
<td>Hydraulic Crane</td>
<td>315</td>
</tr>
<tr>
<td>Excavator 2</td>
<td>232</td>
<td>Rubber Tire Loader</td>
<td>196</td>
<td>Mulcher</td>
<td>275</td>
</tr>
<tr>
<td>Excavator 3</td>
<td>140</td>
<td>Scraper 1</td>
<td>175</td>
<td>Pavement Profiler</td>
<td>750</td>
</tr>
<tr>
<td>Excavator 4</td>
<td>140</td>
<td>Scraper 2</td>
<td>265</td>
<td>Pneumatic Roller</td>
<td>100</td>
</tr>
<tr>
<td>Excavator 5</td>
<td>140</td>
<td>Skid Steer 1</td>
<td>56</td>
<td>Crane 1</td>
<td>100</td>
</tr>
<tr>
<td>Excavator 6</td>
<td>140</td>
<td>Skid Steer 2</td>
<td>46</td>
<td>Crane 2</td>
<td>85</td>
</tr>
<tr>
<td>Excavator 7</td>
<td>169</td>
<td>Straw Blower</td>
<td>125</td>
<td>Trencher</td>
<td>12</td>
</tr>
<tr>
<td>Excavator 8</td>
<td>100</td>
<td>Tandem Roller</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excavator 9</td>
<td>140</td>
<td>Trencher</td>
<td>120</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The emissions per activity were also calculated using both data sources for both projects. Tables 6 and 7 show total emissions per activity for the Apex project for field data and RS Means, respectively. The activities with the largest contribution to emissions were consistent for field and RS Means data with earthmoving and paving activities on the top of the list for both. These activities are performed by simultaneously using many different items of equipment that results in a large quantity of emissions.

Table 6. Field Emissions per Activity for the Apex Project

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pollutants (Thousands of Grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
</tr>
<tr>
<td>Mobilization</td>
<td>0.38</td>
</tr>
<tr>
<td>Clearing and Grubbing</td>
<td>36.7</td>
</tr>
<tr>
<td>Erosion Control</td>
<td>4.91</td>
</tr>
<tr>
<td>Grading</td>
<td>55.2</td>
</tr>
<tr>
<td>Storm Drain</td>
<td>17.0</td>
</tr>
<tr>
<td>Concrete Work</td>
<td>3.07</td>
</tr>
<tr>
<td>Guardrail and Fence</td>
<td>4.23</td>
</tr>
<tr>
<td>Markings and Signs</td>
<td>0.92</td>
</tr>
<tr>
<td>ABC and Paving</td>
<td>28.1</td>
</tr>
<tr>
<td>Traffic Signals</td>
<td>2.37</td>
</tr>
<tr>
<td>Utilities</td>
<td>4.88</td>
</tr>
</tbody>
</table>
Table 7. RS Means Emissions per Activity for the Apex Project

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pollutants (Thousands of Grams)</th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
<th>CO₂</th>
<th>SO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobilization</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clearing and Grubbing</td>
<td></td>
<td>48</td>
<td>294</td>
<td>197</td>
<td>1</td>
<td>147,000</td>
<td>26</td>
</tr>
<tr>
<td>Erosion Control</td>
<td></td>
<td>50</td>
<td>333</td>
<td>280</td>
<td>1</td>
<td>265,000</td>
<td>47</td>
</tr>
<tr>
<td>Grading</td>
<td></td>
<td>13</td>
<td>100</td>
<td>116</td>
<td>0</td>
<td>120,000</td>
<td>21</td>
</tr>
<tr>
<td>Storm Drain</td>
<td></td>
<td>8</td>
<td>32</td>
<td>121</td>
<td>0</td>
<td>110,000</td>
<td>19</td>
</tr>
<tr>
<td>Concrete Work</td>
<td></td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>3,020</td>
<td>1</td>
</tr>
<tr>
<td>Guardrail and Fence</td>
<td></td>
<td>4</td>
<td>31</td>
<td>34</td>
<td>0</td>
<td>34,400</td>
<td>6</td>
</tr>
<tr>
<td>Markings and Signs</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ABC and Paving</td>
<td></td>
<td>21</td>
<td>197</td>
<td>242</td>
<td>1</td>
<td>237,000</td>
<td>42</td>
</tr>
<tr>
<td>Traffic Signals</td>
<td></td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>2,630</td>
<td>0</td>
</tr>
<tr>
<td>Utilities</td>
<td></td>
<td>2</td>
<td>8</td>
<td>24</td>
<td>0</td>
<td>22,100</td>
<td>4</td>
</tr>
</tbody>
</table>

Another metric used to compare the two different data sources is emissions per day. Figure 1 shows CO₂ emissions by day for both field and RS Means for the Apex Project. The RS Means calculation resulted in shorter project durations than the actual duration but matched up well in emissions quantities per day. The emissions per day metric for the field data was 8.55x10⁶ grams of CO₂ while the RS Means data resulted in 8.82x10⁶ grams of CO₂. The results for the other pollutants are also comparable between the two data sources. Figure 1 shows that the project schedule for the field data was 124 days while the schedule for the RS Means data was 77 days. The difference in duration between the two is due to the difference in equipment fleet. The difference in productivity of the different equipment resulted in different activity durations even when the same quantity of work was used for both.

![Figure 1. Apex CO₂ Emissions for Field and RS Means](image)

5 CONCLUSIONS

Our seven projects clearly indicate that RS Means data often produces a different emissions estimate than the results obtained using field data. Where these differences exist they are largely due to the differences in fleet composition recommended by RS Means versus the fleet composition a contractor might actually use. However, on an emissions per day basis, published and field data matched well thus...
verifying the utility of this emissions metric. Finally, we also found that earthmoving and paving activities are by far the largest polluting activities.

The projects compared in this paper have differences not only in type but also in size and complexity. The Wake Forest project was a simple and small road widening project that lasted 13 days. The Apex project included the relocation of a road and an intersection and lasted 124 days. The street and utility projects included the installation of water distribution, sewer, and storm water systems, while the building project was a medium-sized commercial structure. These projects are typical of different construction projects types, although we readily acknowledge that they are not fully representative of all construction project sizes and types. Still, they do provide insight.

Our first research goals was to determine the extent to which project type affects the total quantity of emissions produced. The comparison presented on this paper shows that it is possible to calculate emissions metrics to compare different types of projects.

Another research goal was to determine how different project types vary in their emissions during construction. The results showed that the Apex and Wake Forest projects had similar emissions profiles with large amounts of emissions produced during earth movement and paving activities. This emissions pattern was similar to the one presented by the street and utility projects. Furthermore, the road and street projects produced pollutant emissions throughout the entire duration of the project. In contrast, the building project produced the majority of its emissions at the beginning of the project with almost all the emissions produced during the first two thirds of the project and two thirds of the emissions were produced before the project was even half completed.

More work is needed to increase the number of projects for which forecasts have been produced. However, this very small sample shows that it is possible to identify patterns of emissions production for different types of projects, thus enabling us to begin to develop an inventory and a hierarchy of project type emissions production, thereby alerting designers, in early project stages, of potentially dangerous emissions situations that are a function of project type.

The third research goal addressed whether or not emissions metrics could be used to compare different project types. One such metric was emissions per day. The results showed that all highway projects had higher emissions than the building. However, emissions per day may not be a good method to compare different projects because this metric can vary depending on schedule changes that do not affect total emissions. A better metric for comparison is emissions per unit, but the building project did not have a production unit comparable to the road and street projects. When the street and utility and the road projects are compared using emissions per square foot the results showed that road construction produced more emissions than street and utility projects.

Calculations presented herein included total emissions, emissions per activity, and emissions per equipment type. Activities with a larger contribution to total emissions include earth movement and paving. The activities with the largest contribution for the Apex project were clearing and grubbing, grading, and aggregate base course (ABC) and paving. Gravel subgrade and backfill were the activities with the largest emissions for the Wake Forest project. The emissions for these activities were the highest for both the field and RS Means estimation methods and are all similar in nature.

The equipment types with the largest contribution to total emissions were motor graders, backhoes, front-end loaders, and bulldozers. The large contribution of some of these types of equipment is linked to their high emissions factors. For other equipment types, such as bulldozers, their large quantity of emissions is due to the long hours of use of the equipment for a variety of different activities.

This study shows that it is possible to use published data to obtain a forecast of total emissions at the early stages of the project, making it possible to have emissions forecasts earlier in the project process. An early forecast can be used during the planning process to compare alternatives or to estimate the environmental impact of a potential project. As with any forecast, the accuracy of the numbers can be improved when additional information is available.
Contractors can use a forecasting model during the construction process to assess their emissions production. The actual equipment type and hours of use can be used as inputs rather than the planned (and potentially highly variable) schedule. The forecast could be used to monitor their equipment use and productivity in addition to monitoring emissions produced. Improving productivity could reduce hours of operation for each item of equipment and could result on lower total emissions for the project.

The data collected during construction could be used to calculate a final total emissions quantity for the entire project. This total could be viewed as an equivalent to an “as-built” emissions total that owners can use to evaluate total effect or future activities to offset this effect. Researchers could use the equipment use and total emissions information to improve emissions metrics for different equipment types.

References
INFRASTRUCTURE REHABILITATION PLANNING: COMBINED SYSTEM DYNAMICS AND OPTIMIZATION METHODS

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Abstract: To improve the performance of the increasingly deteriorating infrastructure, effective strategic policies must be combined with optimum tactical rehabilitation plans. In the literature, limited efforts have focused on strategic policy analysis and its integration with tactical/operational planning. This paper, therefore, presents a framework that combines the strategic and tactical dimensions of infrastructure rehabilitation. At the strategic level, the System Dynamics (SD) modeling technique has been used to simulate the long-term effect of different policy scenarios on physical performance and backlog accumulation. The optimum policies are then used as inputs to a detailed tactical planning model. The objective of such model is to provide detailed fund allocation plans for the assets that need rehabilitation on a yearly basis. The proposed tactical model deals with large number of asset components over a 5-year plan to determine the best possible combination of repair types and timings. The paper compares the processing time and solution quality of three models that use different optimization approaches: Genetic Algorithms (GA); mathematical mixed integer programming; and Microeconomic-based heuristics. The paper discusses the conceptual formulation of the proposed integrated framework, the developments made so far, present limitations, and future enhancements.

1 INTRODUCTION

A major challenge for asset managers is to determine the appropriate actions needed to preserve the performance of rapidly deteriorating civil infrastructure, over a long service life. Adequately budgeting and planning of infrastructure rehabilitation programs is of extreme importance in achieving this objective (Hudson et al. 1997). Budgeting and planning, however, are complex tasks that require many details about each asset, including present condition, multi-criteria performance, deterioration pattern, possible rehabilitation actions, and rehabilitation impacts. All these are then used to formulate a detailed life cycle cost analysis (LCCA) model of the whole network of assets to facilitate the appropriate allocation of limited rehabilitation funds among the assets (Frangopol et al., 2012). In the literature, infrastructure rehabilitation has been extensively studied and a number of life cycle optimization models have been introduced for different asset domains. Examples are: pavements (De la Garza et al. 2011); water and sewer (Halfawy et al. 2008); bridges (Frangopol et al. 2012); buildings (Rashedi and Hegazy 2014). Most of the existing models, however, suffer from performance degradation when facing large-scale and complex life cycle optimization problems, yet the results are also difficult to explain or economically interpret (Rashedi and Hegazy 2014; Hegazy and Saad 2014).

While existing efforts provide useful life cycle cost models, they do not provide an overall understanding of the rehabilitation dynamics in large networks of assets, over a long period of time. Some efforts
focused on individual assets over a long period (more than 50 years) (e.g., Frangopol and Liu 2007) while others focused on a large number of assets over a short period (5 years) (e.g., Rashedi and Hegazy 2014). These efforts do not provide a comprehensive view that examines strategic decisions and their impact on the life cycle dynamics over a long span of time. Such a comprehensive view, however, is essential for strategic decision-making. This paper therefore attempts to combine the long-term strategic perspective that relates to the setting of budget policies with the short-term tactical perspective that relates to detailed allocation of a decided budget among asset components. The paper explores the potential of the system dynamics (SD) technique as an effective tool for modeling and analysis of the dynamic processes within infrastructure rehabilitation at the strategic level. Also it compares various optimization techniques that can be used to optimize tactical fund allocation decisions. The combination of the two levels of decisions creates a more comprehensive framework for analyzing infrastructure rehabilitation plans.

2 PROPOSED FRAMEWORK FOR REHABILITATION PLANNING

A proposed policy optimization framework is illustrated in Figure 1. The overall objective of this framework is to understand the dynamic interactions among different aspects of asset management, generate various ‘what-if’ scenarios, and optimize strategic policies. The framework’s initial inputs can be categorized into two groups: asset information and organizational information. Asset information is mainly determined using inspection and condition assessment methods. They include asset inventory data, current conditions, historical condition indices, deterioration rates, maintenance costs, and costs of rehabilitation alternatives. Organizational information, on the other hand, includes key performance indicators (KPIs), strategic objectives, and different policies such as budget allocation strategy. To develop the strategic and tactical models of this comprehensive framework, the asset inventory of the Toronto District School Board (TDSB), which administrates a network of more than 550 school buildings, has been used. Also, in this study the key strategic variables have been identified based on reviewing the literature, previous research on TDSB assets, and other guidelines obtained from the TDSB and the Ontario Ministry of Education (OME). The two main components of the proposed framework are as follows:

![Figure 1: Proposed framework for rehabilitation planning](image-url)
Strategic System Dynamics (SD) Model: The strategic SD model investigates the long-term organizational objectives and seeks to examine the impact of different strategic policies, such as rehabilitation budgeting, sustainability policy, or public private partnership (PPP), on asset performance and backlog accumulation. As shown in the conceptual framework of Figure 1, the proposed SD model has four integrated modules: 1) the central policy analysis module; 2) physical condition; (3) backlog accumulation; and (4) sustainability performance. Accordingly, the SD model simulates the dynamic interactions within and among these modules, and can be used to provide policymakers with a clearer understanding of the long-term impact of their policies.

Tactical Optimization Model: After performing the strategic SD analysis, the outputs of the model, such as budget policy, is used as an input to the tactical optimization model to perform a detailed fund allocation analysis over a tactical planning horizon. At the tactical level, three approaches: genetic algorithms (GA), mathematical optimization, and microeconomics-based heuristics are used to achieve the most optimum fund allocation plan.

3 STRATEGIC SD MODEL

System dynamics (SD) is perhaps one of the most promising simulation methods in the area of policy optimization and strategic decision-making (Forrester 1961). Sterman (2000) describes it as “a method to enhance learning in complex systems. Just as an airline uses flight simulators to help pilots learn, system dynamics is, partly, a method for developing management flight simulators, often computer simulation models, to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies.” SD has been applied to a variety of domains from construction to politics, HIV control, and even warfare. In all of its applications, SD has proved to be capable of capturing the dynamics and interactions within complex systems from a holistic perspective, thus making it effective for top-level management (Sterman 2000). In the asset management domain, Rehan at al. (2011) developed an SD model for estimating the financial sustainability of water and wastewater systems and the impact of pricing policies on users. In another effort, Xu and Coors (2012) combined SD with GIS and 3D visualization to examine the sustainability of urban residential development. Other applications have also established the significant potential of system dynamics with respect to the development of holistic models for macro-level management.

To examine the dynamics within complex systems, SD models are developed through three main steps: (1) creating causal loop diagrams (CLDs) to capture the dynamic interactions among the key variables/parameters; (2) mapping the developed CLDs into stock-and-flow simulation components; and (3) running the simulation, testing the model, and analysing the long-term impact of various parameters. These steps, along with the proposed rehabilitation analysis model, are discussed in the next section.

3.1 Casual Loop Diagramming

The development of the proposed strategic SD model starts with identifying the interactions among four main groups of key strategic variables (as shown in Figure 1), related to: policy aspects of asset management, physical condition, backlog accumulation, and sustainability performance. Figure 2 depicts the proposed causal loop diagram (CLD) that captures the dynamic interactions among the key strategic variables. In system dynamics, Causal Loop Diagrams (CLDs) are tools for capturing SD hypotheses about the interactions among different variables/parameters, causes of dynamics, and determining the important feedbacks in the strategic model. A causal loop diagram consists of variables connected by links denoting the causal influences among them. Casual links show effects of variables on each other by link polarities. A positive link, i.e., (+) polarity, implies that the cause and effect are moving in the same direction meaning if a cause increases, the effect increases and if a cause decreases, the effect decreases. A negative link, i.e., (-) polarity, means if the cause increases, the effect decreases and vice versa (Sterman 2000). As and example, a CLD is highlighted in Figure 2 that involves two variables: “asset condition” and “asset deterioration”. In this CLD, “asset deterioration” is linked to “asset condition” by a negative link polarity, which models the fact that higher deterioration typically results in lower condition. Similarly, another negative link in the same loop represents the causal relationship in which higher condition leads to lower deterioration. The combination of these two links then creates a positive
(or reinforcing) feedback loop as highlighted in Figure 2. This positive loop models the dynamic behavior of infrastructure deterioration in which growing deterioration rates results in decaying physical condition in a continuous cycle. With time, such a reinforcing loop exhibits an accelerated rate of deterioration and lower condition indices, until other parameters take part to influence these dynamics.

Figure 2: Causal loop diagram for the proposed SD model

3.2 Stock-And-Flow Modeling

After identifying the dynamic interactions among the parameters that are impacted by strategic policy, the developed causal loop diagram (CLD) has been mapped into a stock and flow simulation model. While the CLD shows the underlying feedback structure of the model, the stock and flow diagram captures the physical dynamic structure of the system. Stocks, represented by rectangles, are accumulations that characterize the state of key system variables over the simulation time. Flows, on the other hand, represent system variables that generate quantities accumulated into (inflows) or out of (outflows) the stocks over time. Figure 3 shows a partial screen capture of the SD simulation model, which has been developed in the VENSIM software. The model includes around 100 decision variables and equations including key and intermediate parameters. Developing the stock and flow diagram of Figure 3 and its underlying simulation model was a demanding process of translating all the loops in the CLD diagram one by one into stocks and flows and writing the related equations. This iterative process includes numerous rounds of modifications of the stock and flow diagram and performing various tests to verify model relationships and the accuracy of results.
3.3 Analyzing Budget Policy

As an example to show the application of the proposed model in determining different strategic policies, a set of experiments was performed to investigate the effect of government investment on asset condition and backlog accumulation, to determine a proper annual budget level. Four scenarios have been generated based on different investment values. Scenario 1 allows assets to deteriorate over time without any rehabilitation (i.e., $0/year), and the next three scenarios (Scenario 2, 3, and 4) investigate the effect of increasing the annual government investment from 0 to $2, $3, and $4 million, respectively. Figure 4 shows the backlog and condition results. As expected, the no rehabilitation scenario causes significant backlog accumulation (almost 7 times more than the $4 million/year scenario at year 50) and results in a decaying overall asset condition (Figure 4). Increasing government investment, as shown in Figure 4, can significantly reduce backlog accumulation and improve asset condition. Sustainable performance results also indicated that increasing the annual budget by only $1 million (e.g., form $3 to $4 million/year) can improve the sustainable performance by 39%. The positive effect of increasing investment on condition and backlog might be obvious, however, the presented analysis can be very useful for the TDSB administrators (or other asset owners) to justify the required budget and its impact on their inventory while negotiating with the ministry of education (or other authorities).
4 TACTICAL OPTIMIZATION

With a budget level imposed on a public agency as a constraint on rehabilitation work (as a result of strategic analysis), tactical decisions are concerned with determining the optimum rehabilitation type (project-level decisions) and rehabilitation timing within a planning horizon (network-level decisions). At the tactical level, this paper utilizes a fund allocation method that integrates both project and network levels of decision. The method is built upon the Multiple Optimization and Segmentation Technique (MOST) of Hegazy and Elhakeem (2011) that reduce problem size to handle large-scale problems. In the MOST technique, the project-level analysis is done first, one year at a time, to determine the most cost-effective rehabilitation scenario (e.g., minor, major, or full replacement) for each asset that maximizes overall condition. This analysis provides a pool of best potential repair strategies, and their associated costs. This information is then used as a lookup input table to simplify the network-level analysis. At the network-level, the problem is segmented into yearly smaller-size optimizations to determine optimum renewal timings (facilitated only by the pre-analysis at the project level) using genetic algorithm (GA), as shown below in Figure 5.

![Figure 5: Schematic of MOST and its adaptation to the network-level fund allocation model](image)

The performance of GAs, however, is highly sensitive to problem size, problem formulation and other operational parameters that govern the GA evolutionary process. As such, a steep degradation of solution quality has been noticed from experimenting with GA on larger problems (Rashedi and Hegazy 2014). Thus, at the network-level, this paper presents three different models to improve solution quality: 1) GA + Segmentation optimization, 2) Mathematical optimization, and 3) Microeconomic Enhanced benefit-cost analysis (EBCA) heuristic. To compare solution quality, the three models are applied to a base case involving 800 school building asset components. The models have a planning horizon of 5 years, an assumed $10M annual budget yielding from the strategic-level SD model, and the objective function of maximizing the overall network condition.

4.1 GA + Segmentation Model

To suit real-life problems that are much larger in size, a segmentation method by Hegazy and Rashedi (2013) has been applied to enhance the performance of GAs. The GA+Segmentation process divides the original network-level problem into smaller sub-problems (segments), handles them separately, and combines their results to produce the final solution. To implement the segmentation process within the tactical model, the available budget, decision variables and optimization constraints have been segmented, without compromising the integrity of the model. Also, the model has been modified to
accommodate the redistribution of unallocated (leftover) money from one segment to the next. Considering these aspects, the GA+Segmentation approach has been fully automated, which makes it practical for real-life applications. In the GA+Segmentation method, the budget is divided among segments (e.g., size of 200 assets) based on the relative criticality (RC) of each segment, which is calculated as a function of the relative importance and the deterioration behaviour of the components within each segment. Subsequently, the budget constraint in year j for the components within a segment is proportional to the segment’s RC value divided by the sum of RCs for all segments. Application of the GA+Segmentation model on the building case study showed significant improvement to solution quality in comparison to the traditional GAs (comparison is shown in Table 1), and effectiveness in handling large-scale problems. The major drawback of this approach, however, was its processing time that showed exponential increase on larger size problems.

<table>
<thead>
<tr>
<th>Tactical Optimization Approach</th>
<th>Network * Condition</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Rehabilitation</td>
<td>54.15</td>
<td></td>
</tr>
<tr>
<td>Simple Ranking</td>
<td>44.89</td>
<td>Poor Solution Quality</td>
</tr>
<tr>
<td>GA (Hegazy &amp; ElHakeem 2011)</td>
<td>33.18</td>
<td>Limited to 800 assets</td>
</tr>
<tr>
<td>GA+Segmentation (Hegazy &amp; Rashedi 2013)</td>
<td>32.09</td>
<td>Applicable to large-scale; long processing time; suitable for nonlinear problems</td>
</tr>
<tr>
<td>GAMS/CPLEX (Rashedi &amp; Hegazy 2014)</td>
<td>31.71</td>
<td>Applicable to large-scale; very fast; provides close to global optimum results</td>
</tr>
<tr>
<td>EBCA Heuristic (Saad 2014)</td>
<td>31.79</td>
<td>Applicable to large-scale; high quality solutions; provides economic justifications</td>
</tr>
</tbody>
</table>

* Smaller is better

**4.2 Mathematical Optimization Model**

To reduce processing time and to find globally optimum solutions, Rashedi and Hegazy (2014) developed a mathematical optimization model that utilizes an advanced mathematical optimization tool, General Algebraic Modeling System (GAMS), which consists of an array of integrated high-performance built-in solvers. The model uses CPLEX solver engine, a powerful mathematical optimization solver that uses advanced algorithms for variety of optimization problems, including mixed-integer programming. The optimization model is designed to be generic enough to accommodate any type of data. The model’s objective function is to maximize the assets’ overall network condition index, which is an aggregation of one or more performance parameters of all individual assets. Each asset can be selected in a year over the planning horizon using a binary decision variable (e.g., \( X_{ij} \)). If \( X_{ij} \) for a certain asset \( i \) and year \( j \) is equal to 1, then the asset is selected for rehabilitation at this year, and the associated rehabilitation cost and benefit would be retrieved from the appropriate lookup tables (value of zero represents no action). The Objective function is set to maximize the network overall condition index, which is the weighted sum of all assets’ condition, considering the relative importance factor of each asset. The total rehabilitation cost, which is the sum of all assets’ costs in any year \( j \), is another constraint that is limited by the available budget for that year. Also, each asset can only be selected once for rehabilitation within the planning horizon to satisfy a single-visit criterion (Rashedi and Hegazy 2014). The GAMS/CPLEX model proves to be promising in terms of both solution quality and processing time and can be effectively used by asset managers for tactical optimization solutions. Using this model a network of more than 50,000 asset components, that is close to the real size of the problem, has been optimized in a matter of minutes resulting in a close to global optimum network condition of 31.71 as shown in Table 1.
4.3 Microeconomic EBCA Heuristic Model

While the previous two models are effective in handling large-scale tactical optimization problems, their development was not simple, thus it is difficult to provide an economical interpretation for the optimization results. The results are typically a set of decisions (usually binary, i.e., a combination of \([0, 0, 1, 0, 0]\) represents a decision to repair an asset in year 3 of a 5-year plan). In case of thousands of assets, which is typical, the combination of zeroes and ones is not easy to interpret or justify economically. Several combinations of zeroes and ones might lead to close-to-optimum solutions, and thus it is not easy to determine the logic behind those solutions.

To handle this issue, an Enhanced Benefit-Cost Analysis (EBCA) heuristic approach has been introduced that uses the microeconomic consumer theory of equal marginal utility per dollar, to arrive at near optimum balanced fund-allocation decisions in a structured way, while providing an economic justification behind decisions (Saad 2014). This theory of equal marginal utility per dollar has been proven, in the microeconomics literature (Chugh 2014), to arrive at optimum allocation of a limited fund by targeting equilibrium (equality) among the marginal utility per dollar spent on the different consumption categories, rather than the typical approach of maximizing benefits or minimizing costs. The basic premise of this approach is an analogy between a consumer who has a limited income to spend on various expenditure categories, and a public agency with a limited budget, from taxpayers’ money, to allocate to various rehabilitation expenditures. As such, optimum fund-allocation is represented by an equilibrium state at which the marginal utilities (benefits) per dollar (MU/$) associated with the rehabilitation of the last selected asset from each category (e.g., Architectural, Mechanical, etc.) are equal. This approach involves a five-step process that is applied one year \((j)\) at a time to facilitate mapping the consumer case in each year in the planning horizon. To arrive at the optimum decision that maintains equilibrium state among the different asset categories the heuristic process is applied to the building case study as follows:

1. For each year in the planning horizon group unfunded assets into their categories (Architectural, Mechanical, and Electrical);  
2. List the performance improvement and the renewal cost for each asset based on the LCCA calculations, assuming all assets will be funded this year;  
3. Compute the Marginal utility per dollar (MU/$) for each asset by dividing the performance improvement by the renewal cost;  
4. Sort the assets in a descending order, according to the MU/$; and  
5. Select assets for funding starting from the top of the sorted list in each category till the MU/$ value of the last selected asset in each category is almost equal, and the budget for this year is fully exhausted. Move unfunded assets beyond this equilibrium point to the next year in the planning horizon.

![Figure 6: Sample of selected assets in first year using EBCA approach](image-url)
Figure 6 shows the application of the heuristic process steps to the school building case study in first year. The assets are grouped according to their system-level categories (Architectural, Mechanical, and Electrical), and sorted in a descending order according to their marginal utility per dollar values. The “Cum. Cost” column represents the total cumulative rehabilitation costs that correspond to a total number of allocated assets in each category. The shaded part shows the optimum (equilibrium) combination of assets for year 1, which is 124 architectural, 51 mechanical, and 43 electrical assets. The total cost associated with this combination is $9,994,640 ($4,509,670 + $3,415,870 + $2,069,100), which almost fully exhausts the available budget while maintaining an equilibrium state among the asset categories. The microeconomic EBCA approach can handle large-scale problems due to its formulation, and it is comparable to the mathematical model in terms of solution quality, yet with a structured strategy supported with economic justification.

5 CONCLUDING REMARKS

This paper discussed a comprehensive infrastructure rehabilitation framework that combines a strategic SD-based policy analysis model with tactical optimization to create detailed fund allocation plans. At the strategic level, the development of a holistic the SD model, including causal loop diagrams and stock-and-flow simulation model, have been discussed. The model was experimented on a policy analysis example with regard to rehabilitation budgeting. Using an appropriate budget level, three tactical optimization models have been discussed, each with a particular advantage, to effectively allocate the selected rehabilitation budget. The GA+Segmentation model can handle large-scale and nonlinear problems, but its processing time increased exponentially as problem size increased. The mathematical GAMS/CPLEX model had the highest solution quality and could optimize large-size problems within a very short processing time. The microeconomic-based enhanced benefit-cost analysis (EBCA) also results in high quality solution that can be economically interpreted, and can handle large-scale problems due to its formulation. The proposed framework of this paper can be applied to variety of asset types and can address the asset management needs at both strategic and tactical levels. This comprehensive model can be used to ultimately improve the economics of infrastructure rehabilitation by allowing asset owners to align all levels of decisions to maximize the impact on asset condition and backlog accumulation.

References


A FRAMEWORK OF ORGANIZATION PERFORMANCE ASSESSMENT IN THE CONSTRUCTION INDUSTRY USING FUZZY APPROACH

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² zrathore@purdue.edu

Abstract: Organizations have been trying to increase their efficiency and improve their performance in order to achieve their goals. The organizational success is determined by various factors that impact organization's performance. The ability to predict construction organization performance will enable practitioners to identify the weak points and in searching solutions to improve, thus leading to better efficiency and increase profit. Previous research works have focused on measuring project success and in the process the importance and evaluation of organization's performance in non-financial aspects has received little attention. Uncertainty and uniqueness of projects are inherent characteristics of this industry. Hence, developing an effective construction performance assessment model has been very difficult. Therefore, the objective of the present research is to identify and study the success factors and to propose a performance prediction model(s) for construction organizations. The potential success factors are collected from literature and shortlisted based on construction expert's opinion. A questionnaire is prepared and sent to evaluate the effect of these potential success factors on organizational performance. The collected data will be analyzed using Fuzzy modelling approach to build a prediction model, which will show robust results when verified and tested. The proposed research/model will benefit both researcher and practitioners to predict accurate company performance.

1 INTRODUCTION

Construction is a diverse, project based industry (Ozorhon, 2012). The project-based nature of construction industry makes every project unique (Veshosky, 1998). The unique nature of concerns and challenges often render the generalizable decision rules and frameworks for organizational phenomena unusable (Pinto & Covin, 1989). Financial and tangible assets gained are often translated to organization success. In a review of project success factors conducted by Müller et al. 2012, it is has been noted that project success was considered only as a subject of implementation in the 1980s. The approach towards the subject has evolved over the years. It is now gradually extending from inception to closing out of a project. Today, the literature in this field spans the entire product life cycle from product success to business success. This change has led to shift in emphasis from project success to organization success. The need to examine A/E/C organizations and the factors that impact the performance of organizations is now necessary to compete in an ever-changing marketplace (Liu et. al., 2014).

2 BACKGROUND

A company is a complex structure, comprising of various interconnected components that influence its performance (Tang & Ogunlana, 2003). The existing literature shows that numerous models were developed to measure performance by using critical success factors, performance measures, and
indicators. However, they mostly address metric requirements for the manufacturing industries rather than construction. Studies conducted in the construction industry have laid more emphasis on the measurement of project performance rather than company performance (Isik, Arditi, Dikmen, & Birgonul, 2010). Bontis et al. 1999 proposed Balanced Scorecard (BSC). The framework laid emphasis on qualitative measure at organizational level and advocated the balance between measure of financial and non-financial success. Another example of performance measurement and management framework is Performance Prism. The first part of this framework encourages to assess stakeholder satisfaction, and assess the needs of stakeholder. The second part is to understand the needs of organization (i.e. reciprocal relationships) as well as on how to align strategies, processes and capabilities (Neely et. al., 2001). The prism focuses on significant measures and connects the performance practices within the organization. These frameworks are more than a decade old. Hence, in order to keep up with the ever changing markets, many new studies are being carried out.

Performance prediction of construction organizations enables identification of the weak points in order to improvise processes and to increase profits (Zayed et al. 2012). The attention of organizations is usually focused on improving the efficiency of its tangible assets as they can be measured and evaluated (Hauser & Katz, 1998). In the process, the organizations often do not consider the invisible and intangible assets that impact the overall performance. A good metric systems empowers organization (Hauser & Katz, 1998). In a recent study and analysis of a case study by Gustavsson et al., 2012, a need for new collaborative project practice development and organizational change has been discussed. Company performance can be assessed by evaluation of measurable characteristics of performance indicators (Bititci & Muir, 1997).

2.1 Critical Success Factors in construction organization

Organizations that focus on satisfying the customers with greater efficiency and effectiveness have an edge over their competitors (Neely et. al., 2005). Studies have shown that practitioners have been able to settle that improving communication has a major impact on construction practice. It allows better customer engagement, leading to better performance of organizations. Neely et al. 2005 stresses on importance of metrics associated with quality, time, cost and flexibility, thus relating performance of organizations with project success. Pinto and Covin (1989), Müller et al, 2012 have discussed that project success is dependent on the interaction of individuals, project teams and organizational success. Chinowsky et al. 2000 proposed the concept of seven guiding principles of strategic management for construction industry. These comprise of Vision, Mission, Goals, Core Competencies, and Knowledge resources, Education, Finance, Markets and Competition (Chinowsky & Meredith, 2000). Knowledge and information are now considered as critical factors that influence a company's life. They are rated higher than land, capital or labor (Bontis & Dragonetti, 1999). A good knowledge data base will allow organizations to leverage against their competitors in future and thus giving organizations a competitive edge (Arthur, 1994). Unfortunately, Knowledge being an intangible asset is difficult to measure and hence often forgotten in the process (Bontis & Dragonetti, 1999).

Organizations are conceptualized as “the product of thought and action of [their] members” (Gioia & Sims, 1986) or as Weick 1987 stated “the body of thought by organizational thinkers” (Nicolini & Meznar, 1995). Human elements are the assets of organizations that are capable of learning, evolving, innovating and creatively propelling the growth of organization, which is essential for long-run survival of the organization. It has been noted that majority of Human Resource Accounting (HRA) techniques have been designed for industries like accounting firms, banks, insurance companies and financial service firms, where human resources represent a substantial share of the organization value (Bontis & Dragonetti, 1999). However, construction organization lacks such initiatives that are designed to evaluate employee performance, satisfaction and compensation. Factors such as organization's employee culture and engagement are important aspects for an organization. Other important factor is the feedback systems, as they are extremely crucial for implementation of metric system and evaluating performance of organization. Feedback evaluation is one of the critical success factors that aid in analyzing and improving organization performance (Hauser & Katz, 1998).
2.2 Previous studies

In a study conducted by Zayed et al. 2012 classified 18 Critical Success factors into four categories. i.e. (i) Administrative and legal factors, (ii) Technical factors, (iii) Management and (iv) Market and finance, as shown at Figure 1.

The research work is in continuation to the study carried out by Elwakil et al. 2009. The previously published paper was an overview for an outline or a framework for performance assessment of organizations in the construction industry. The procedure included a literature review and identification of 18 potential critical success factors. This was followed by preparation of questionnaire designed to assess the impact of these factors in the construction industry. The questionnaire had two parts where Part I asked the experts from construction organizations to answer the questions, reflecting their experience and corporation information. Part II asked the experts to use a specified 5 point subjective scale to rate the impact of identified success factors on organization performance. Additionally, the decision-makers were asked to evaluate the overall success of his/her construction organization using a value out of 100. One hundred and fifty questionnaires were sent out to top and middle management decision makers in construction organizations across different countries, i.e., Canada, Egypt, France, Greece, Germany, USA, Saudi Arabia and United Arab Emirates. A total of Sixty three responses were received i.e. A response rate of 42%, which is considered good. A sample response from data is provided in Table 1 (Zayed et al., 2012).

![Figure 1: Categorisation of 18 Critical Success Factors](image-url)
Table 1: A sample of questionnaire

<table>
<thead>
<tr>
<th>Category</th>
<th>Success Factors</th>
<th>Responses (Scale: 1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative and legal</td>
<td>1. Clear Vision, Mission, and Goals</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2. Competition Strategy</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3. Organizational Structure</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4. Political Conditions</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5. Number of Full Time employees</td>
<td>4</td>
</tr>
<tr>
<td>Technical</td>
<td>6. Usage of International Aspects (ISO)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>7. Availability of Knowledge</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>8. Usage of IT</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>9. Business Experience (no. of years)</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10. Product Maintenance</td>
<td>5</td>
</tr>
<tr>
<td>Management</td>
<td>11. Employee Culture Environment</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>12. Employee compensation and Motivation</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>13. Applying Total Quality Management</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>14. Training</td>
<td>4</td>
</tr>
<tr>
<td>Market and Finance</td>
<td>15. Quick Liquid Assets</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>16. Feedback Evaluation</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>17. Research and Development</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>18. Market Conditions/ Customer Engagement</td>
<td>4</td>
</tr>
<tr>
<td>Overall Company Performance (%)</td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>

* Data is shared by co-author

Since the responses from questionnaire dealt with 18 factors, it is very difficult to analyse the impact of all the factors. Hence, these factors were evaluated and allotted ranks using ANN training i.e. ranking the factors to determine the relative importance of each variable and the highest impact on the model. Analysis of weights of the trained neural network are used to derive the contribution percentages. The higher the value implies that the variable contribution to classification/prediction is also high. Based on the ANN rankings, 9 factors with highest contribution factor were shortlisted from the pool of 18 factors as shown at Figure 2.

Figure 2: Factors shortlisted using ANN ranking method
2.3 Previous modelling techniques

The previously published paper guides the researchers to the starting point of a detailed research in the field. The previous paper discussed the overall impact of the factors. The selected nine CSFs were used to develop prediction models for performance of construction organization using Artificial Neural Network (ANN) model and regression. Neuroshell software package was used to develop and train the ANN model. Similarly, MINITAB software is used to build a regression model for construction organizations’ performance using the selected CSFs (Zayed et al., 2012).

One of the many advantages of theoretic properties of ANN is the ability to distinguish unspecified relations such as nonlinear effects and/or interactions. However, this advantage comes at the cost of minimized interpretability of the model output. The “black box” quality of an ANN model makes it next to impossible to gain insight into a problem based on an ANN model. Regression technique allows the user to sequentially remove possible explanatory variables that do not contribute to the fit of the model (Sargent, 2001). Regression techniques permit hypothesis testing concerning both the univariate and multivariate association amongst each explanatory variable and the outcome of interest. However, it fails to recognize or identify the highly nonlinear factors, or correlation among variables (Sargent, 2001). Human reasoning being more approximate than precise in nature often makes it difficult to measure and determine the measure of factors affecting a particular cause. Introduced by Zadeh (1965), Fuzzy logic can be used as a tool to understand imprecision and qualitative aspects of natural language and imprecise cognitive reasoning. Fuzzy logic-based systems are used to analyze and process linguistic inputs to derive outputs or decisions, refer Figure 1 (Senouchi et al 2014).

The background shows a lack of a model that considers the qualitative factors and the expert opinions. The objectives of this paper will be: identify and study the success factors and to develop performance prediction model(s) for construction organizations.

![Figure 3: Fuzzy expert system (FES) (Senouci et. al.2012)](image)

3 Research Methodology

The methodology of this research is presented in the schematic diagram (figure 4). The steps are summarized as following:

1. Conduct a literature review to identify the success factors that can impact performance of construction organization. Data collected from questionnaire in the previous study conducted by Zayed et al 2012 will be studied and analyzed.
2. Model the impact of individual factors and establish correlation between factors. It is proposed to develop a performance assessment model for construction organization using Fuzzy Expert System. The model will focus on analyzing the impact of preselected 9 CSFs on the performance assessment model.
3. The model will be tested and validated by results of ANN and regression analysis in order to determine their accuracy in assessing the performance of construction organization.

3.1 Development of Fuzzy Logic-based performance assessment model

Factors that have an impact on an organization's performance are the inputs for the fuzzy model. The selected CSFs have been identified and classified into 4 categories ie. 1. Administrative and Legal, 2. Technical, 3. Management and 4. Market and finance. The output will be the performance of construction organization. The methodology used to build the model using fuzzy expert system is shown in figure 5.
3.2 Values of Fuzzy Input and Output Linguistic Variables

The previous research paper included identification of potential success factors that impact an organization’s performance. These factors were compiled from various literature and expert professionals. A questionnaire was prepared to evaluate the impact of each factor on performance. (Zayed et al 2014). The values of linguistic input variables under the four categories (i.e. Administrative & legal, Technical, Management and Market & Finance) are allotted on a scale of one to five as they don’t have a tangible mean of measure. For example, an input value for a variable such as importance of factor of Clear vision, mission and goals cannot be given any crisp value. Such a factor can only be given rating on a subjective scale. The same concept applies to other variables as shown in Table 2. Miller et. 1956 suggested that maximum number of pieces of information should be seven, plus or minus two.

3.3 Fuzzy Member Function, Inference, Composition and Defuzzification

Inferencing is the process wherein specific values are applied to the input variables to calculate the values of the output variables. In FES, the inference process comprises of four subprocesses: fuzzification, inference, composition, and defuzzification. Inference is a step that involves computation of true value for the range of each fuzzy rule and then applying it to conclusion of each. The next step is called Composition where in fuzzy subsets are assigned to each output variable and then combined together to form a single fuzzy subset for each output variable; and followed by Defuzzification, where the fuzzy output set is assigned a crisp number. (Horstkotte, 2002)

3.3.1 Fuzzy Decision Rules

A FES computes the task formulated as a collection of fuzzy if/then rules. These are rules are formulated by combining certain scenarios and the corresponding output. These rules are represented in the form of linguistic if-then statement. They are describes as: IF precondition 1 exits AND precondition 2 exits AND precondition 3 exits AND THEN consequence 1 AND consequence 2 will be the output (Chao & Skibniewski, 1998). For instance,

\[
\text{IF } C \text{ is } c_n, \quad \text{AND } S \text{ is } s_n, \quad \text{AND } O \text{ is } o_n, \quad \text{AND } P \text{ is } p_n, \quad \text{AND } K \text{ is } k_n, \quad \text{AND } N \text{ is } n_n, \quad \text{AND } E \text{ is } e_n, \quad \text{AND } F \text{ is } f_n, \quad \text{AND } R \text{ is } r_n, \quad \text{THEN } OP \text{ is } op_n
\]
Where C= Clear Vision, Mission, and Goals; S= Competition Strategy; O= Organizational Structure, P= Political Conditions, K= Availability of Knowledge, N= Business Experience (no. of years), E= Employee Culture Environment, F= Feedback Evaluation, R= Research and Development and OP = Overall Performance. For example:

IF Clear Vision, Mission, and Goals is 4, 
AND Competition Strategy is 4, 
AND Organizational Structure is 4, 
AND Political Conditions is 4, 
AND Availability of Knowledge is 5, 
AND Business Experience (no. of years) is 5, 
AND Employee Culture Environment is 4, 
AND Feedback Evaluation is 4, 
AND Research and Development is 4, 
THEN Overall Performance is 70

Table 2: Input and Output Linguistic Variables and Fuzzy/Crisp Value

<table>
<thead>
<tr>
<th>Input / Output</th>
<th>Linguistic Variable</th>
<th>Crisp/fuzzy value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative and</td>
<td>Clear Vision, Mission, and Goals</td>
<td>1-5</td>
</tr>
<tr>
<td>legal</td>
<td>Competition Strategy</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>Organizational Structure</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>Political Conditions</td>
<td>1-5</td>
</tr>
<tr>
<td>Technical</td>
<td>Availability of Knowledge</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>Business Experience (no. of years)</td>
<td>1-5</td>
</tr>
<tr>
<td>Management</td>
<td>Employee Culture Environment</td>
<td>1-5</td>
</tr>
<tr>
<td>Market and Finance</td>
<td>Feedback Evaluation</td>
<td>1-5</td>
</tr>
<tr>
<td></td>
<td>Research and Development</td>
<td>1-5</td>
</tr>
<tr>
<td>Overall Performance</td>
<td></td>
<td>0-100%</td>
</tr>
</tbody>
</table>

3.4 Model Implementation

It is proposed to utilize the software Matlab R2014b Fuzzy Logic Tool Box to process fuzzy logic inference. The input of the linguistic variables are fuzzified using the membership functions. One by one the strength of variable is determined and its impact on the output value. The minimum operator is used to calculate the firing strength of each fuzzy rule. The firing strength is directly proportional to the impact on the output. Output membership function maps the height corresponding to the firing strength of rules (Chao & Skibniewski, 1998).

\[ F_i = \min(x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9) \]

where \( F_i \) is the firing strength of rule \( x_1, x_2, x_3, x_4, x_5, ... \) are the parameters representing membership of linguistic variables (Chao & Skibniewski, 1998).

After all the rules are evaluated, union member function is used to combine the consequences of all the rules to form an overall membership function. This function is then converted into crisp value using defuzzification method.
### 3.5 Model Validation

The purpose of this step is to check the accuracy of results provided by the model. It is proposed to set aside 20% i.e. 13 responses out of 63 responses from questionnaire for validation purposes. In order to predict error and validate the model, it is proposed to use average validity/invalidity percentages (AIP and AVP), followed by Root Mean Square error (RSME).

In addition to the mathematical validation, the results from previous study by Zayed et al., 2012 will also be used to determine the soundness of model. The models developed in previous study to assess the performance of organization used ANN modelling technique and Regression analysis.

### 4 CONCLUSION

The present study includes a literature survey to validate the importance of critical success factors identified in previous studies. This paper represents development of framework to assess the performance of construction organizations based on nine CSFs using fuzzy approach. These nine critical success factors (i.e. Clear Vision, Mission, and Goals, Competition Strategy, Organizational Structure, Political Conditions, Availability of Knowledge, Business Experience (no. of years), Employee Culture Environment, Feedback Evaluation, Research and Development) were selected in the previous study using ANN ranking system. In order to assess the impact of individual factors on the overall organization performance, they have been modelled using FES. Fuzzy input and outputs and the rules governing them are designed in order to cover maximum possible cases. The study will be a step towards understanding a detailed analysis of factors that may impact the overall performance. The study shows a need for further investigation on critical success factor to select the optimum number and nature for modeling the organization’s performance. The developed research/model benefits both researcher and practitioners to predict accurate company performance.

### References


Abstract: Public private partnerships (PPPs) are a method for the delivery of social and economic infrastructure services in over 80 countries worldwide. PPPs are a contractual arrangement between public and private entities through which the skills, assets and/or financial resources of both sectors are allocated in such a manner that provides optimal service delivery and good value to society. Central to the operation of public private partnerships is the systematic evaluation of the procurement options available to government, an output specification to encourage private design, risk transfer, construction and operational innovation, the detailed analysis of projects over their operational lifecycle, a rigorous and competitive bid process, and the selection of proposals that deliver value for money. Unlike traditional procurement, which is predominantly based on lowest cost to government, value for money (VFM) is a measure that takes into account both the quantitative and qualitative outcomes over the term of a contract. This paper is based on a larger study for the Asia Development Bank (ADB) which contained an international survey prepared by the authors. The ADB report reviewed PPP policy and using six case studies as a basis for comparison. Each study considered experience of policy and institutional frameworks, value for money evaluations and infrastructure projects delivered. The Australian case study is included in this paper as an example of good procurement practice.

1 INTRODUCTION

First introduced as part of the Private Finance Initiative (PFI) in the United Kingdom in the 1990s, public private partnerships (PPPs) have come into wider use around the world as an important method for government procurement of economic and social infrastructure services. In contemporary practice, the PPP is a specialised form of procurement that changes the role of government from owner and manager of infrastructure assets to a buyer of infrastructure services.

PPPs are a method of public procurement that employs a combination of private sector capital and management to deliver infrastructure services to, or on behalf of, government (Regan, 2010). To determine which procurement method is best for government, a comparison of the procurement options is undertaken in the early stages of the procurement process. The criteria used to select the optimal procurement method is known as value for money (VFM) although the criteria used to ascertain which method or which bid offers the best deal for government is determined under PPP policy and this varies significantly between nations. VFM was introduced to infrastructure procurement in the 1980s and has
long served as a measure of the impact of international aid and assistance programs, and spending programs of government agencies for audit purposes (Australian National Audit Office, 2012). In OECD countries, VFM generally includes the formal cost benchmarking of the PPP option against a traditional procurement option on a life cycle costed basis over the term proposed for the PPP contract (the public sector comparator or PSC). This occurs in the bidder selection or investment stage of the project. Further VFM analysis may be conducted following a competitive auction process (the procurement stage of the project) after bids have been received. Policy may also require a qualitative comparison of the best bid and the PSC to identify the best VFM for government.

VFM enables government to measure two key dimensions of infrastructure procurement. First, it requires government to undertake a detailed \textit{ex ante} quantitative evaluation of a project over its life cycle in order to compare and select the best procurement option. Second, with adjustment for risk and competitive neutrality, it provides a means of comparing the most efficient procurement mechanism available to government with proposals received from contractors in a competitive bid process.

1.1\hspace{1em}What is Infrastructure?

Infrastructure refers to the hard assets, networks and human capital that facilitate the functioning of both the economy and civil society. Economic infrastructure refers specifically to the services produced by airports, roads, ports, railway systems, electricity generation plants, water supplies, telecommunications, and waste management and recycling. Social infrastructure refers to services provided to develop human capital in areas such as primary, secondary and tertiary education, facilities for police services, court facilities and corrective services, the health sector, and public buildings. The cost of providing social infrastructure is mostly met from the government’s budget and services possess the characteristics of a public or merit good. However, economic infrastructure may also be fully or partly financed from user-charges, which enables services to be outsourced to private providers on a stand-alone basis.

Infrastructure is an important national asset class contributing to an economy’s output capacity, productivity, and its economic and social development. Infrastructure investment is also linked to employment (short and long-term), reduced private sector costs, productivity and growth (Weber and Alfen, 2010; Regan, 2004).

As an asset class, infrastructure assets and services possesses a number of distinguishing features:

- Investment is long-term, involves high sunk costs and is capital intensive
- Output quality standards and prices are generally regulated
- Long service intervals favour life cycle costing
- Assets generally form part of complex networks
- Output pricing of utilities such as electricity, gas and water have important impacts on the input cost structures of most sectors of the economy
- Assets are generally site and use specific
- Services are generally essential public goods
- Investment is subject to limited competition and economies of scale.

The investment economics of infrastructure assets are well matched to the PPP method of procurement and analysis based on VFM principles.

1.2\hspace{1em}What are the Infrastructure Procurement Options?

There are several procurement options available to government, which can be grouped into three distinct categories. The first is traditional procurement, which accounts for the majority of infrastructure provision throughout the world today. Traditional contracts have a number of distinguishing characteristics that generally include:

- The contract is based on an input specification
- Contractor selection methods is mainly determined on price
• An adversarial contractual framework in which the objectives and incentives adopted by the client, the contractor and other parties to the contract are non-aligned and therefore contributing to agency problems
• Mostly used with short-term complete contracts for construction-only services
• There is limited risk transfer beyond the typical time and cost provisions that apply under fixed price contracts.

The second group of contracts covers a variety of arrangements that adopt a less adversarial contractual framework and make greater use of the benefits of long-term contracts that incorporate both asset provision and service delivery, privately sourced capital and a greater sharing of project risks. The most common procurement forms include the build operate transfer (BOT) family of contracts, PPPs and outsourcing, franchises and concessions. These alternative procurement methods generally possess some or all of the following characteristics:
• An output specification
• A long-term incomplete contractual framework with a much greater alignment of the objectives and incentives of the parties compared with traditional contracts
• Transfer of decision-making to the contractor designed to encourage greater innovation in the construction and service delivery process
• Private finance
• The contractor carries a greater level of project risks than other procurement methods which may include construction time and cost, life cycle costs and operational risks
• Embedded regulatory arrangements including alternative dispute resolution mechanisms and a performance-based remuneration arrangement.

The third group of contracts are relationship-based arrangements for short-term or staged projects. These are an alternative to traditional and PPP procurement methods and are widely used for complex projects in which the specification may be incomplete or the contract price difficult to ascertain prior to commencement of works. The characteristics of relationship contracting include:
• Contractor selected on qualitative criteria including track record, expertise, previous experience with collaborative contracts and cultural match with client values
• A collaborative contractual framework with cost overruns and cost savings shared between the client and the contractor
• A contractual relationship based on high levels of trust and cooperation supported by a joint project management group, “open book” project accounting and an agreed contractor margin
• Agreed project scope and specification.

Procurement methods should be selected on a case-by-case basis and no single method is suitable for all projects. PPPs are a specialised form of procurement that may entail longer preparation times, complex documentation and higher transaction costs than other forms of procurement. Nevertheless, these disadvantages may be outweighed by better VFM outcomes for government determined on a risk-weighted comparative basis. PPP’s are not an appropriate procurement vehicle for delivery of all infrastructure projects or services. VFM is best achieved with projects or services involving complexity, economies of scale, where there is scope for significant risk transfer from government to private contractors, and when opportunities exist for innovation in design, construction and operations.

1.3 What is a Public Private Partnership?

A Public Private Partnership refers to a contractual arrangement between public (national, state, provincial or local) and private entities through which the skills, assets, and/or financial resources of each of the public and private sectors are allocated in a complementary manner, thereby sharing the risks and rewards, to seek to provide optimal service delivery and good value to society (Asia Development Bank, 2012). In contemporary practice, the term PPP has no precise
meaning and is used to describe a number of procurement forms including operations and maintenance contracts, management or service contracts (outsourcing contracts), the BOT family of contracts, franchises, concessions and partnering arrangements (World Bank 2007: 2; Hodge and Greve, 2005: 5-8). PPP is a generic description for long-term contracts between government and a private firm for the provision of economic and social services to, or on behalf of government. In a number of jurisdictions, PPPs are also called the PFI or Private Finance Initiative (United Kingdom and several Commonwealth member countries), PPF or Privately Financed Projects (New South Wales), PPI or Private Participation in Infrastructure (World Bank), BOT, concessions and franchises.

PPP policy may take the form of a special PPP law, the amendment of existing procurement laws and regulations, or a policy and guidance framework issued by a central agency of government such as Treasury and Finance. The characteristics of a typical PPP include the following:

1. An output specification that specifies the service to be delivered and not how it will be delivered (effectively transferring control rights and creating performance incentives for the contractor)
2. Scope for the exercise of private expertise, innovation and incentivised management
3. The transfer of significant service delivery and life cycle cost risk to the contractor
4. Contractor selection relies on qualitative and quantitative criteria (VFM) and not simply lowest price
5. Contracts are incomplete, long-term and generally self-regulating
6. The delivery process may be more complex than alternatives
7. Payment for performance: the government pays only for services that conform to specification.

In OECD member countries, a PPP is generally understood to mean a long-term contractual arrangement under which a private contractor is selected through a competitive bid process to finance and deliver goods or services to, or on behalf of the state (Burger and Hawkesworth 2011: 3; Hodge and Greve 2005, p. 4; Delmon 2009: 93-121; Regan et al., 2011: 364). Contractor selection is on the basis of best VFM, determined using quantitative and qualitative criteria and/or the application of a comprehensive and rigorous PPP policy framework (Regan et al., 2011).

Central to PPP procurement is the criteria used to select both the procurement method and the best proposal received from the contractors bidding for the project. Unlike traditional procurement that compares lowest-cost bids by contractors with an input specification, VFM is a life-cycle costed measure of the qualitative and quantitative aspects of a proposal. It describes the aggregate benefits from a particular procurement solution and measures the net positive gain or welfare benefits that a procurement strategy brings to government. VFM is a technique for selecting the best possible outcome for the money spent by government on a particular activity, program or undertaking (NAO 2009; HM Treasury, 2006: 7; Audit Commission 2010; Australian National Audit Office, 2012: 5, 8). It is widely used in project procurement and particularly for PPPs to determine whether a particular bid or proposal offers a lower cost and better service solution than an alternative procurement route (European Investment Bank, 2011). VFM is an objective that allows procuring agencies to ascertain whether service delivery is designed to appropriately meet the service specification while achieving a reasonable return on investment (Infrastructure Australia 2008a).

In contemporary PPP practice, VFM has assumed greater importance for measuring procurement solutions for infrastructure applications. In some jurisdictions, VFM is the critical determinant for determining whether the PPP is the optimal procurement method. This is done with a comparison of detailed models of a PPP with a traditional procurement alternative. In some jurisdictions, VFM is implied by creating a rigorous project implementation process and a competitive bid market (Delmon, 2009: 13-15). In other countries PPP policy requires the use of the PSC for both the procurement and contractor selection processes.

Value for money (VFM) in public–private partnership (PPP) projects is gained through the engagement of private sector efficiency, effectiveness, and economy and through the appropriate allocation of risks in the
project. The assessment of the potential to secure VFM is a key element of the PPP assessment process. The conclusions on VFM potential will inform governments in developing member countries (DMCs) on whether to proceed with a PPP procurement, and, if so, the form of PPP that could be used. (ADB 2012, Public–Private Partnership Operational Plan 2012–2020). Value for money allows procuring agencies to establish whether service delivery has been structured to appropriately meet the service output while continuing to ensure reasonable stewardship of financial resources. The assessment of value for money should encompass all aspects of the proposal including both quantitative and qualitative elements (Infrastructure Australia 2008). Value for money is the best deal that satisfies the government’s service objectives (National Audit Office 2009).

2 VFM ASSESSMENT IN PROCUREMENT

In some countries, PPP policy may endorse VFM principles without providing specific criteria to determine how VFM will be calculated. The reasons for this may be that government needs to fast-track projects or the government’s fiscal position limits public investment options. The informal assessment of VFM uses systematic approaches to the procurement process that embeds VFM principles in project evaluation and procurement methodologies.

In jurisdictions where a formal VFM process is not required, a comprehensive procurement process that embeds VFM principles may achieve a similar outcome. The elements of a VFM procurement process include a detailed feasibility or procurement options analysis, a pre-qualification procedure, competitive dialogue, technical and administrative requirements that incorporate quantitative and qualitative performance benchmarks, and adoption of a gateway system that prescribes the stages through which a project must pass before it is finally approved. Delmon (2009: 13) describes this approach as "... a holistic assessment of the project delivery and the marginal benefits provided by private investment and the competitive procurement process used".

A PPP policy that adopts one or more of these principles has a greater likelihood of achieving VFM outcomes for government than a PPP policy that does not. However, informal VFM methods do not provide government with sufficient data with which to improve the procurement process, document lessons learnt, raise the skill levels in line agencies and optimise risk transfer with future projects. These outcomes can only be achieved with adoption of a formal approach to VFM assessment.

A number of countries use a competitive bid market to enhance VFM outcomes. The competitive bid market approach is based on the assumption that private infrastructure procurement delivers projects at lower cost and in shorter periods of time than traditional public procurement methods and represent a better VFM option for government. Competition between private contractors in a well-managed bid market is considered the one of the drivers of VFM with PPPs (Ismail et al., 2011). VFM is more likely to be produced by a competitive procurement process over one that is not. However, competitive bidding alone does not ensure VFM outcomes.

When this option is chosen, the government will generally prepare an output specification, consult widely with the market ahead of the bid, make an allocation of project risks and proceed with a competitive bidding process. This is the practice adopted with many concessions and BOT contracts and it relies on a competitive bid market to deliver a better outcome for government than could be achieved with traditional procurement, which is widely accepted as the benchmark for measuring procurement performance. Unlike a PPP, a traditional contract based on an input specification is an adversarial contract and contractor selection employs criteria heavily weighted toward lowest cost. Policies that use competitive bid markets rely on bidder depth, transaction flow, risk transfer, and rigorous management of the bid process. Procurement method is also important and policies may require a minimum number of bidders, pre-qualification, open or closed bids, and competitive dialogue during negotiations. In some jurisdictions, a best and final offer may be requested from short-listed bidders although this may contribute to hold-up delays and rapid escalation of bid costs if not carefully managed. Experience in a number of OECD countries suggests that VFM outcomes are determined by the efficiency with which government manages the competitive bid process, an appropriate risk allocation strategy, and post-selection negotiations to

3 AUSTRALIAN CASE STUDY

3.1 Partnerships Victoria, State Government of Victoria, Australia

The PPP program of the State of Victoria was implemented in 2001 and is managed by Partnerships Victoria, a unit of the Commercial Division, Department of Treasury and Finance. All PPP projects in Victoria are implemented under the Partnerships Victoria policy that operates under the uniform national PPP policy implemented by the Australian Government in 2008. While national policy applies throughout the country, states and territories may modify the national guidelines to achieve a better interface with local institutions, practices and market conditions.

Victoria has a long tradition of outsourcing, concessions and BOT contracts although major projects initiated prior to 2001 are not technically PPP projects, they meet the general policy principles contained in Partnerships Victoria policy. The policy is contained in a comprehensive set of guidance materials without an enabling legislative framework. Victoria has commissioned 22 PPP projects and has two additional projects in the bidding stage. The project list spans a large number of different applications including corrective services, bioscience and medical research facilities, hospitals, waste water reclamation and processing services, court buildings, a convention centre, a rail and road transport interchange complex, toll roads, schools, desalination plants, telecommunications and data services. The Partnerships Victoria project list may be viewed at Partnerships Victoria web site (www.partnerships.vic.gov.au).

Projects that conform to Partnerships Victoria Policy are referred to as PPPs and projects delivered before the commencement of Partnerships Victoria or which involve alternative implementation procedures are described as BOT contracts, franchises or concessions. Victoria has undertaken a large number of non-conforming projects in the past 20 years including the franchising of operations and management for the Melbourne metropolitan public transport system and the construction and operation of the extensive Citylink toll road network. BOT projects are also undertaken by statutory authorities and institutions but no PPPs have been commissioned by local government.

3.2 Institutional Framework

The effectiveness of a government’s PPP policy and delivery schedule is influenced by the effectiveness of its institutions, both formal and informal. International indicators (The World Economic Forum 2013; Transparency International 2010; World Bank 2011) provide comparable data about the efficacy of institutions for most nations but not subnational governments. Victoria holds a similar credit rating to Australia and the national institutional survey data serves as an appropriate proxy for Victoria’s institutions.

3.3 Policy Framework

Partnerships Victoria is a policy-based framework that operates in parallel with conventional government procurement policy. The policy is issued by the Commercial Division of the Department of Treasury and Finance which operates a specialist PPP unit to assist line agencies with project selection, evaluation and implementation. Comprehensive guidance has been issued for the program and periodic updating takes place to meet changes in the operating environment and document the lessons learnt from both policy and project implementation over time. As a subnational government, Victoria’s PPP policy applies only within the state of Victoria although Partnerships Victoria policy has been adopted in other states and territories and serves as a best practice benchmark in many countries.

The foundations of Partnerships Victoria policy are the following guidelines:

- 2001 Policy Overview
- 2001 Practitioners Guide
The PPP framework for Partnerships Victoria involves a number of well-defined steps in the procurement process. The procurement evaluation process is initiated by the line agency responsible for service delivery and involves identification of the service need, an appraisal of procurement options, and the construction of a PSC. The project implementation stage refers to the bidding and contractor selection process, negotiation of the contract and contract close.

3.4 Value for Money (VFM)

Prior to the introduction of the national PPP policy in 2008, Partnerships Victoria required line agencies to approve PPP projects through a “gateway” system of eight well defined steps (Table 1). National PPP policy recognises the need for policy to be adapted for local conditions. In Victoria, the PSC is developed for a reference project that is constructed from the initial scoping exercise, the benefit cost analysis, the business case and procurement options analysis. It is finalised during the project development stage and before the distribution of expression of interest documentation to the bid market. When formal bids are received at the end of the request for proposal process, a comparison is made with the PSC and an assessment made of the qualitative attributes of each bid. Bidders are asked to submit bids that meet the output specification, scope and risk allocation nominated in the RFP. In reality, bids may not fully comply with the reference project: some may refuse to accept the risks nominated and others may offer alternatives ways to meet the service requirement. The assessment of VFM will need to consider these variations in bids and their impact in quantitative as well as qualitative terms. The PSC may be modified after bids are received if the agency believes that a significant component has been mispriced or omitted, and when there has been significant change in underlying assumptions between the commencement of the PSC and the receipt of formal bids (Partnerships Victoria 2013, pp. 15-16).

3.5 Value for Money Framework

Partnerships Victoria policy is based on VFM principles and employs the PSC to undertake the quantitative analysis in both the procurement and the bidder selection stages of the project. The policy provides comprehensive guidance to assist line agencies to undertake options analysis, identify and measure risk and construct a life cycle costed and risk-weighted PSC. For a PPP project to be approved, it is necessary for the line agency to establish that the PPP option represents a better VFM proposition than government delivery using a traditional model. This decision is not based solely on a quantitative comparison of a bid with the PSC but takes into account both the quantitative and qualitative dimensions of the bid. All things being equal, strong qualitative attributes may outweigh a more costly procurement option for government. The VFM assessment conducted for recent Partnerships Victoria projects is fully disclosed on the agency’s website www.dtf.vic.gov.au/Infrastructure-Delivery/Public-private-partnerships/
Table 1 - Major Stages in Developing a Partnerships Victoria Project (Gateway)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The Service Need</td>
<td>Identify the service need</td>
</tr>
<tr>
<td></td>
<td>Preliminary output specification</td>
</tr>
<tr>
<td></td>
<td>Consider wider long-term service needs</td>
</tr>
<tr>
<td>2. Option Appraisal</td>
<td>Options analysis</td>
</tr>
<tr>
<td></td>
<td>Preliminary work on risk identification, allocation and costing</td>
</tr>
<tr>
<td>3. Business Case</td>
<td>Begin construction of the PSC</td>
</tr>
<tr>
<td></td>
<td>Benefit cost analysis</td>
</tr>
<tr>
<td>4. Project Development</td>
<td>Form the in-house project delivery team</td>
</tr>
<tr>
<td></td>
<td>Continue work on the PSC</td>
</tr>
<tr>
<td></td>
<td>Develop commercial principles</td>
</tr>
<tr>
<td></td>
<td>Market consultation</td>
</tr>
<tr>
<td>5. Bidding Process</td>
<td>Conduct an expression of interest (EOI)</td>
</tr>
<tr>
<td></td>
<td>Evaluate responses, develop short-list</td>
</tr>
<tr>
<td></td>
<td>Design project brief and contract</td>
</tr>
<tr>
<td></td>
<td>Conduct request for tender (RfT)</td>
</tr>
<tr>
<td>6. Project Finalisation</td>
<td>Confirm VFM</td>
</tr>
<tr>
<td></td>
<td>Final approval to proceed</td>
</tr>
<tr>
<td>7. Contract Close</td>
<td>Negotiate contract with preferred bidder</td>
</tr>
<tr>
<td>8. Contract Management</td>
<td>Prepare brief and finalise monitoring arrangements</td>
</tr>
</tbody>
</table>

Source: Partnerships Victoria 2012, Practitioners’ Guidance, p.14

3.6 Projects Delivered

Few international PPP programs have delivered PPPs in as many industry applications as Partnerships Victoria which has delivered 22 PPP projects with a capital value of AUD11.5 billion since 2001 with a further AUD1.1 billion presently under tender (see Table 2). The industry sectors include:

1. Toll roads and non-tolled motorways (2)
2. Biosciences research facilities
3. Water reclamation works (2)
4. Hospitals (4)
5. Medical research facilities
6. Corrective services (3)
7. Waste water and bio-solids management (2)
8. Railway station and multi-modal transport node
9. Public facilities (showgrounds)
10. Convention centre
11. Schools
12. Judicial facilities
13. Desalination project
14. Emergency and security telecommunications and data storage (3).

Case studies for these projects and details about the PSC and VFM assessment are available at Partnership Victoria:

PPP contracts accounted for around 10% of Victoria’s capital spending between 2001 and 2013. The majority of Partnerships Victoria projects are delivered within 24 months of commencement, which reduces transaction costs and has assisted the development of a competitive bid market.
3.7 Role of Agencies

Partnerships Victoria policy is managed by the Commercial Division, Department of Treasury and Finance which operates as a PPP unit providing technical and other assistance to line agencies for project evaluation and delivery. The Department also applies considerable resources to the training of contract managers, conducting market briefings, preparing data and completion reports for commissioned projects, and assisting line agencies to build their own in-house capacity to deliver PPP projects under the Department’s oversight. Only one of the projects listed (Ararat Prison) has had construction problems.

Table 2 - Partnerships Victoria Projects 2001 - 2013

<table>
<thead>
<tr>
<th>Project</th>
<th>Sector</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biosciences Research Centre</td>
<td>Agriculture Research</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Ballarat North Water</td>
<td>Water Recycling</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Ararat Prison</td>
<td>Corrective Services</td>
<td>Operational and Continuing, Works Contractor Replaced.</td>
</tr>
<tr>
<td>Barwon Water Bio-solids</td>
<td>Water Recycling</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Peninsula Link</td>
<td>Motorway</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Campaspe Water Reclamation</td>
<td>Water Recycling</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Casey Community Hospital</td>
<td>Health Services</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Country Court of Victoria</td>
<td>Judicial Services</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Desalination Project</td>
<td>Water Supply</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Eastlink</td>
<td>39km Toll Road</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Emergency Alerting System</td>
<td>Communications</td>
<td>Contract Completed</td>
</tr>
<tr>
<td>Melbourne Convention Centre</td>
<td>Conventions</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>MM Radio Network</td>
<td>Communications</td>
<td>Contract Completed</td>
</tr>
<tr>
<td>Mobile Data Network</td>
<td>Communications</td>
<td>Contract Completed</td>
</tr>
<tr>
<td>Schools Project</td>
<td>Education Services</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Royal Melbourne Showgrounds</td>
<td>Public Amenities</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Southern Cross Station Complex</td>
<td>Transport Interchange</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>New Royal Children’s Hospital</td>
<td>Health Services</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Royal Women’s Hospital Project</td>
<td>Water Recycling</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Victorian Correctional Facilities</td>
<td>Corrective Services</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>VCCC Victorian Cancer Centre</td>
<td>Health Services</td>
<td>Under Construction</td>
</tr>
<tr>
<td>Wodonga Wastewater Project</td>
<td>Water Recycling</td>
<td>Operational and Continuing</td>
</tr>
<tr>
<td>Bendigo Hospital</td>
<td>Health Services</td>
<td>Under Construction</td>
</tr>
<tr>
<td>Ravenhall Prison Project</td>
<td>Corrective Services</td>
<td>Operational and Continuing</td>
</tr>
</tbody>
</table>

Source: Partnerships Victoria 2013

4 CONCLUSION

There is a divergence in PPP policies between advanced countries and those at other levels of development. Advanced economies typically employ VFM principles in their policies both as an objective and as an assessment requirement, and explicitly include risk transfer, a PSC/quantitative measurement, or an output specification in their procurement decision-making. However, VFM can be achieved with a rigorous and well governed PPP process, a two-stage (pre-qualification and tender) bid process, competitive bidding and bid selection criteria that takes into account qualitative and quantitative factors. The evidence suggests explicit recognition of VFM as a PPP procurement objective and the adoption of
an output specification, risk allocation practices, and quantitative benchmarking will enable PPP policies to better harness the benefits offered by the PPP procurement method.

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COMPARING PERFORMANCE OF CONSTRUCTION PROJECTS DELIVERED THROUGH DIFFERENT DELIVERY METHODS

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Abstract: When new delivery methods are introduced in public procurement, it is customary to analyze and compare their performance against traditional methods. Many early studies compared performance of different project delivery systems, and often developed decision support tools to help owners follow a structured path in measuring performance and, consequently, choose the most appropriate project delivery method. However, the measurement process adopted by these studies was mostly specific to the dataset to be analyzed. Only rarely, it took into account differences deriving from varying project characteristics, and, therefore was not generalizable. Building upon these studies, this study proposes a general framework for comparing performance of projects delivered through different delivery methods. A discussion of how the framework could also be adapted to every industry sector is included. This work can help owners choose a set of metrics to evaluate and compare the performance of project portfolios delivered with more than one delivery method and different industry sector.

Keywords: project delivery methods, construction project success evaluation, project performance metrics

1 INTRODUCTION

When in 1996 the U.S. Congress passed the “Clinger Cohen Act” authorizing public agencies to use the Design-Build (DB) project delivery method, the uncontested predominance of the traditional Design-Bid-Build (DBB) method was brought into question. Encouraged by results obtained on projects delivered through DB, a growing number of states passed legislation to allow other delivery methods including Construction Management at Risk (CMR), Design Build Operate (DBO), and Public-Private-Partnership (PPP). Early on, analyzing and comparing the performance of newly introduced delivery systems was required to allow public owners to assess and often justify their choice. Therefore, many early studies compared performance of different project delivery systems, and often developed decision support tools to help owners follow a structured path in measuring performance and consequently, choose the most appropriate project delivery method. However, the measurement process adopted by these early studies was mostly specific to the dataset to be analyzed, only rarely took into account differences deriving from varying project characteristics and size, and, therefore was not generalizable (Heisse et. Al. 2011).

Over the years, as the success of project management has become inextricably linked with cost, time and quality performance (Atkinson 1999), a number of relative, static and dynamic performance measurement metrics have been developed (Gransberg et al. 2003). Relative metrics are those independent from the size of the project, allowing for comparison among projects that consistently differ for size. Examples are time and cost growth metrics. Static metrics depend on project size, allowing comparison for those
projects that have roughly the same size only. Examples are cost per square foot of constructed area or charge days per lane-mile of highways. Dynamic metrics vary according to both time and size; construction placement expressed in dollar is an example. However, despite the increasing availability of various types of metrics to compare and analyze performance of delivery systems, a general understanding of the metrics that may be applicable to compare project portfolios delivered using different methods in various industries is still missing. As an attempt to overcome this gap and enhance the understanding on how to perform internal benchmarking for delivering diverse project portfolios, we propose a framework developed through a critical analysis of previous studies.

Following a meta-analytical approach, we combined results from previous studies to identify patterns and sources of disagreement among results, or other interesting relationships that may help us formulate a general framework for evaluating the performance of a diverse project portfolio. A small set of projects was also used to narrate the application of the framework. The framework is presented as follows. Firstly, we analyze previous studies. Secondly, we propose the methodology and develop our framework. Then, we give an interpretation of results. Finally, we draw conclusions with future research directions.

2 LITERATURE REVIEW

As previously highlighted, this paper relies significantly on the studies of the main authors who analyzed project performance according to the delivery method adopted.

Konchar and Sanvido (1998) were the first authors to introduce a model of performance comparison among DBB, DB and CMR delivery methods in terms of cost, schedule and quality performance. A sample consisting of 351 building projects in the U.S. was used in their analysis. The model consisted of two t-tests to verify if the difference in means among the delivery systems was significant, as well as a Mood's median test for sample medians (95% confidence interval). Two multivariate regression analyses were performed, aimed to develop three models explaining the variability of unit cost, construction speed, and delivery speed, and the second for cost growth and schedule growth. This first empirical study on the performance of project delivery methods strongly concluded that DB provided cost and schedule advantages over DBB and CMR without sacrificing quality. Allen (2001) performed a study on 110 MILCON projects of the Southwest Division, Naval Facilities Engineering Command (SWDIV), from fiscal year 1996 to 2000 to compare performance of DBB and DB projects. Performance of DBB and DB projects were classified and compared in subcategories as vertical and horizontal projects, homogeneous projects and Bachelor Enlisted Quarters (BEQs) projects. Again, this study found DB to outperform DBB in terms of cost and schedule, but quality performance of the two delivery methods varied depending on the quality target being measured. Gransberg et al. (2003) analyzed 88 federal building projects that were developed under DB and DBB delivery methods. The aim of their work was to establish a framework for making programmatic decisions about the expected results delivered by the two project delivery methods exploiting performance metrics. Project performance was compared using cost growth, time growth, completed unit costs, design placement, construction placement, DB placement. They found that DB projects were completed with much lower cost and time growth than DBB projects.

Ibbs et al. (2003) structured a model for performance comparison among DBB, DB and other available project delivery methods. A number of 67 projects from the Construction Industry Institute (CII)’s database were taken into account; and change cost, change schedule and productivity were the performance metric used in their study. This study confirmed previous studies when concluded that DB delivery results in time savings, but could not conclude that a method was better than the other in term of cost performance. Instead, the authors suggested that project management expertise and experience of the contractor impacted project performance more than project delivery strategy. Kuprenas et al. (2007) presented a comparison study of public sector municipal facilities projects delivered using DBB and In-House construction delivery method. Cost comparison was possible through 18 public sector municipal facilities projects completed for the Bureau of Engineering over two years. Project size, construction cost, change order value, design cost, construction management cost, total project cost, percentage breakdown by phase, and cost per square meter/square foot were the performance metrics utilized in this study. Results identified several benefits of the in-house delivery route over DBB, but also recognized that this approach was employed on smaller size projects.
In recent years, Hyun et al. (2008) set up a model for evaluating the level of design performance of DB and DBB multifamily housing projects begun in 2000, conducting a quantitative analysis on quality performance. Construction drawings and specifications of public multifamily housing projects were taken into account. Similarly to Allen (2001), Hale et al (2009) analyzed MILCON projects, but limited their analysis to BEQs projects. Thomas et al. (2009) used data from 617 projects from the CII, Benchmarking and Metrics (BM&M) database to compare performance of the DB and DBB delivery methods. This study relied on a set of performance metrics to evaluate performance in terms of cost, schedule, safety, changes, and rework. It also relied on a set of practice use metrics, including pre-project planning, constructability, project change management, design/information technology, team building, zero accident techniques, material management, planning for startup, quality management. Moreover, projects were compared by delivery system, sector, industry group, cost category and project nature, for both owners and contractors. Data were used to determine the relationship between practice use and performance. Practices that provided the greatest performance benefit for both owners and contractors of DB and DBB projects were identified. Moreover, Thomas et al. (2009) also analyzed the effects of fast tracking (i.e. difference between the actual construction phase start date and the actual detail design phase finish date) and schedule adherence (i.e. ahead/on time/behind) on safety performance for both owners and contractors of DB and DBB projects.

Shrestha et. al. (2007) performed an input-versus-output benchmarking approach to assess the performance of large DB highway projects, and found clear trends between project cost and schedule performance and 15 input factors, including location, pavement type, and nature of construction among others. Later, Shrestha et.al. (2012) compared and analyzed the relationship between DB and DBB project delivery methods and performance metrics of highway projects costing more than $50 million using a dataset of 130 projects, with the goal of developing a generic approach to compare performance of large highway construction projects. After normalizing the project for their size using per lane mile metrics, they found that DB projects were constructed and delivered significantly faster than DBB projects. Bogus et al. (2010) collected data from 100 water and wastewater projects with a total price of at least $3 Million to show the influence that project delivery method and contract payment provisions have on schedule and cost performance. As performance metrics, the authors utilized overall schedule growth, construction schedule growth, design and construction cost growth, and intensity. Three different statistical tests were performed during this study: a t-test to verify that the difference between the two population means exists, a Pearson goodness-of-fit to test for the difference between the two population medians, and a z-distribution test for the difference between two population proportions. The authors found that schedule or cost growth was more likely to appear when lump-sum contracts were used than when cost-plus-fee with a guaranteed maximum price (GMP) contract pricing provisions were used. Shane et al. (2013) collected data on 31 DB projects and 69 DBB projects through a survey from municipal water/wastewater facility owners. The aim was to compare performance of DBB over DB delivery method on cost (i.e. growth, unit, total) and schedule (i.e. growth, duration, construction speed, delivery speed). Finally a hypothesis testing to check for a difference between two population means was performed by treating the variable rating as a quantitative variable. These analyses led to quantify that schedule growth under DB was about fifty percent that under DBB. Similarly, DB led to better performance in terms of cost growth. Still, quality of projects delivered through the two delivery methods was comparable.

3 RESEARCH METHODOLOGY

3.1 Metric collection

The main objective of this research is to provide construction project owners and stakeholders with an unbiased and structured overview of the tools available for evaluating performance of project portfolios executed via different delivery methods and in different industry sectors. Starting from the broad concepts of project delivery and project performance, an articulated research was performed to identify previous studies that had compared the performance of project delivery methods or compared project performance in relation to the delivery method.
A thorough literature search process was carried out. This initially relied on the “snowballing” technique, but later moved toward a more systematic approach. In the first stage, the authors initially analyzed a sample of about 60 papers. Then, a more structured process was established that exploited standard searches in various research databases, including “Google Scholar”, “Engineering Village” and “JSTOR.” These searches relied on keyword strings, such as “project delivery method comparison”, “project delivery method performance comparison”, “project delivery method construction” and “project delivery method using performance metrics”. This search allowed analyzing work by the most influential authors, which led to identify a subset of 21 papers, named the project delivery method (PDM) sample that was further analyzed to retrieve the metrics that the authors utilized in their work. This subset included papers from authors who had analyzed the project performance in relation to the project delivery method. The set of metrics extracted from this subset was named PDM metrics sample. Table 1 provides examples of how the information was collected and organized.

Table 1: PDM metric collection format

<table>
<thead>
<tr>
<th>ID-#</th>
<th>Full Reference</th>
<th>Metric</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDM-3</td>
<td>Allen, L. N. (2001). “Comparison of Design-Build to Design-Bid-Build as a Project Delivery Method.” Master’s Thesis, Monterey, CA</td>
<td>Award Schedule Growth, Cost Growth, Schedule Growth, Construction cost growth, Design Construction placement, Unit Cost, Start up, Call backs, Operation and maintenance, Envelope, roof, structure and foundation system, interior space and layout, environmental system, equipment</td>
<td>Buildings, Infrastructure</td>
</tr>
</tbody>
</table>

An ID number was assigned to all 21 papers taken into account; the full reference of the work with author, year and related source was listed together with the metrics utilized in their studies. An additional field was dedicated to the industry sector of the project samples. Table 2 highlights how the industry sector division was performed.
Table 2: Industry sector division

<table>
<thead>
<tr>
<th>Sector</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. RESIDENTIAL BUILDINGS</td>
<td>Individual Homes, Small Condominiums, Small Apartment Complexes</td>
</tr>
<tr>
<td>B. OTHER BUILDINGS</td>
<td>Offices, Hospitals, MILCON Projects, Schools, Large Apartment Complexes, Barracks, Light Industrial</td>
</tr>
<tr>
<td>C. INFRASTRUCTURE</td>
<td>Highways, Highways Paving, Bridges, Water/Wastewater</td>
</tr>
<tr>
<td>D. HEAVY INDUSTRIAL</td>
<td>Steel Mills, Automobile Production Facilities, Chemical Processing Plants</td>
</tr>
</tbody>
</table>

While reviewing the 21 papers to extract the relative metrics, we underwent a classification into either measurable (i.e. metrics or variables) or abstract in nature (i.e. constructs) factors. Any factors that could not be measured because they were abstractions intended to conceptualize latent variables were excluded from the metric sample because they were not suited for this work. Following this approach, factors, such as administrative burden, conformity to expectations, operation and maintenance, system quality and satisfaction (Owner/Overall) were deleted from the metric list because they were intended as constructs. At the end of this operation, the PDM database consisted of 43 metrics.

3.2 Metric Validation

Since the PDM metrics sample relied on only 21 papers (i.e., PDM sample), we underwent a validation task to verify if any additional relevant metrics adopted in the construction industry to assess project performance were missing. A structured research was carried on the SCOPUS database with the following key-words: “Project Success” AND “Construction” AND “Cost”, “Project Success” AND “Construction” AND “Price”, “Project Success” AND “Construction” AND “Time”, “Project Success” AND “Construction” AND “Schedule”, “Project Success” AND “Construction” AND “Safety”, “Project Success” AND “Construction” AND “Quality.” Since construction literature on these topics mostly builds upon previous work, only the last three years were taken into account (i.e. 2012, 2013, 2014). This search resulted in the identification of about 80 papers that were analyzed to extract the metrics used by the authors in their project performance evaluation.

The validation process is based on the concept that the metrics found in our PDM sample are representative of the vast majority of the “metric population” in the construction industry. The objective of the database consultation was to highlight the fact that the PDM metric database is sufficiently reliable and no important metrics were excluded. A set of 28 factors was identified, of which, four (i.e. formality, phase schedule factor-design, profitability, and integration) were not present in the PDM databases, but with a frequency lower than 6%, and 6 that were considered constructs, so they were not included in this study.

After the filtering, the frequency of each of the 22 remaining metrics was computed in relation to the total occurrence in each paper (59), in relation to the number of papers containing the specific metric (15) and over the total number of metric appearance (71).

Once PDM metrics were separated from constructs and validated through the triangulation with the SCOPUS database, Table 3 below, was created with the relative metrics, occurrence of the latter with respect to all the papers in the sample and the relative frequency in relation to the total occurrence in each paper (21) and in relation to the number of papers containing the specific metric. An additional computation was made to obtain the frequency of appearance of each single metric, among all 21 papers, in the specific industry sector.
Table 3: PDM metric sample classification and industry sector occurrence

<table>
<thead>
<tr>
<th>Metric</th>
<th>Frequency (Paper)</th>
<th>Frequency (Metric)</th>
<th>Industry Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Growth</td>
<td>95%</td>
<td>16%</td>
<td>A</td>
</tr>
<tr>
<td>Unit cost</td>
<td>38%</td>
<td>6%</td>
<td>B</td>
</tr>
<tr>
<td>Phase Cost Growth-Design</td>
<td>10%</td>
<td>2%</td>
<td>C</td>
</tr>
<tr>
<td>Phase Cost Growth-Construction</td>
<td>19%</td>
<td>3%</td>
<td>D</td>
</tr>
</tbody>
</table>

4 RESULT INTERPRETATION

Figure 1 shows the frequency distribution of PDM metrics. The mean value of the frequencies equals 2%; in particular, it can be observed that 21% of the metrics distribution is above the mean value, as follows: (a) Cost Growth (16%); (b) Schedule Growth (14%); (c) Unit Cost (6%); (d) Call Backs, Delivery speed, Intensity and Start-up costs (4%); (e) Change Order Cost, Phase Cost Growth-Construction (3%).

Figure 1: PDM metric frequency

Four main industry sectors have been identified though the analysis of the PDM metrics sample, as shown in Table 2. Figure 2 presents the Industry sectors distribution for each single PDM metric.

In particular, it can be observed how the maximum percentage value of the Residential building factor (25%) is at rework costs metric where the remaining factors cover the same percentages; the lower values of the same factor are recorded at schedule growth and cost growth metrics (9%). Nearly 79% of the total PDM metrics do not involve the residential building sector.

Some PDM metrics are representative for the building sector only; in particular, it has been observed how Phase Cost Factor-Design, Cost per Bed, Cost performance index, Fiscal year duration, Project duration per bed, LEED certification characterize only this industry factor. The lower values are recorded at Rework costs, Phase Cost Growth-Award, Change Cost Factor, Phase Schedule Growth-Construction, Phase Cost Growth-Design (9%). Nearly 7% of the total PDM metrics do not involve the building sector.
Some PDM metrics are representative for the infrastructure sector only; in particular, it can be observed how Phase Cost Growth-Design, Cost per lane, Phase Schedule Growth-Design are specific to this sector. The lower value is at unit cost (14%). Nearly 42% of the total PDM metrics do not involve the infrastructure sector.

As far as the Heavy Industrial sector is concerned, the maximum percent value (50%) is for the Phase Cost Growth-Startup, Phase Cost Factor-Startup, Phase Cost Factor-Rework, Change Schedule Factor, Phase Schedule Growth-Startup, Phase Schedule Factor-Rework, Phase schedule factor-Construction, Phase schedule factor-Startup, Recordable Incident Rate (RIR), Lost Workday Case Incident Rate (LWCIR). The lower value of this sector is at unit cost (14%). Nearly 14% of the total PDM metrics don’t involve heavy industrial sector.

When comparing the PDM metrics, filtered from the constructs, with the SCOPUS database, just 21 PDM overlapping metrics, appearing in both samples, have been studied over a total of 43 PDM metrics.

![Graph showing industry sector distribution by metric](image)

**Figure 2. Industry Sector Distribution by metric**

Figure 3 shows the frequency distribution of the overlapped metrics. It can be observed how the maximum and the minimum values in the two different datasets are found at the same metrics.
5 CONCLUSIONS AND FUTURE PERSPECTIVES

Recent advances in contracting approaches, delivery methods and technology have been making the construction industry more complex. Inefficient and biased evaluations about the project performance deriving from the involving technology, blurring geographical borders, green products or high quality
requirement, and vague identification of roles may lead to worsening management of construction projects. Apparently, owners tend to evaluate performance through personal preferences or previous experience rather than exploiting a systematic approach; these biases could result in misevaluation, subjective measurements or ultimate failure in generating the right motivations for the involved parties.

Based on a thorough research on previously used metrics, this paper is proposed as a support for selecting the appropriate metrics that optimize evaluations and help owners efficiently make better and more objective decisions. This work is intended to provide owners of construction projects with: (1) an objective and exhaustive overview on the metrics adopted by the most influential authors in the field; and (2) a structured selection approach for choosing the most suited set of metrics for the evaluation of their projects and project portfolios.

A set of definitions is proposed for all the identified metrics, which highlights what they measure and how they properly work as an instruction booklet. With this aided selection tool, the choice of the right metrics set requires only few simple steps. After the definition of the industry sectors involved in the project portfolio, a list of metrics, previously validated through the SCOPUS database, will be identified. The result is a subset of metrics, taken from the PDM database, that have been successfully exploited in the analysis of projects involving the same industry sectors.

As a practical example presented in Figure 5, a hypothetical project owner could aim to compare the effectiveness and efficiency of a project portfolio, ranging from residential buildings, infrastructure, to heavy industrial. Using the results of our work, this owner could timely access to the list, and develop his own subset of metrics, which includes nine available metrics to choose from. This guide not only saves time for owners, but also produces a more objective outcome for projects in cross-sector evaluations.

![Structured metric selection approach](image)

Figure 5: Structured metric selection approach

In this study, the small dimension of the PDM metric sample could be source of reduced results accuracy. Whereas the cross-validation against the SCOPUS database was designed to reduce this issue, it may be the risk that the literature on this topic may not be mature enough to encompass all possible metrics to evaluate project performance. These suggestions can be the basis for new studies in the project evaluation and delivery system field. Trying to consider in the analysis each project delivery method analyzed by the authors could lead to more accuracy.

**References**


Abstract: Retrofitting existing buildings has received significant attention due to the potential opportunities that it can offer for energy saving. This, in turn, has increased the demand for building a better workforce for advanced energy retrofit industry to successfully support planning, designing, and implementing energy improvement projects. Recently, the National Renewable Energy Laboratory, in conjunction with the National Institute of Building Sciences (NIBS) and the U.S. Department of Energy convened a study to identify the critical duties and tasks required for four of the advanced commercial energy job titles including Building Operations Professional, Energy Auditor, Building Commissioning Professional, and Energy Manager. In the present study, a competency model is developed for these four job titles, based on the job task analyses and best practices. In addition, focus groups and individual interviews were conducted to supplement and corroborate the findings. The goal of the competency model is to help articulate and classify the competencies required for engagement and advancement of talented individuals needed to complete energy retrofit projects. The model will also help to match job requirements with industry-recognized skills and reveal gaps in competencies in the industry to enhance the expansion of the energy retrofit market. It will also support the growth of the energy retrofit workforce by guiding the development of new education and training programs or modifying the existing programs to address the missing parts. The methodology followed through this research also informs future efforts to identify key competencies and associated work products in new and emerging fields in the building industry.

Keywords: Energy retrofits, commercial buildings, competency model, workforce demands

1 INTRODUCTION

Energy efficiency has a key role in achieving our nation’s goal of improving the use of resources. According to the preliminary results from the 2012 Commercial Building Energy Consumption Survey (CBECS), the United States has more than 5.6 million commercial buildings with approximately 87.4 billion square feet of floor space, representing a 14% increase in the number of buildings since 2003 (US Energy Information Administration 2014). This increase will greatly impact the energy consumption and expenditures. A 2011 survey conducted by Institute for Building Efficiency indicated a high interest in energy efficiency projects among building owners. This, in turn, is increasing the demand for building a
better workforce with advanced competencies in operations, maintenance, and energy-related technologies of buildings (Institute for Building Efficiency 2012).

To meet the needs of a high-growth sector such as the advanced commercial building workforce, business/industry leaders, educators, trainers, career counsellors, and job seekers must understand what competencies are necessary for workplace success. An industry competency model can serve as a resource to help articulate the workforce needs. Competency models also establish the basis on which instructional designer and curriculum developers ensure that workers are developing the right skills. Furthermore, an industry competency model can communicate the crucial competencies required for occupational licenses and certifications (Personnel Decisions Research Institutes, Inc. and JBS International, Inc., Aguirre Division 2012). Distinctive from the common articulation of knowledge, skills and traits associated with positions, competencies are typically aligned with the ability to create results.

In the early 1970s, McClelland indentified competencies as significant predictors of employee performance and employee success. A competency is an assortment of knowledge, skills, abilities (commonly called KSAs), behaviors, and personal characteristics, that encompasses mental, intellectual, cognitive, social, emotional, attitudinal, and physical aspects necessary for success in a given role, job, or position (Boyatzis 1982, McClelland 1976). McClelland regarded competency models as an assessment tool that can help to develop behaviorally-based interview protocols; clarify hiring requirements in terms of finding the right fit; equip the staff with complete information regarding succession into specific positions, inform employers about the necessary development strategies; and finally educate potential job seekers to be employable. Competency models are also regarded as an asset for human resources to assist employees, both at entry points into a position and moving up or over to other positions, in order to benefit the organization (Boyatzis 1982, McClelland 1994).

A competency model is a descriptive tool often represented through illustrations that map competencies in a hierarchical manner, which identifies the competencies needed to operate in a specific role within a(n) job, occupation, organization, or industry. Competency models can take a variety of forms (Campion, et al. 2011. Cao and Thomas 2013). Typically, they include the following elements:

- Competency names and detailed definitions;
- Descriptions of activities or behaviour associated with each competency; and/or
- A diagram of the model.

Thus, a competency model can benefit both supply and demand sides of employment. Learners, students, incumbent workers, or employment candidates applying for a position can all take advantage of it. Competency models are also equally useful for individuals seeking employment, advancing in their jobs, or transitioning between careers. Furthermore, educators, trainers, and human resource professionals can utilize the competency model to develop initiatives and programs that meet the needs of employees (Campion et al. 2011, Ennis, 2008). The Department of Labor’s Employment and Training Administration (DOLETA) provides job training and assistance with finding jobs and careers in government, and has started putting more emphasis on competency models as a means to build a better workforce (Ennis 2008).

2 DEVELOPING ADVANCED COMMERCIAL BUILDINGS WORKFORCE COMPETENCY MODEL

It is recognized by the Consortium for Building Energy Innovation (CBEI) and the DOE Office of Energy Efficiency and Renewable Energy (EERE) that there is a need to develop a support system to build a better workforce. Currently, there is an extraordinary amount of technical standards, training, and credentials related to the commercial building workforce. To help support these efforts, the CBEI began working on the competency model for the energy industry in 2012. The competency model was updated in 2014 to include updated job task analysis (JTA) information and align with the Better Buildings Workforce Guidelines.
2.1 Job Task Analysis

The JTA project was under the DOE Office of EERE by the National Renewable Energy Laboratory (NREL). Four job titles were selected as part of the Better Buildings Workforce Guidelines initiative and were the basis of the Advanced Commercial Buildings Workforce (ACBW) competency model. JTA is a procedure for analyzing the tasks performed by individuals in an occupation, as well as the knowledge, skills, and abilities required to perform those tasks. Specifically, a JTA can be defined as "any systematic procedure for collecting and analyzing job-related information to meet a particular purpose" (Raymond 2001). JTAs can be used to describe, classify, and evaluate jobs, ensure compliance with legal and quasi-legal requirements, develop training, promote worker mobility, plan workforces, increase efficiency and safety, and appraise performance (Brannick et al. 2007). The JTAs identified and cataloged all of the activities a worker performs for a given job, and determined the essential knowledge, skills, and abilities which define the minimum requirements necessary for an individual to adequately perform their job. The four job titles the JTAs were completed on include:

1. Building Operations Professional
2. Energy Auditor
3. Building Commissioning Professional
4. Energy Manager

2.2 Competency Model Framework

After analyzing JTAs and the background information, the building blocks model was utilized to depict the key competencies needed for the ACBW. The building block model is a visual representation of the competencies for an entire industry (Figure 1). Levels in the model correlate with the likely arenas in which competencies are cultivated from personal traits developed through life experiences to those learned in training, and onward and upward through increasingly focused work experiences. The model can be used to understand the competencies required to work in an industry and how they to match job requirements with industry recognized skills. The model can also illuminate gaps in competencies in the industries where short-term training programs can be developed to address them or where existing programs can be modified (Ennis 2008).

- **Occupation Related**
  - Management Competencies
  - Occupation-Specific Requirements
  - Occupation-Specific Technical Competencies
  - Occupation-Specific Knowledge Competencies

- **Industry Related**
  - Industry-Specific Technical Competencies
  - Industry-Wide Technical Competencies

- **Foundational Competencies**
  - Workplace Competencies
  - Academic Competencies
  - Personal Effectiveness

![Figure 1: The Competency Model framework](image-url)
The DOLETA Competency Model Clearinghouse describes the generic framework used for this study. Figure 1 represents the competencies that exist on three tiers. The first tier has a broader application to many industries or occupations and includes: workplace competencies, academic competencies, and personal effectiveness. The next tier is more specific to an industry and an occupation. These competencies are industry-related and include: industry-specific technical competencies and industry-wide technical competencies. The top tier is occupation-specific (Ennis, 2008).

2.2.1 Competency Modeling Process

The objective for creating a competency model for the ACBW is to provide resources that can keep pace with the changes in the industry and maintain a robust and diverse future talent pipeline. The following process describes how researchers in collaboration with the DOE and industry leaders used existing resources, collected and analyzed data to develop the framework of competencies. Figure 2 illustrates the steps that were followed to develop the ACBW competency model.

![Figure 2: Competency Modeling Process](image)

At first, general knowledge, duties, tasks, specialized knowledge, skills and abilities from JTA data were added to the competency database. Then, the database was reviewed to determine the tasks, duties, skills and knowledge that are consistent across all JTA's and to identify ones that are specific only to certain occupations. In addition, the critical competencies were highlighted. In the next step, we grouped the skills, abilities, and specialized knowledge into competencies associated with the tiers of the building blocks competency model. The model provides guidance but does not contain a strict definition of each competency level. Therefore, our team used their subject matter expertise when classifying the data into the competency groupings. A second review of the category groupings was performed after all of the JTA data has been analyzed. The intention is to determine if additional refinement was needed, such as further grouping of categories, if they were too similar or there were too many categories. Using this research process, the competency model was developed and aligned with the building blocks model.

The analysis identified the knowledge and skills that are common across the four jobs and highlighted those that are unique to each position. The researchers utilized the structure of the building blocks model as a basis for categorizing the knowledge and skills identified in the JTA. The knowledge and skills were categorized into competencies at the high level of the building blocks category (Industry Wide) and at the mid-level of the created competency categories (Fundamentals of Energy & Power, Measurement, Verification & Reporting, etc.). At the Occupation Specific Level, the competencies were grouped and categorized based on the knowledge and skills that were unique to each position. During the second refinement, the occupation-specific knowledge competencies were further analyzed to determine if those knowledge and skills were truly unique to each position. Additional sub-tiers were added to those categories that had a large amount of knowledge items associated with them. After the data was categorized, it was viewed through the lens of the original critical competencies to examine if each of these critical competencies were represented in the model.

3 COMPETENCY MODEL FOR ACBW

The final result is presented as a Competency Model for ACBW as illustrated in Figure 2. The pyramid graphic that illustrates the ACBW illustrates how most tiers consist of several building blocks, each of which represents a competency cluster. The tiers of the model are divided into blocks representing the skills, knowledge, and abilities essential for successful performance in the industry or occupation represented by the model. Each competency is described by key behaviors or by examples of the critical work functions or technical content common to an industry.
3.1 Foundational Competencies

Tier 1, titled as “Personal Effectiveness Competencies” are personal attributes, or also viewed as the soft skills that are needed for all four job categories. Tier 2 and Tier 3 are titled as “Academic Competencies” and “Workplace Competencies”, respectively, and include the cognitive functions and thinking skills one would typically learn in school or on the first couple of years working in the industry. Tiers 1, 2 and 3 are the foundational competencies and are the building blocks for this workforce group and can apply to many industries and occupations.

3.2 Industry Related Competencies

Tier 4 and Tier 5 identify the specific competencies for the advanced commercial building workforce industry and are the background knowledge, skills, and abilities for the specified work group. Tier 4 represents the building and construction industry including design, construction, and maintenance of buildings. The Tier 5 technical competencies are related to the more specific energy industry. Identifying this subset allows for cross-functional opportunities and promotes an agile workforce. The top tier isolates the specific competencies unique for each job category.

3.3 Occupation-Specific Competencies

Recall that the competencies become more targeted or specific as you move up the tiers of the model. Every occupation requires a different mix of knowledge, skills, and abilities, and is performed using a variety of activities and tasks. The top tier describes the occupation-specific knowledge, skills, and technical competencies for each of the job titles including Building Operations Professional, Energy Auditor, Building Commissioning Professional, and Energy Manager. Table 1 is a sampled list of Occupation Specific Competencies for Advanced Commercial Buildings Workforce.

Figure 2: Advanced Commercial Buildings Workforce Competency Model
Table 1: Sample list of Occupation Specific Competencies for Advanced Commercial Buildings Workforce

<table>
<thead>
<tr>
<th>Occupation</th>
<th>Knowledge</th>
<th>Skills</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Commissioning Professional</td>
<td>• Ability to identify specialty workers needed</td>
<td>• Ability to assess building performance</td>
</tr>
<tr>
<td></td>
<td>• Climate zone variations</td>
<td>• Ability to assess timeframes for construction and commissioning</td>
</tr>
<tr>
<td></td>
<td>• Commissioned systems knowledge</td>
<td>• Ability to conduct a needs assessment</td>
</tr>
<tr>
<td></td>
<td>• Cx budgeting</td>
<td>• Ability to determine appropriate sampling procedures</td>
</tr>
<tr>
<td></td>
<td>• Cx manpower requirements</td>
<td>• Ability to distinguish between systems, equipment, and components</td>
</tr>
<tr>
<td></td>
<td>• Cx processes and procedures</td>
<td>• Ability to interpret the TAB report</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ability to review controls graphics</td>
</tr>
<tr>
<td>Building Operations Professional</td>
<td>• Labor contract agreements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Load demand schedules</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Local weather issues</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Location of facility equipment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Locksmith skills</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Management requirements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Material availability</td>
<td></td>
</tr>
<tr>
<td>Energy Auditor</td>
<td>• Building physics</td>
<td>• Ability to determine tools needed for an audit</td>
</tr>
<tr>
<td></td>
<td>• Building pressurization</td>
<td>• Ability to interpret thermography</td>
</tr>
<tr>
<td></td>
<td>• Minimum required time period of utility data</td>
<td>• Programming skills</td>
</tr>
<tr>
<td></td>
<td>• Sampling protocols and procedures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Types of audits (level 1, 2, or 3, etc.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Typical energy analysis methodologies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Typical energy usage by building type</td>
<td></td>
</tr>
<tr>
<td>Energy Manager</td>
<td>• Energy accounting</td>
<td>• Ability to download data from different types of meters</td>
</tr>
<tr>
<td></td>
<td>• Project delivery methods (ESCO, PPA, etc.)</td>
<td>• Ability to read future markets</td>
</tr>
<tr>
<td></td>
<td>• Reliability of sources of meter data</td>
<td>• Ability to use Energy STAR portfolio manager</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Adept at reusing and reapplying existing systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Energy accounting skills</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Regression analyses</td>
</tr>
</tbody>
</table>

1Table list a sample of the competencies. To assess the entire list go to (Maureen can we add a link to the data)
4 CONCLUSION

Since the 1990s, competencies have been the key word used by human resources and talent management professionals relating to attracting, recruiting, assessing, selecting, placing, developing, training, evaluating, and rewarding employees. In addition, competency models are also being used in other areas of human resources management, such as aligning the organizational goals with the existing talents of its workers, organizing the business needs, directing strategic plans, and driving the mission of a company. However, the identification and application of the competencies required for effective job performance has become a complex and sophisticated approach. The most critical aspect of a competency model is that it must be robust, dynamic, fluid, and flexible, allowing it to change with technological advancements, economic volatilities, and uncertain conditions. Competency models are not an “end product,” but are developed as a resource for multiple uses including:

- Develop workforce planning;
- Conduct labor analysis;
- Communicate the needs of the industry;
- Guide career development;
- Establish career pathways;
- Inform curriculum and instructional developers; and
- Highlight requirements for certifications and licensure

The ACBW Competency Model aims to articulate and classify the competencies that employees must possess and use in appropriate ways on the job. However, ACBW Competency Model has many applications, such as retraining transitioning workers for new employment in the advanced commercial building sector. For example, there is a large number veterans transitioning out of the military. Many of these individuals have foundational skills and training that makes them an ideal candidate for a job in the ACBW. The ACBW Competency Model can help identify the skills and knowledge that employers are looking for. Another practical use of the model is creating a job-matching tool such as a career pathway or career map, which the research team is currently developing. The ACBW career map will be used to demonstrate what a possible career looks like in terms of sequential positions, roles, credentials, experience and education/training. A career map typically outlines common paths for moving within and across jobs in ways that facilitate growth and career advancement, which will ultimately support the development of a robust and diverse future pipeline for the advanced commercial building workforce (ACBW).

Acknowledgements

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References


Cao, J. and Thomas, D. 2013. When Developing a Career Path, What are the Key Elements to Include? ILR Collection at Digital Commons, Ithaca, NY, USA.


ASSESSMENT OF THE LEVEL OF SERVICE (LOS) OF PUBLIC RECREATIONAL CENTRE BUILDINGS: AN UNCERTAINTY BASED APPROACH

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Abstract: The federal sustainable development strategy (FSDS) for Canada advocated that public sector operations should aim at shrinking the environmental footprint while enhancing social benefits. In this quest, improving the sustainability performance of public buildings becomes a key constituent since buildings are responsible for the highest portion of the corporate GHG emission and energy usage of public entities. Moreover, public buildings are an important constituent of the socio-economic environment of a local region. Hence, there is a need for improving the sustainability performance of the future and existing public buildings. Currently, various innovative methods are used by federal, provincial and municipal entities to improve the sustainability performance of public buildings. However, asset management of building has been overlooked from the above studies. There is a lack of comprehensive methods to assess the level of service (LOS) of a building that is crucial for life cycle asset management. To address this problem, this paper proposes an approach to calculate the LOS of a recreational centre building operated by municipal government. Firstly, a LOS framework is formulated for recreational centre building by taking into consideration the key aspects. Secondly, a fuzzy synthetic evaluation method is used to assess the building performance. Thirdly, a case study was conducted to validate the proposed methodology. Results from this approach provide detailed information about the performance of the building assets. This approach facilitates in identifying areas that require immediate attention for improvement. This study provides a novel approach to life cycle asset management of public sector buildings.

1 INTRODUCTION

Public buildings represent a key component of the socio-economic environment of any nation (Wright 2006). Despite the numerous benefits to the society, dramatic environmental and social concerns are associated with construction, renovations and operation of buildings (United States Environmental Protection Agency, 2009a; Industry Canada, 2013). There are over 28000 federal buildings and a large number of municipal buildings operating in Canada, that account for 15% of the Canadian infrastructure portfolio (Mirza, 2007; Environment Canada, 2013). Presently, Canadian building infrastructure stock is aging and have deteriorated considerably (Mirza, 2007). Moreover, there is a lack of financial resources to replace, repair or rehabilitate current infrastructure stock or to construct new infrastructure facilities, highlighting the importance of a systematic asset management approach for municipal buildings (Federation of Canadian Municipalities 2003).
A majority of public sector organizations of British Columbia (BC) had signed BC climate action charter and were committed to become carbon neutral by 2012 (Government of British Columbia 2013). In the quest of becoming carbon neutral, municipal governments are compelled to implement programs and policies to reduce the carbon footprint of both corporate and community operations. Federation of Canadian Municipalities, (2011) have stated that public buildings are one of the main contributors to GHG and smog-forming emissions in Canada. Statistics shows that, buildings account for over 80% of the public sector GHG emissions (Government of British Columbia 2013). Therefore, it is important for public sector organizations to improve the environmental performance of public buildings to comply with the ongoing climate action agenda.

Previous studies revealed that significant reductions in life cycle energy consumption and CO₂ emission can be achieved from the building operations phase (Wu et al., 2011; Airaksinen & Matilainen, 2011). However, currently, municipal facilities managers are faced with an onerous task of inspecting, repairing, maintaining, renewing and replacing a diverse portfolio of infrastructure facilities owned by the municipality in the most sustainable way (Vanier and Rahman 2004). Hence, there is an alarming need to focus on life cycle asset management (LCAM) of public buildings to prolong its life cycle as well as comply with contemporary legal and policy obligations. Consequently, many organizations around the world are turning to asset management to ensure optimized utilization of the asset (Félio 2006; Halfawy 2008). Asset management is the systematic process to maintain a desired service level of an asset at the lowest life cycle cost while complying with legal obligations and standards (Asset Management BC, 2011; USEPA, 2009b).

Assessment of the current level of service (LOS) is a main underlying process in the life-cycle management of infrastructure assets (Asset Management BC 2011). Félio & Lounis, (2009) and Federation of Canadian Municipalities, (2002) stated that the LOS is an assessment of the quality of the service provided with respect to the society and economy. Determination of LOS assists decision makers in prioritizing the infrastructure assets in investment planning related to the development, operation, maintenance, rehabilitation, planning, and replacement of municipal infrastructure (Ireland et al. 2008). Factors related to LOS includes customer relations, quality, consistency of service, capacity, reliability, responsiveness, environmental acceptability, cost, and availability (Federation of Canadian Municipalities, 2002 ; Félio & Lounis, 2009; Ireland et al., 2008). Asset Management BC, (2011) recommends that asset owners should regularly track service levels provided by the infrastructure assets. However, as per author’s knowledge, asset management of buildings has largely been disregarded in North America.

Recreational buildings represent an interesting component of the infrastructure portfolio of municipal governments. A recreational centre building can be classified as desire rather than a necessity for an area. However, recreational centre buildings have become an important element for the health and wellbeing of residents. Several GHG inventory reports indicate that recreational buildings account for a significant portion of the corporate energy consumption and the GHG footprint of small and medium municipal governments (Stantec Consulting Ltd. 2011). Recreational centre buildings are comprised of more building components and systems compared to conventional buildings. Moreover, such buildings also serve as service centres for the public. Hence, recreational centre buildings require more systematic management in maintaining its level of service and to prolong its life cycle. However, asset management of recreational building have been largely overlooked in the literature. Currently, lack of adequate operational knowledge and understanding among decision-makers is a key challenge in infrastructure management (Federation of Canadian Municipalities 2003). Therefore, better resources are required for LCAM of specialised buildings such as recreational centre buildings.

The objective of this paper is to develop a comprehensive LOS index for public recreational centre buildings. This index will assess the performance of the recreational centre building by considering the facility performance and the service level. Fuzzy logic would be used to characterize the imperfect information. This index would provide an objective basis for LCAM decision making for recreational centre buildings. As a proof of concept, the developed LOS index was used in a case study of a model recreational building identified from the literature. Findings of this research could be adopted in assessing the performance of other types of municipal buildings.
2 LITERATURE REVIEW

Published literature has largely overlooked performance assessment of public recreational centre buildings. Only a handful of studies related to this subject area were observed. Howat and Crilley (2007) developed a performance assessment model for aquatic centres integrating customer service quality, satisfaction, and operational performance. Another study by Howat et al. (2008) studied the relationships between service quality, overall satisfaction and loyalty measures in Australian aquatic buildings. This study revealed that main factors influencing the overall satisfaction are relaxation, staffing and facility presentation. Priyadarsini (2014) studied energy performance of aquatic centre buildings in Victoria and revealed that energy intensity of aquatic centres ranges from 632 to 2,247 kWh/m².

Sharma et al. (2008) mentioned that customer expectations, legislative requirements and community are important criteria for assessing the LOS of an infrastructure asset. The stakeholders of recreational centre building have different and conflicting expectations from the municipal infrastructure. Moreover, minimum service standards associated with an asset, financial constraints, and delivery mechanisms should be considered when setting up a target LOS.

Indicators based systems are a popular method of identifying the condition of an infrastructure. There is an overwhelming trend towards an indicator assisted planning and decision making within the Canadian municipalities (Federation of Canadian Municipalities 2003). An indicator provides information to identify the condition or status quo of an object or a service in consideration. Indicators associated with municipal infrastructure could be in a hierarchy reflecting the decision-making structure within the municipalities (i.e. operational indicators, functional indicators to strategic indicators) (Federation of Canadian Municipalities 2003). The Federation of Canadian Municipalities (2003) defines these indicators as defined below.

i. Operational indicators: Operational indicator includes data collected by operational crew while performing their duties or as a part of the inventory process. Operational indicators are expressed as survey results or score boards.

ii. Functional indicators: Functional indicators are identified by analyzing the operational indicators that provide an overview of the condition of the infrastructure asset. These indicators are applicable to managerial level decision makers of the municipality.

iii. Strategic indicators: Strategic indicators provide general and abstract information of the infrastructure asset. The top level decision-makers (i.e. city manager, the city board) require this information in the strategic decision-making. These indicators provide a measurement of the quality of life of a municipality or meeting the infrastructure budget.

The funding decision makers related to municipal infrastructure often does not have sound understanding of the condition of the municipal asset (Federation of Canadian Municipalities 2003). Sudden and unexpected problems create tension within the users, and expedited assessments can result in financial destitution for building owners (Condominium homeowners association, 2010). Therefore, it is important to identify meaningful indicators displaying the performance of infrastructure assets to support the decision-making process. Indicators are expected to assist in decision-making process but are not intended as substitute while exercising judgement related to infrastructure (Federation of Canadian Municipalities 2003). LOS indicators should display, strategic goals, stakeholder goals and organizational goals (Asset Management BC 2011).

3 METHODOLOGY AND FRAMEWORK DEVELOPMENT

LOS of a recreational centre building depends on the building performance associated with multiple criteria (i.e. technical, social, environmental, and economic attributes). Hence, LOS assessment is a multi-criteria decision analysis (MCDM) process that incorporates conflicting criteria into the asset management. This LOS framework is based on a fuzzy set MCDM technique that is presented in the next section. Approaches proposed by Félio & Lounis, (2009) and Khatri et al., (2011) were considered in developing the LOS assessment framework. Figure 1 presents an overview of the LOS framework.
The proposed LOS assessment framework, as outlines below, involves five steps in calculating the LOS of a recreational centre building:

i. Identification and classification of performance indicators.
ii. Fuzzification of the performance indicators.
iii. Weight calculation and weight assignment.
iv. Aggregation of performance indicators using MCDM.
v. Defuzzification of the aggregated indexes to calculate the overall systems performance.

3.1 Identification and classification of performance indicators

Two main paradigms associated with the LOS of a municipal facility includes asset LOS and the customer LOS (USEPA 2007). Hence, a hierarchical framework has been developed to assess the LOS of a recreational centre building. The framework consists of LOS indicators at level 1; LOS dimensions at level 2; LOS categories (level 3) and overall building performance (level 4). Dimensions for LOS categories and LOS indicators were obtained from building rating systems such as BOMA Bst, Living Building Challenge etc. (Building Owners and Managers Association of Canada., 2013; International Living Building Institute, 2014; Japan sustainable building Consortium, 2011). Published literature was referred to identify indicators and dimensions related to customer LOS (Howat and Crilley 2007, Howat et al. 2008, Priyadarsini 2014). The framework developed for assessment of LOS of recreational centre building is presented in Figure 2.
3.2 **Fuzzification of the Performance Indicators**

Fuzzy set theory is a powerful mathematical model to characterize uncertainty in reality (Zimmermann 2010). This theory has been used in a vast range of disciplines such as engineering, logistics, management, data processing. Moreover, fuzzy set theory is a powerful tool to be used in decision support due to imperfect information about the reality.

Equation 1 presents the basic definition of the fuzzy set theory. The fuzzy set \( \tilde{A} \) is denoted as a set of ordered pairs in a universe of \( X \), where \( x \) denotes the objects of \( X \). The membership function, \( \mu_A(x) \), maps \( x \) values to \( \tilde{A} \) in the interval 0 to 1.

\[
\tilde{A} = \{(x, \mu_A(x)) | x \in X\}
\]

Equation 1

This approach was used to convert a crisp number to a fuzzy set that is represented by the membership function. Four membership function levels (i.e. poor, satisfactory, good, and excellent) were described for LOS assessment using triangular and trapezoidal shaped membership functions. Excellent is the highest achievable performance level. Good level is the acceptable performance level while satisfactory level requires further performance improvement. Poor is the lowest performance level that requires immediate attention. Fuzzified value would be the places where the performance value intersects with the membership function. As an example for a hypothetical performance value of 55, the fuzzified value would be \((0, 0.22, 0.8, 0)\) (Figure 3).

![Figure 3: Membership functions and fuzzification](image)

3.3 **Weight calculation and weight assignment.**

Various subjective methods are used in MCDM to derive the weights (e.g. AHP, ANP). Analytic hierarchy process method (AHP) is a popular method of deriving the weights in MCDM (Khatri et al. 2011). In AHP method, expert opinion is sought to conduct pairwise comparisons. The opinions however, should be consistent to ensure the accuracy of the weights.

3.4 **Aggregation of performance indicators**

The aggregation operation consists of combining the lower-level performances to the upper levels. The hierarchical process is presented in Figure 1. For each level, the synthesised performance value is a four-tuple fuzzy number.
3.5 Defuzzification of the Aggregated Indexes to Produce the Overall Systems Performance

Four-tuple fuzzy number derived from LOS indicators would be made a crisp number through defuzzification operation. A commonly used defuzzification method, centroid method (Equation 2) would be used for defuzzification operation.

\[ C_A = \frac{\int_a^b x \mu_A(x) dx}{\int_a^b \mu_A(x) dx} \]  

Equation 2

Overall LOS index is calculated using Equation 3.

\[ LOSI = D^T C^T \]  

Equation 3

Where,

\( C^T = \) transpose of a vector of centroid values of the membership functions

\( D = \) performance of a dimension/category in the framework

4 A CASE STUDY FOR PROOF OF CONCEPT

The LOS index developed above was used to assess the LOS of a recreational centre building. Operational data were obtained from primary and secondary sources. Performance level data were obtained from published literature (e.g. Sydney Water, (2011)). Table 1 presents the performance values for indicator categories comprised in the index. Due to the time restrictions researchers could not obtain the required data to calculate weights for AHP method. Therefore, equal weights were assumed for all criteria.

Table 1: Input data for LOS index.

<table>
<thead>
<tr>
<th>LOS dimensions and indicators</th>
<th>Operational data</th>
<th>Weight</th>
<th>Performance levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight Excellent</td>
<td>Good</td>
<td>Satisfactory</td>
</tr>
<tr>
<td><strong>Robustness of building components</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition rating of components</td>
<td>5</td>
<td>50%</td>
<td>&gt;8</td>
</tr>
<tr>
<td>% service life remaining</td>
<td>70</td>
<td>50%</td>
<td>&gt;80%</td>
</tr>
<tr>
<td><strong>Water-energy use</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity use intensity (kwh/ft²/year)</td>
<td>22</td>
<td>50%</td>
<td>&lt;12</td>
</tr>
<tr>
<td>Natural gas use intensity (kwh/ft²/year)</td>
<td>40</td>
<td>50%</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Water use intensity (l/patron/year)</td>
<td>26</td>
<td>50%</td>
<td>&lt;10</td>
</tr>
<tr>
<td><strong>Economy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benefit /cost ratio</td>
<td>0.5</td>
<td>50%</td>
<td>&gt;0.8</td>
</tr>
<tr>
<td>Asset value increase from previous year</td>
<td>1</td>
<td>50%</td>
<td>&gt;5%</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spending's for safety and security of the</td>
<td>10%</td>
<td>50%</td>
<td>&gt;15%</td>
</tr>
<tr>
<td>users from O &amp; M expenses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of safety incidents</td>
<td>2</td>
<td>50%</td>
<td>&lt;1</td>
</tr>
<tr>
<td><strong>Consistency of service</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of component breakdowns</td>
<td>4</td>
<td>50%</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Number of days facility was closed for</td>
<td>35</td>
<td>50%</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>
4.1 Results

Khatri et al., (2011) have defined performance levels for municipal infrastructure. The same was assumed for LOS of recreational centre building. Table presents the LOS of the recreational building.

Table 2: Performance levels for LOS.

<table>
<thead>
<tr>
<th>Membership function</th>
<th>Value range</th>
<th>Centroid value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>&gt;80</td>
<td>85</td>
</tr>
<tr>
<td>Good</td>
<td>80-60</td>
<td>60</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>60-40</td>
<td>33</td>
</tr>
<tr>
<td>Poor</td>
<td>&lt;40</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3 presents the fuzzification process and results of LOS indicators, dimensions and categories. Results of Table 3 were used to calculate the overall LOS of the recreational centre building.

Table 3: LOS of the recreational centre building.

<table>
<thead>
<tr>
<th>LOS indicators</th>
<th>LOS dimension</th>
<th>LOS categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robustness of building components</td>
<td>(0,0.21,0.12,0)</td>
<td>49.9</td>
</tr>
<tr>
<td>Water-energy use</td>
<td>(0,0.9,0,0)</td>
<td>45.9</td>
</tr>
<tr>
<td>Economy</td>
<td>(0,0.0.13,0.08)</td>
<td>16.4</td>
</tr>
<tr>
<td>Security</td>
<td>(0,0.0.13,0)</td>
<td>16.5</td>
</tr>
<tr>
<td>Consistency of service</td>
<td>(0,0.6,0.01,0.04)</td>
<td>19.1</td>
</tr>
</tbody>
</table>

(0,0.25,0.75,0)
<table>
<thead>
<tr>
<th>Quality of service</th>
<th>Social equity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0.5, 0.5)</td>
<td>(0, 0, 0.1)</td>
</tr>
<tr>
<td>(0.05, 0.5, 0)</td>
<td>(0, 0, 0.019)</td>
</tr>
<tr>
<td>28.9</td>
<td>12.0</td>
</tr>
</tbody>
</table>

LOS of the recreational centre building = **28.16**

Therefore the LOS of the recreational building is poor and needs immediate improvement.

5 DISCUSSION

This paper presented an approach for calculating the LOS of municipal recreational centre buildings. An MCDM based systematic framework has been used to calculate the LOS. Fuzzy synthetic method has been used to account for incomplete and qualitative information. The paper presented a case study using literature data to illustrate the underlying concept.

Currently, LOS of buildings is overlooked by asset managers. Even though performance assessment is common practise for regular buildings, there has not been any sound research focusing on specialized buildings such as recreational centre building. The concept of LOS in buildings has largely been disregarded in practise. Development of decision support tools would support facilities managers for the above purpose. Due to its convenience, indicator based assessment frameworks should be promoted among municipal decision makers and engineering departments. However, it is important to exercise cautious approach as indicator-based systems are not a silver bullet, and users should be reasonable in their expectations.

The proposed framework incorporated multiple criteria associated with the LOS of a recreational building. The LOS is evaluated primarily from the perspective of asset and customers. The LOS of a building is further, assessed considering various underlying dimensions. Therefore, a municipality could identify which aspect is affecting the building performance and take corrective action accordingly. This approach has the capability to customize the LOS index based on the priorities of the municipality. The fuzzy-based approach enables handling data that is incomplete, ambiguous, linguistic, and uncertain.

LOS indicators were identified from the published literature and building rating tools. The number of performance indicators could be improved using further analysis. When selecting indicators for rating systems, it is important to ensure indicators are manageable, meaningful, quantifiable, well defined and aligned with objectives. The fittingness of performance indicators could be further assessed considering relevance, measurability, etc. This approach would provide a more robust set of indicators. The results presented in this paper also illustrate a range of benchmark values for public aquatic centre managers.

The case study evaluated the LOS of a recreational centre building. Literature was used to obtain the indicator data to assess the LOS. This analysis identified that LOS of the recreational building considered is poor with a rating of 28.16. Therefore, this building requires immediate improvement. The water-energy performance of the building is satisfactory (49.9) while social equity is the extremely low (12.0). With this information, municipality could improve the LOS of the recreational centre by focusing on the areas that needs immediate attention. During the case study, equal weights were assumed for all the performance categories. The accuracy of LOS would heavily depend on the indicator types considered, the quality of data available and the weights assigned to the performance measures. Hence, the result observed could be different from the actual LOS of the recreational centre building.
There are several limitations associated with this study. Inclusion of limited number of performance measures for model is the main limitation of this paper. In addition, this framework considers equal weight for the criteria considered. However, it is important to realize that this approach should be tailored to meet the individual needs and priorities of the municipality. Data associated with LOS are uncertain and possesses considerable subjectivity. Several assumptions were used where ever data was not available. This concern could be resolved by using expert interviews and validating the interview responses using literature. Above issues would be corrected in the future publications with improved data collection and MCDM methods.

6 CONCLUSIONS

Assessing the LOS of public buildings is a challenge for municipal facilities managers. This paper presents a novel approach for analyzing and calculating the LOS of a recreational centre building. The LOS framework has been developed by integrating systems approach with fuzzy logic. This approach is reinforced by measures and data that is easily understood and can be used in diagnostic decision-making. This concept could be extended to assess the level of service of other municipal building classes.

The credibility of this framework depends on the types of indicators used and the precision of data and weights calculated. Further research is needed to identify more indicators and their interdependencies. Furthermore, it is important to identify sound data for LOS classifications (i.e. excellent, good, satisfactory, and poor). It is important to realize that when assigning weights, expert judgement could be subjective and be potentially biased. Hence, expert judgments from a diverse group of experts could be obtained to minimize the biases of the LOS index.

The outcomes of this research will inform LCAM of recreational centre buildings in Canada. The approach proposed in this study could be used to assess LOS of complex municipal infrastructure systems. Hence, an extension of the model would provide the Canadian municipalities with an integrated model to assess the LOS while developing holistic infrastructure system.

References

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IDENTIFYING INFLUENTIAL FACTORS FOR CAPITAL CONSTRUCTION PROJECT PLANNING STRATEGIES

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Abstract: Construction companies devote significant resources to front end planning (FEP). The potential substantial benefits of the strategic implementation of FEP practices across an entire portfolio have made FEP evaluation an important issue for both project leaders and scholars. The primary objective of this study is the use of multiple regression analysis for the identification of factors for use in predicting the gaps in project definition and for evaluating the FEP. FEP data from 59 North American capital construction projects from the same industry segment have been examined in order to establish such indicators and to enable the monitoring of project resources throughout the project lifecycle. When employed as a proactive approach during FEP, the results of this analysis have the potential to guide project managers in their search for important potential project definition gaps, and to prioritize there definition efforts. Its contribution to the body of knowledge is a methodology for understanding how to focus project definition efforts most effectively.

1 INTRODUCTION

Long-term strategies associated with a large capital project are established during front end planning (FEP), a process that is influenced by a number of risks and constraints, such as resource limitations, changes in government regulations, environmental restrictions, and financial and economic crises (Safa et al. 2013, Gibson 2005). A review of studies in this area reveals adequate FEP to be an essential component in the overall success of a project David Grau et al. 2012, George et al. 2008, Gibson et al. 1995, Hartman and Ashrafi 2004, Smith 2000, Webster 2004). The potential for acquiring substantial benefits from FEP and the opportunity to address problems encountered during the planning process have thus made the evaluation of the FEP phase of construction capital projects an important concern for both scholars and industry practitioners. With a focus on construction firms that have implemented a Project Definition Rating Index (PDRI) as a standardized tool across their capital project portfolios, the research presented in this paper has identified the most important influential factors for FEP assessment. Also included are the results of an investigation of key PDRI elements, including the statistical analysis method used, an evaluation of its effectiveness with respect to predicting gaps during the strategic phase of a project, details of potential uses of the indicators, and a synopsis of the benefits available for the construction industry.

Recent construction research has been directed at the establishment of a common set of construction phase metrics and their corresponding definitions (Park et al. 2005, Beatham et al. 2004, Rankin et al.
2008, Willis and Rankin 2012). Large capital construction projects are fraught with significant risk, with cost and schedule remaining key areas of scrutiny because failure to exploit opportunities for improving project value and decreasing risks could lead to the undervaluation of such projects (Ford 2002). Acquiring an in-depth understanding of this type of risk during the FEP phase is challenging because neither spending nor delivery has technically begun during this phase. A proven leading risk indicator employed during FEP is the PDRI. In current use as a widely adopted FEP standard, the PDRI stipulates key project elements suitable for representing the project team’s own assignment of scope definition ratings. The PDRI provides a framework for these ratings that allows project stakeholders to contribute important content and helps them acquire an understanding of the cross-functional impact of any risks identified.

Functioning as a multifaceted front end planning tool, a PDRI operates as a vehicle for the facilitation of strategic decision making through the evaluation of scope readiness as a means of measuring project risk. PDRIs are tailored to meet the specific needs of the building, industrial, and infrastructure sectors of the construction industry (Dumont et al. 1997, Weerasinghe et al. 2007, Gibson et al. 2010, Nasir et al. 2012). The correlation between a PDRI and risk factors related to project performance is based on published analyses of data from many hundreds of projects. The opportunity now exists to employ those historical project data sets at a portfolio level as a means of mining the powerful constituent elements of the index in order to develop methods that can support construction firms as they form proactive planning strategies for the execution of each new capital project. Such strategies encompass the use of influential factors, information technology systems, and common knowledge gaps that have been identified in the companies.

Since PDRIs are available in a variety of versions that vary according to the unique characteristics of each project, the authors have carefully considered each set of individual project features while developing the proposed analysis method for FEP risk assessment. The contribution of this study to the existing body of knowledge is to employ the data from 59 actual capital industrial projects from the same industry segment as a means of demonstrating the influential factors for analyzing and assessing the entire FEP process. The names of the projects and companies have been kept confidential. In accordance with the terms of the confidentiality agreement, because all materials related to these projects are also strictly confidential, including the designs, plans, specifications, models, reports, and other documents, their publication is not permitted. The results of this study have the potential to serve as a measureable process for aligning the owner and contractor with respect to complete scope definition for one or several projects as each is being defined.

2 PROJECT DEFINITION RATING INDEX

The primary deliverable of the FEP phase is an adequate level of design that enables the project team to prepare cost and schedule estimates, to make strategic decisions, and to identify risk (Dobler and Burt 1996, Safa et al. 2014). Once project funding has been approved, the FEP design deliverables become the primary input for the next phases in the project life cycle: procurement and detailed design. The FEP gates, four PDRI potential application points, and other life cycle project phases are illustrated in Figure 1. A gate is defined as the existence of the discrete information and definitions required for a decision to be made that determines whether to proceed.
The Construction Industry Institute (CII) offers a great positioning of PDRI and proven project risk review methodology based entirely on an assessment of the completeness of the scope definition of key project elements. The PDRI that the CII team created for construction projects includes a comprehensive checklist of about 70 scope definition elements spanning three sections – basis of project decision, basis of design and execution approach. The list elements were categorized through an extensive assessment of past and current industry best practices and were weighted in order of importance using input from more than 50 skilled project managers and proficient estimators (CII 2010). The process drills down to the essential details so that stakeholders can contribute critical content and understand the cross-functional impact of the risks identified. This tool enables an individual or a team to evaluate the status of a construction project during FEP and to determine a score that corresponds to its level of definition. Empirical evidence has shown that the PDRI can result in 6% to 25% savings in the overall cost of a project (CII 2010).

All PDRI's provide high-level project assessment following designated FEP phases. Figure 1 indicates the points where PDRI's are recommended. PDRI 1 follows the FEP feasibility phase and entails a high-level assessment of the project, which is usually held at an early project kickoff meeting with an architectural/engineering firm. The PDRI 2 review involves a high-level assessment of the project following the concept development phase, with the goals of evaluating the alignment of project objectives with stakeholder needs, identifying high-priority project deliverables, helping to anticipate late project surprises, and facilitating communication across the project team and stakeholders. PDRI 2i is an intermediate (i) assessment of the project, which is held at the midpoint of the detailed scope phase of the FEP. Its purpose is to provide further assurance of the alignment of project objectives with stakeholder needs, to confirm the efficient deployment of resources, to verify that the scope corresponds to the original project goals, and to identify and plan any remaining activities necessary for proceeding to the next FEP phase. PDRI 3 is the final assessment of the project during FEP, at which point risk issues have been identified and mitigation plans have been prepared. The overall maximum score to quantify the level of scope definition at any stage of the FEP is a 1000-Point Scale. Usual scores at the completion of this evaluation are between 150 and 250, with a preferred score being 200 or less. Acceptable PDRI score ranges for individual FEP phases are summarized in Table 1 (Gibson 1996, Wang and Gibson 2010). The suggested procedure is for all PDRI's to be conducted for all projects. However, if for any reason, the project management team is unable to implement all PDRI's, as a minimum, PDRI 3 should be completed in order to identify risk issues.

Table 1: Acceptable PDRI scores for FEP phases

<table>
<thead>
<tr>
<th>Stage</th>
<th>PDRI 1: Feasibility</th>
<th>PDRI 2: Concept</th>
<th>PDRI 2i: Detailed Scope</th>
<th>PDRI 3: Detailed Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Min</td>
<td>550</td>
<td>450</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>Typical Max</td>
<td>800</td>
<td>600</td>
<td>450</td>
<td>250</td>
</tr>
</tbody>
</table>
Project A is a Canadian project that was selected as an actual example. Its completion resulted in the conversion of a coal-burning process to one that burns wood pellets for the production of electricity and enabled the continued use of the majority of the plant equipment. The focus of Project A was on the unloading, storage, and handling of new materials; combustion; and control system upgrades. The project life cycle is assumed to be approximately 10 years, and the use of biomass fuel rather than coal will result in a reduction in net carbon emissions. The financial impact of the project will be moderate, with spending (approximately $200 million over 3 years) focused on the fuel-handling, combustion, and control systems. Table 2 shows the PDR12, PDR12i, and PDR13 scores for each FEP section as well as the total normalized scores for each PDR1.

<table>
<thead>
<tr>
<th></th>
<th>PDR1 Score</th>
<th>PDR12 Score</th>
<th>PDR13 Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECTION II - BASIS OF DESIGN</td>
<td>250</td>
<td>132</td>
<td>79</td>
</tr>
<tr>
<td>SECTION III - EXECUTION APPROACH</td>
<td>261</td>
<td>151</td>
<td>91</td>
</tr>
<tr>
<td>TOTAL NORMALIZED PDR1 SCORE</td>
<td>575</td>
<td>321</td>
<td>191</td>
</tr>
</tbody>
</table>

As can be seen in Table 2, the PDR12 score of 575 is very close to the upper boundary of the acceptable CII industry range: 600. The graph presented in Figure 2 shows that this critical score was remedied by addressing the comments, recommendations, and suggestions provided by the project team, resulting in substantial improvement, as evidenced by the PDR12i score of 321, which is very close to the typical minimum industry range: 300. This trend was continued and enabled the achievement of a score of 191 for PDR13, which is a very good score for a final project assessment. The trend in the PDR1 evaluation of this project demonstrates that even if the project involves numerous and serious risks during the first FEP phase, the PDR1 evaluation can help the project team identify risk issues and then provide mitigation plans. In addition, knowledge of the gaps identified during the earlier FEP phases enables project managers to find solutions to deal with the deficiencies.

![Figure 2: Comparison of PDR12, PDR12i, and PDR13 scores for Project A with acceptable industry ranges as defined by CII](image)
3 IDENTIFYING INFLUENTIAL FACTORS

As mentioned, the primary thrust of this research has been to highlight the influential factors that have the greatest effect on final PDRI scores. For this study, the prediction of such potential indicators was based on the use of a multiple regression analysis technique that relies on a dependent variable and a number of independent variables. This type of analysis helps with the modeling of the relationship between a response variable (Y) and the dependent variables (X1, X2,...), as \( E(Y) = b0 + b1X1 + ... + bnXn \). While its successful application requires a balance of theoretical results, empirical rules, and subjective judgment (Chatterjee and Hadil 2013, 2004), it offers the following benefits:

1. Project managers can concentrate their efforts on the more difficult aspects of projects.
2. Consistent deficiency predictions are provided.
3. The nature of the relationships between variables can be quantified.
4. The time saved allows project managers to focus greater time and energy on the contingency aspects of projects.

The final PDRI score is the dependent variable, and the categories and elements are considered to be independent variables applied over two steps. Using the information about the categories and elements improves accuracy with respect to the prediction of the final PDRI scores. Figure 3 shows the PDRI hierarchy employed in this study.

![PDRI hierarchy diagram]

The regression analysis used for this study involves two steps. In the first step, the regression analysis is applied at the category level. The second step entails the evaluation of the elements of the categories selected. In an effort to develop a truly objective and quantitative analysis method, the authors decided to rely on data rather than only comments from experts, so they collected extensive data for 59 completed North American projects. The data was normalized used in Valency's Carve application, then exported to perform regression analysis using Excel 2010, which has a built-in regression analysis tool as a standard component that is available as an Excel add-in.

For the first step in the analysis, the dependent variable is the final PDRI score. The independent variables are designated as follows: (A) Manufacturing Objectives Criteria; (B) Business Objectives; (C) Basic Data Research & Development; (D) Project Scope; (E) Value Engineering; (F) Site Information; (G) Process/Mechanical; (H) Equipment Scope; (I) Civil, Structural, & Architectural; (J) Infrastructure; (K) Instrument & Electrical; (L) Procurement Strategy; (M) Deliverables; (N) Project Control; (P) Project Execution Plan.

Figure 4 shows the regression results. The top part of the output shown in the figure is the regression statistics table. The most important number in this table is R Square, which signifies how well the regression line approximates the real data. The closer the value is to 1, the better the regression line fits
the data. In this case, R Square equals 0.987, which indicates a very good fit and means that 98% of the variation in the PDRI final scores can be explained based on the independent variables: the categories.

<table>
<thead>
<tr>
<th>OUTPUT SUMMARY</th>
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<tbody>
<tr>
<td><strong>Regression Statistics</strong></td>
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<tr>
<td>Multiple R</td>
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<tr>
<td>R Square</td>
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<tr>
<td>Adjusted R Square</td>
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<tr>
<td>Standard Error</td>
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<tr>
<td><strong>df</strong></td>
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<tr>
<td>Residual</td>
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<tr>
<td>Total</td>
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<table>
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<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
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</thead>
<tbody>
<tr>
<td>Intercept</td>
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<td>15.737</td>
<td>0.062</td>
<td>0.951</td>
<td>-33.02</td>
</tr>
<tr>
<td>A</td>
<td>6.933</td>
<td>1.786</td>
<td>3.883</td>
<td>0.002</td>
<td>3.08</td>
</tr>
<tr>
<td>B</td>
<td>-0.128</td>
<td>0.804</td>
<td>-0.159</td>
<td>0.876</td>
<td>-1.86</td>
</tr>
<tr>
<td>C</td>
<td>1.512</td>
<td>0.883</td>
<td>1.714</td>
<td>0.110</td>
<td>-0.39</td>
</tr>
<tr>
<td>D</td>
<td>2.420</td>
<td>0.661</td>
<td>3.660</td>
<td>0.003</td>
<td>0.99</td>
</tr>
<tr>
<td>E</td>
<td>6.304</td>
<td>1.870</td>
<td>3.371</td>
<td>0.005</td>
<td>2.26</td>
</tr>
<tr>
<td>F</td>
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<td>0.793</td>
<td>-0.241</td>
<td>0.814</td>
<td>-1.90</td>
</tr>
<tr>
<td>G</td>
<td>0.925</td>
<td>0.344</td>
<td>2.690</td>
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<td>0.18</td>
</tr>
<tr>
<td>H</td>
<td>4.092</td>
<td>1.752</td>
<td>2.335</td>
<td>0.036</td>
<td>0.31</td>
</tr>
<tr>
<td>I</td>
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<td>2.370</td>
<td>-3.749</td>
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<td>-14.00</td>
</tr>
<tr>
<td>J</td>
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<td>2.330</td>
<td>2.970</td>
<td>0.011</td>
<td>1.89</td>
</tr>
<tr>
<td>K</td>
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<td>1.598</td>
<td>-2.395</td>
<td>0.032</td>
<td>-7.28</td>
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<td>L</td>
<td>-12.284</td>
<td>5.701</td>
<td>-2.155</td>
<td>0.051</td>
<td>-24.60</td>
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<tr>
<td>M</td>
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<td>5.000</td>
<td>1.379</td>
<td>0.191</td>
<td>-3.91</td>
</tr>
<tr>
<td>N</td>
<td>3.091</td>
<td>2.675</td>
<td>1.156</td>
<td>0.269</td>
<td>-2.69</td>
</tr>
<tr>
<td>P</td>
<td>3.317</td>
<td>1.238</td>
<td>2.680</td>
<td>0.019</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Figure 4: Regression analysis output at the category level

The ANOVA table is shown in the center section of Figure 4. The F value indicated under the Significance F heading indicates the probability that the regression analysis output could have been achieved by chance. A small F value confirms the validity of the regression output. It should be noted that the Excel default is scientific notation, so 6.51958E-10 means 6.551958 * 10^-10 (0.000000000651958). To check whether the results are reliable (statistically significant), the significance F value (0.000000000651958) should be considered. If this value is less than 0.05, the model is statistically significant. If F is greater than 0.05, it suggests that the use of this set of independent variables should be discontinued.

The regression output of greatest interest is the bottom table in Figure 4: the regression coefficient table. The P-value column gives the p-value for testing H0: βj = 0 against Ha: βj ≠ 0. The p-value is the estimated probability that the null hypothesis (H0) of a research question will be rejected when that hypothesis is true. Variables with high p-values (greater than 0.05) have been omitted, and the regression is returned until Significance F drops below 0.05. In Figure 4, unacceptable p-values greater than 0.05 are highlighted.

Following a review of the results of the first analysis, an additional regression analysis was run using a different combination of variables in which those with p-values over 0.05 were eliminated. This process was performed five times. The results were as shown in Figure 5, and the categories A (Manufacturing Objectives Criteria) and P (Business Objectives) were selected.
In step 2, the elements of categories A and P were considered as the independent variables: (A1) Reliability Philosophy; (A2) Maintenance Philosophy; (A3) Operating Philosophy; (P1) Owner Approval Requirements; (P2) Engineering/Construction Plan & Approach; (P3) Shut Down/Turnaround Requirements; (P4) Pre-Commission Turnover Sequence Requirements; (P5) Startup Requirements; (P6) Training Requirements. The final PDRI score is considered to be the dependent variable. Three regressions produced the results displayed in Figure 6.

The analysis results reveal that two elements of category A, (A1) Reliability Philosophy and (A2) Maintenance Philosophy, as well as one element of category P, (P2) Engineering/Construction Plan & Approach, can be considered influential factors for evaluating the FEP phase of industrial construction projects.

4 ANALYSIS

As the results indicate, A1, A2, and P2 were identified as influential factors. However, the use of these results must be accompanied by the following provisos:
1. These elements can be used consistently only across an entire portfolio of projects for a specific construction industry sector (e.g. oil and gas).
2. These powerful influential factors cannot be used to replace the PDRI process.
3. The elements selected can vary from one construction industry sector to another (e.g. oil and gas and commercial buildings).

Regression analysis can indicate only how or to what extent variables are associated with one another. The results can therefore not be considered as establishing precise cause-and-effect relationships, which means that any conclusions about the relationships should be based on the judgment of project managers and experts. In fact, the use of expert intuition represents one method of model validation, and was the method performed by the authors in this case. In practice, a project management team embodies a combination of domain expertise and operational experience. Therefore, on September 18, 2014, the authors met with two experts who had been involved with some of the projects included in the study in order to gain insight and to benefit from the unique opportunity to influence the direction of this research. The experts validated and confirmed the accuracy of the results obtained from the statistical analysis. This type of analysis offers a number benefits for a company:

1. It enables a determination of whether PDRI scores are a reliable leading indicator of performance when a PDRI is implemented as a strategic tool and is used consistently across an entire portfolio of projects.
2. Given the positive correlation between PDRI scores and improved project performance across an entire portfolio, a construction company can use these results as a means of validating their process and their commitment to using best practices in project management in order to maximize the financial return on their capital investments.
3. PDRI data analysis will provide a formal framework for FEP evaluation, thereby enhancing the quality of project management, facilitating management succession, and forming the basis for the long-term educational value of the FEP process.
4. With respect to performance over both the short and long term, this analysis will add to the impressive body of studies related to the evaluation of FEP results.
5. These results can contribute to an analysis of trends or common gaps in FEP data to be used as indicators of the organizational effectiveness of a project because they provide a benchmark at the element level of baseline conditions that are related to project success.

The results of this study can also be employed at pre-meetings held by PDRI facilitators before they conduct PDRI sessions to analyze project documents with key project stakeholders. Critical powerful indicators are also useful for enhancing the speedy evaluation of FEP phases; the periodic evaluation and prediction of common gaps in projects, portfolios, and the organization; and the assessment of small projects, organizational strategic issues, and contingency planning.

5 CONCLUSION

More rigorously analyzed PDRI data can substantially improve the level of project managers’ understanding in this area. The primary contribution of this study is the identification of influential factors for FEP evaluation. The potential exists for construction companies to optimize their current use of such best practices and to integrate this new knowledge into their existing FEP. Data from 59 industrial projects have been evaluated and the results reported. It should be noted that the analysis and case projects all belong to the industry sector, which means that the results are not applicable for other sectors; however, the same methodology could be employed in additional construction industry sectors. Given the complexity of many construction capital projects, significant value accrues to the engineering and construction industry if the proposed method could be effectively utilized to enhance risk assessment for construction projects. Approaches to risk mitigation could then be more accurate and better focused, with fewer wasted resources. Other benefits include increased construction time and cost savings resulting from effective planning, which can further increase the success of risk avoidance procedures. PDRI users will have the opportunity to be at the forefront of the development, implementation, and exploitation of this crucial new method. The methodological limitations identified in these empirical studies (e.g. regression analysis constraints) suggest several avenues for future research in other construction industry sectors. As additional data become available, the results of this study will also be more broadly
applicable for use with further discoveries, such as operational excellence management, for which project risk management reporting represents a constant challenge for capital project teams and owners.

References


TELEMATICS DATA-DRIVEN PROGNOSTICS SYSTEM FOR CONSTRUCTION HEAVY EQUIPMENT HEALTH MONITORING AND ASSESSMENT

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\textsuperscript{4} hsaid@scu.edu

Abstract: Construction heavy equipment is a valuable asset for construction and equipment rental companies, which requires continuous monitoring and assessment for potential failures. Predictive maintenance has recently been proposed as an alternative to preventive maintenance strategy by scheduling maintenance tasks just before a predicted failure of the equipment. Such predictive approach is dependent on the existence of a data collection and analysis system that monitors the equipment performance, compares it to the previous history, and predicts the failure events before their occurrence. This paper presents the development and validation efforts of a data-driven prognostics system that utilizes timely collected telematics data to monitor the equipment health condition and predict its failure hazard. The system is designed to utilize equipment telematics data to develop regression-based Cox's proportional hazards functions. Regression analyses are performed for the historical telematics data to develop time-varying hazard functions for the successive life intervals of the equipment to generate dynamic predictions of its failure events. Accordingly, the outcome of the system would be the predicted probability of the equipment failure event considering the timely collected telematics data. The proposed prognostics system was validated by developing the hazard functions of two fleets of dozers and backhoes that provided high fit to the observed data and high prediction accuracy for the testing data. For both analyzed fleets, higher predictive and data fitting performance were achieved for later life intervals due the increased reliability of failure prediction for equipment with longer survival lives.

1 INTRODUCTION

Construction heavy equipment is a valuable asset for construction and equipment rental companies, which requires continuous monitoring and assessment for potential failures. The absence of a properly implemented maintenance program leads to premature equipment failure and increased construction crew idle time. Predictive maintenance (Gransberg et al. 2006) has recently been proposed as an alternative to corrective and preventive maintenance strategies by scheduling maintenance tasks just before a predicted failure of the equipment. Such predictive approach is dependent on the existence of a data collection and analysis system that monitors the equipment performance, compares it to previous history, and predicts the failure events before their occurrence. Despite the great promise of predictive maintenance, its wide implementation was not realized yet due to its need for large data collection process and supporting technology.
Telematics is a data collection technology that integrates wireless communications, vehicle monitoring systems, and location devices to provide real-time spatial and performance tracking of the fleet machines (Lovett et al. 2003). As a witness to its great benefits, the telematics industry has significantly grown to be installed in 5.8 million equipment units with revenue volume of $2 billion in 2009 (Fletcher and Lauron 2009). Telematics can be installed by either the original equipment manufacturer (OEM) or a third-party service provider (TSP). Telematics has been utilized as mainly a real-time monitoring system of equipment fleet for the purposes of theft protection, fuel consumption, and prevention of undesired behaviors of operators/drivers. Fleet managers are challenged to expand the utilization of telematics technology due to the difficulties in inking telematics data to business functions and performance metrics (Monnot and Williams 2011, Trimble and Bowman 2012, Jackson 2012, Sutton 2013).

2 RESEARCH OBJECTIVE AND METHODOLOGY

This paper presents the development and validation efforts of a data-driven prognostics system that utilizes timely collected telematics data to monitor the equipment health condition and predict its failure hazard. Prognostics is the field and methodologies of predicting the future health behavior, failure events, and remaining useful life (RUL) of equipment and machines by diagnosing the recorded temporal behavior (Mesgarpour et al. 2013). Current approaches of prognostics can be classified into three main classes (Lee et al. 2006): 1) model-based prognostics that depends on developing virtual models of the machine that mimic its behavior under healthy and faulty conditions; 2) data-driven prognostics that utilize collected sensor data of the machine’s previous behavior toward failure, and 3) hybrid prognostics that integrates models formulation with sensor data calibration. This paper proposes a data-driven prognostics model that utilizes equipment telematics data to estimate its failure probability.

To accomplish this objective, the research methodology encompassed four main tasks. First, a thorough literature review was performed to study the previous research in the areas of equipment health prognostics and telematics application in construction. Second, a brief description of telematics system architecture and data was presented. Third, the formulation of the proposed telematics-based prognostics system was developed and illustrated. Fourth, the performance of the developed system was validated by analyzing the telematics data of two types of heavy equipment fleets. The paper is concluded by summarizing the contribution of the proposed system to heavy construction and equipment rental companies, as well as recommendations for future research.

3 PREVIOUS RESEARCH

Relevant previous research related to this paper is summarized into two main categories: equipment health prognostics and application of equipment telematics in construction. First, previous research on equipment and machine prognostics focused on monitoring the condition of stationary mechanical machines or electrical micro-machines by majorly measuring their vibrations (Dutta and Giurgiutiu 2000; Yan R. and Gao 2007; Da et al. 2011, Thomson 2013). Equipment manufacturers have encouraged research and development efforts to develop health monitoring systems that integrate remote sensing and equipment oil sampling to diagnose its condition and estimate its life expectancy (Murakami et al. 2002). Little research was found to indicate the potential of utilizing telematics data in prognostics, with no development of proven models or systems (Mesgarpour et al. 2013). Second, little research was performed to investigate the use of the telematics technology in construction and heavy equipment fleet management. Monnot and Williams (2011) highlighted the possible use of telematics in various equipment fleet management tasks, like reporting of machines hours, locations, fuel consumption, and health. Aslan and Koo (2012) proposed an implementation plan for the use of telematics technology in the improving the productivity of roadway maintenance operations. The plan was to me completed in a future study with testing a telematics data collection system and developing productivity measurement metrics.

The careful study of previous studies identified the critical research gap and need for new prognostics systems that would enable the use of telematics data to assess equipment failure potential, as an essential part of effective predictive maintenance (Gransberg et al. 2006).
4 EQUIPMENT TELEMATICS: SYSTEM ARCHITECTURE AND DATA

The architecture of a typical telematics system integrates global position system, available communication infrastructure, and vehicle onboard sensors system. As shown in Figure 1, telematics transponders are installed in the different units of the equipment fleet, where each transponder is connected to the onboard sensors system of the equipment to collect temporal samples of different performance parameters (as discussed in next paragraph). The transponder also has a built-in GPS antenna that collects the location coordinates of every data entry collected. The equipment's performance data and location coordinates are then transmitted through standard wireless communication mediums, which include CDMA (Code division multiple access) and GSM (Global System for Mobile Communications) networks. On the other end, the data is received and stored in a central server that is managed by either the OEM or TSP companies. The data can be accessed by the equipment owners and fleet managers in both push or pull approaches. The system can push notifications to the mobile devices and email addresses of the fleet manager, especially in events when threshold have been activated, like fuel consumption rate, driving speed, or existing in unexpected locations. On the other hand, the data can be pulled from the servers by the fleet manager to view the data on the browser of the World Wide Web (www) or download the data timeline in different file formats.

![Figure 1: Telematics System Architecture](image)

The installed transponders have four types of cable connections that are used to collect three data elements and transmit them wirelessly to the system server. As shown in Figure 2, the transponder unit has four cables: the CAN-bus cable, main interface cable, the GPS receiver cable, and wireless antenna. 

*First*, the CAN-bus cable connects the transponder unit to the controller area network (CAN) of the equipment that connects between the microcontrollers of the equipment different components, such as the engine, transmission, and brakes. The CAN-bus cable enables the transponder to connect to these microcontrollers and their data. The transponders access the CAN-bus data by utilizing the same standard communication protocol used by most heavy equipment manufacturers, called J1939 (developed by the Society of Automotive Engineers). CAN-bus data provides rich and detailed reporting of the different performance aspects of the equipment, such as the engine oil pressure, oil temperature, coolant temperature, engine error codes. CAN-bus data is the main source of equipment health parameters that can be used in health diagnosis and prognosis, as discussed in section 5 of this paper. However, it should be noted that only heavy equipment of the third tier and later are equipped with CAN-bus network. This means that for older equipment, the transponder’s CAN-bus cable is left unconnected and all CAN-bus data cannot be collected or reported. 

*Second*, other basic data of the equipment are collected through the main interface cables, which connect to different points of the equipment to: 1) identify ignition events of the engine that can be used to calculated idle and working times; 2) obtain the odometer reading; and 3) provide a power supply to the transponder itself. Such basic data can be used for elementary utilization and fuel consumption analysis, not health diagnosis/prognosis. Third, the GPS receiver cable provides the location coordinates for every data entry (reading) collected by either the main interface or CAN-bus cables. Fourth, all collected data are communicated through the wireless antenna cable to the system servers. For this study, a commercial TSP telematics system is utilized to
study the telematics data and collect its samples for the development and validation of the proposed heavy equipment prognostics system.

![Diagram of telematics data types]

Figure 2: Telematics Data Types

5  EQUIPMENT HEALTH PROGNOSTICS USING TELEMATICS-BASED SURVIVAL ANALYSIS

The development of the proposed equipment prognostics system is presented by listing the proposed telematics health data, providing an overview of survival analysis, and describing the modeling approach of the equipment failure hazard functions.

5.1  Proposed Telematics-Based Health Parameters

Telematics provides a rich data source that is utilized in this research to derive diagnosis and prognosis parameters of the equipment health. The proposed prognostics system is generic and can be applied to any set of telematics health parameters available in the collected data. However, the inputted telematics health parameters may affect the quality of the generated equipment health hazard functions. Accordingly, the following eight health parameters available in every telematics entry at time $t$, were proposed in this research based on available literature review (Murakami et al. 2002, Dekate 2013) and consultation with equipment telematics professionals:

1. Maximum coolant temperature ($MCT_t$) in degrees Fahrenheit, which is observed on the day when the telematics data entry is received.
2. Maximum engine oil pressure ($MOP_t$) in pounds per square inch (psi).
3. Maximum engine oil temperature ($MOT_t$) in degrees Fahrenheit.
4. Maximum engine speed ($MES_t$), in rounds per minute (rpm).
5. Maximum engine percent torque ($MPT_t$), which indicates the load on the engine as a percentage value.
6. Maximum fuel rate ($MFR_t$) in gallons/hour.
7. Engine working hours ($HW_t$), which reports the cumulative number of hours the engine run with a speed (rpm) above a specified threshold, set by the fleet manager.
8. Engine Idling hours ($HI_t$), which reports the cumulative number of hours the engine ran with a speed (rpm) less than the specified threshold.
5.2 Survival Analysis and Failure Hazard Functions

Survival analysis is a regression approach of reliability studies to assess the times and probabilities to failure events. Survival analysis has been applied before to analyze the lifetime of orgasms, survival times of cancer patients, occurrence of accidents, and failure times of machines (Gu et al. 2011). Survival analysis deals with the failure event time as a random variable $T$ using different representations (Allison 1995), such as 1) the cumulative distribution function of variable $T$, $P(t) = Pr(T \leq t)$; 2) the survival function $S(t)$ as the complement of the distribution function, $S(t) = Pr(T > t) = 1 – P(t)$; and 3) the hazard function $h(t)$ that assesses the instantaneous at time $t$. The goal of the survival analysis is to develop these representations of the failure event as a function of its determinant, i.e. its health parameters.

Survival analysis models can be classified as non-parametric, parametric, and semi-parametric models (Ma and Krings 2008). Cox’s proportional hazards model (Cox 1972), one of the fundamental semi-parametric survival models, is utilized for this study due to its ability to capture the failure covariates more effectively than non-parametric models with less modeling restriction like the parametric models (Bailey et al. 2006). As shown in Equation 1, a dynamic time-varying hazard function $h(t)$ of Cox’s model is utilized in the proposed equipment prognostics system to estimate the probability of equipment failure at time $t$, which is based on: 1) the telematics health parameters $X(t)$ (covariates) and their coefficients $\beta(t)$ that can be determined by performing a regression analysis to fit the observed health parameter values to the failure hazard probability $h(t)$; and 2) a baseline failure rate $h_0(t)$ represents the decay of the equipment health regardless of the values of its health parameters. The next section will explain in more details the methodology of developing the hazard functions and the calculation of the observed equipment hazard probability based on the available telematics data.

\[ h(t) = h_0(t) \times \exp \left[ \beta(t).X(t) \right] \]

5.3 Modeling and Development of Equipment Failure Hazard Functions

The proposed heavy equipment prognostics system follows a novel methodology to model and develop Cox’s proportional survival functions as a function of the available telematics data. As shown in Figure 3, the equipment hazard functions are developed in four main steps:

Step (a) – Telematics data are used to mark the failure events over the lifetime of the equipment and the engine hours. An equipment failure event is recognized if one of two engine lights is reported in the telematics data entry: 1) red stop light (RSL) that indicates a severe enough condition that it warrants stopping the vehicle; and 2) amber warning light (AWL) that reports a problem with the vehicle system but the vehicle does not need to be immediately stopped. Other engine lights, such as engine protection light (EPL) and malfunction indicator light (MIL), are not used to indicate a major equipment failure as they report less severe health conditions related to the vehicle electronic system and emissions-related issues. As shown in Figure 2, the existence of either RSL or AWL marks a failure event and the start/end of a survival life of the equipment. As shown in Figure 3, survival analysis permits the right and left censoring (Ma and Krings 2008) of the data to only consider the complete survival lives that start and end with a recorded failure/survival event.

Step (b) – The observed failure hazard value is quantified using another telematics data element, which is the engine total hours (HT) that reports the cumulative engine hours up to the time of the telematics data entry. As shown in Figure 2, the observed failure hazard is quantified over each of the identified survival lives as the ratio between: 1) the engine hours $E$, since the start of the survival life to time $t$; and 2) the total engine hours $L$ occurred during corresponding survival life. Accordingly, the failure hazard observed values range from 0 (at the beginning of the survival life) to 1.0 (at the end of the survival life).

Step (c) – All telematics entries are combined to form the analysis data population and divided into survival intervals, which each will have its own hazard function to represent the time-varying nature of equipment health performance. As shown in Figure 3, the analysis sample combines all telematics data entries of every unit survival life from the same-type equipment fleet (i.e. dozers, loaders, excavators). Each data entry include the following variables: 1) the observed failure hazard value
(dependent variable) that was quantified in step b; 2) the time t in days since the recovery from last failure; and 3) the proposed telematics-based covariates that are available from the collected data ($MCT_r$, $MOP_r$, $MOT_r$, $MES_r$, $MPT_r$, $MFR_r$, $HW_r$, and $HI_l$). The initial data sample is divided into subgroups of survival intervals to represent different hazard behaviors and rate of the equipment over its survival life.

Step (d) – The survival baseline rate $h_0(t)$ and coefficients vector $\beta(t)$ are estimated for every life interval hazard function using data linearization regression technique. First, the data sample of every life interval is divided into two groups (Lucko and Rojas 2010): a) the estimation data group that is used to estimate the baseline rate and coefficients vectors; and b) the validation data group that is used to assess the prediction accuracy of the hazard functions with the estimated coefficients. The coefficients can be estimated using traditional statistical analysis software packages to improve the fitting of the hazard function to the observed values. The fitting of the hazard function can be assessed using any or all of the following statistical metrics: 1) the p-value for the constant and each covariate coefficient as generated from by regression analysis, which is used to test the hypothesis of survival function dependency on each of the covariates; 2) coefficients of determination (R-square, Multiple R-square, and adjusted R-square) to test the fit of the resulting survival function to the observed data; and 3) analysis of variance (ANOVA) significance level F, which quantifies the probability that the proposed function does not explain the variation in the equipment hazard (Field 2005). Accordingly, the validation data group is used in assessing the prediction accuracy of the estimated hazard functions using the Pearson coefficient of correlation ($R_{corr}$), student t-test to examine and the root mean square error ($RMSE$) (Montgomery et al. 2001, Lucko et al. 2006).

![Diagram](image)

Figure 3: Telematics-based Survival Analysis to Develop Equipment Prognostics Hazard Functions

6 SYSTEM PERFORMANCE ILLUSTRATION AND VALIDATION

The performance of the proposed heavy equipment prognostics system was illustrated and validated using the telematics data of two fleets of an equipment rental company. The Cox’s failure hazard functions of the company’s dozer and backhoe fleets were developed by applying the proposed system methodology to the telematics data of 21 dozers and 29 backhoes. The total telematics data entries were
1836 for the dozers and 3315 for the backhoes that cover a one year observation period. Removal of the outliers resulted in reducing the data sample to 1767 and 3016 data entries for dozers and backhoes respectively. Five arbitrary life intervals were considered to develop the time varying hazard functions: less than 50 days; between 50 and 100 days, between 100 and 150 days; between 150 and 300 days, and more than 300 days. The data entries were split between these time intervals based on their survival lives, accordingly divided into estimation and validation data groups. Tables 1 and 2 list the data entries distribution over the life intervals, the estimated coefficients of the survival functions, and their prediction validation metrics. For example, 676 data entries of the dozers were located in the first life interval (0 – 50 days) and were split equally between the estimation and validation groups. Equation 2 depicts an example of how the estimated coefficients shown in Table 1 can be used to formulate the time-varying hazard function of the dozers fleet.

\[
\begin{align*}
    h(t) &= \begin{cases} 
    \exp[-0.0396 \cdot \text{MOP} + 0.0077 \cdot \text{MOT} + 0.0015 \cdot \text{HW}] & 0 \leq t < 50 \\
    \exp[-0.0165 \cdot \text{MOP} + 0.01835 \cdot \text{MPT} + 0.181 \cdot \text{MFR} + 0.00093 \cdot \text{HI}] & 50 \leq t < 100 \\
    \exp[-0.0145 \cdot \text{MOP} + 0.00047 \cdot \text{MES} - 0.00911 \cdot \text{MPT} + 0.00156 \cdot \text{HW} - 0.0013 \cdot \text{HI}] & 100 \leq t < 150 \\
    \exp[-0.0144 \cdot \text{MOP} + 0.00537 \cdot \text{MPT} + 0.00123 \cdot \text{HI}] & 150 \leq t < 300 \\
    \exp[-0.0132 \cdot \text{MOP} - 0.0009 \cdot \text{MOT} + 0.0079 \cdot \text{HW} - 0.00515 \cdot \text{HI}] & 300 \leq t
\end{cases}
\end{align*}
\]

Table 1: Final Regression Results for the Dozers Hazard Functions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Life Intervals (days)</th>
<th>(0 – 50)</th>
<th>(50 – 100)</th>
<th>(100 – 150)</th>
<th>(150 – 300)</th>
<th>(&gt; 300)</th>
</tr>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
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<tr>
<td>X1 (MCT)</td>
<td>0</td>
<td>-0.00848 (^a)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>X2 (MOP)</td>
<td>-0.04917 (^a)</td>
<td>-0.0206 (^a)</td>
<td>-0.01491 (^a)</td>
<td>-0.00728 (^a)</td>
<td>0</td>
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<tr>
<td>X3 (MOT)</td>
<td>0.01101 (^a)</td>
<td>0.0096 (^a)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>X4 (MES)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-0.0001 (^a)</td>
<td></td>
</tr>
<tr>
<td>X5 (MPT)</td>
<td>0.02792 (^a)</td>
<td>0.0135 (^b)</td>
<td>0.01336 (^a)</td>
<td>0.00659 (^a)</td>
<td>0</td>
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<tr>
<td>X6 (MFR)</td>
<td>-0.35908 (^a)</td>
<td>-0.1408 (^a)</td>
<td>-0.13776 (^a)</td>
<td>-0.09602 (^a)</td>
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<tr>
<td>X7 (HW)</td>
<td>0.00364 (^a)</td>
<td>0.00195 (^a)</td>
<td>0.00193 (^a)</td>
<td>0.00129 (^a)</td>
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<tr>
<td>X8 (HI)</td>
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<td>0</td>
<td>0</td>
<td>0.00101</td>
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<table>
<thead>
<tr>
<th>Estimation Observations</th>
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</thead>
<tbody>
<tr>
<td>Multiple R</td>
</tr>
<tr>
<td>R Square</td>
</tr>
<tr>
<td>Adj. R Square</td>
</tr>
<tr>
<td>Significance F</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Prediction Observations</th>
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<tr>
<td>RMSE</td>
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<td>(R_{corr})</td>
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<table>
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<tr>
<th>Observed t-Test</th>
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<tbody>
<tr>
<td>7.707</td>
</tr>
<tr>
<td>Critical t-Test</td>
</tr>
</tbody>
</table>

\(^{a}\) \(p < 0.001\) \hspace{1cm} \(^{b}\) \(p < 0.05\) \hspace{1cm} \(^{c}\) \(p < 0.01\)
Table 2: Final Regression Results for the Backhoes Hazard Functions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Survival Intervals (days)</th>
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<th>50 – 100</th>
<th>100 – 150</th>
<th>150 – 300</th>
<th>&gt; 300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (C)</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>X1 (MCT)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X2 (MOP)</td>
<td></td>
<td>-0.0396&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.0165&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.0145&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.0144&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.0132&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>X3 (MOT)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>-0.0009</td>
</tr>
<tr>
<td>X4 (MES)</td>
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<td>0</td>
<td>0.00047&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X5 (MPT)</td>
<td></td>
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<td>0.00537</td>
<td>0</td>
</tr>
<tr>
<td>X6 (MFR)</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>X7 (HW)</td>
<td></td>
<td>0.0015&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0.00156&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0</td>
<td>0.0079&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>X8 (HI)</td>
<td></td>
<td>0</td>
<td>0.00093&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-0.0013&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.00123&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.00515&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**Observations** | 664 | 305 | 236 | 241 | 62 |
**Multiple R** | 0.7687809 | 0.8111306 | 0.7679307 | 0.7890777 | 0.9518655 |
**R Square** | 0.5910241 | 0.6579329 | 0.5897176 | 0.6226436 | 0.9060479 |
**Adj. R Square** | 0.5882738 | 0.6512013 | 0.5782841 | 0.6152708 | 0.8839470 |
**Significance F** | 8.52E-128 | 9.4E-69 | 1.03E-42 | 5E-50 | 9.16E-29 |
**RMSE** | 0.374626 | 0.23463 | 0.22687 | 0.26875 | 0.1 |
**R<sub>corr</sub>** | 0.119655 | 0.3971456 | 0.32333 | 0.49067 | 0.878159 |
**Observed t-Test** | 3.103263 | 7.5326 | 5.22682 | 8.7055 | 10.7 |
**Critical t-Test** | 1.647 | 1.65 | 1.651 | 1.651 | 1.671 |

<sup>a</sup> p < 0.001  <sup>b</sup> p < 0.05  <sup>c</sup> p < 0.01

The examination of the developed hazard functions provides useful insights on the dependency of equipment health prognosis on the telematics parameters over the successive life intervals. First, some telematics parameters have shown consistent correlation with the failure hazard probability for both analyzed equipment. The maximum oil pressure (MOP) and working hours (HW) variables were found to be a very significant health prognosis variables (p < 0.001) in the developed hazard function in most life interval. Also, it was consistently shown that higher MOP values result in lower failure hazard (all of its coefficients were negative) as it indicate a lower possibility of oil leakage. On the other hand, the positive coefficients of the working hours (HW) variable reinforce the concept that higher working hours increases the equipment’s failure hazard. Second, the fitting and prediction accuracy of the developed hazard functions were found to increase with the survival time of the equipment. This observation is illustrated by the high multiple R value, the high R<sub>corr</sub> value, and low RMSE value of the last life interval for both equipment types compared to earlier life intervals. This complies with the de facto that the failure of assets with longer survival time can be reliably anticipated compared to younger assets with shorter survival time that just recovered from a failure event.

7 CONCLUSION AND FUTURE RESEARCH

This paper presents the development of a telematics-based equipment prognostics system that can support heavy construction and rental companies to effectively manage their predictive maintenance programs. Telematics is an efficient data collection technology as it integrates equipment onboard...
sensing, global positioning, and telecommunication to provide a timely reporting of different equipment performance data. The telematics CAN-bus data provide a rich source of metrics that can be used to diagnose the equipment health. A new survival analysis methodology is proposed to develop the equipment hazard functions utilizing the available telematics data to: 1) identify equipment failure events and survival lives using the red and amber engine lights; 2) quantify the observed failure hazard probability using the reported engine hours; and 3) estimate the regression coefficients of the failure hazard covariates that are evaluated from a set of proposed telematics health parameters.

The proposed prognostics system was successful in developing the hazard functions of the analyzed equipment fleets that provided high fit to the observed data and high prediction accuracy for the testing data. For both analyzed fleets, higher predictive and data fitting performance were achieved for later life intervals due to the high tear and wear levels that results in increased failure probability.

The proposed telematics-based prognostics system should prove useful to equipment fleet managers to successfully implement predictive maintenance programs. The system would expand the current uses of telematics systems by transforming its timely data into useful decision making information. Future possible research venues of the developed system includes: 1) developing alternative telematics data-driven prognostics systems that utilize other statistical and probabilistic analysis approaches, such as logistic regression and fuzzy clustering; and 2) implementing the proposed prognostics system into an automated online or desktop prototype module that can be integrated into available telematics systems and fleet management operations.

References


CONSTRUCTION SPACE FLOAT DEFINITION, QUANTIFICATION, AND ANALYSIS

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Abstract: Schedule float is a fundamental concept in construction planning and control that refers to the flexibility of delaying project activities. However, traditional schedule floats offer limited help in congested construction sites and cannot answer a common field question of 'how much time is available to use this space to stage material?' This paper therefore presents the development of new theory and metrics of space float for construction activities based on a previously developed spatial scheduling model. It is structured into three main sections. First, it presents a review of a previously developed spatial scheduling model that utilizes singularity functions to represent and schedule activities as interdependent and overlapping workspaces. Second, it presents the different possible activity float types and the detailed calculation of activities shift float. Third, it describes the new space float algorithm to generate dynamic position float contours that change over the project time. The calculation of proposed activity and space floats are illustrated with an example of a small construction jobsite. The proposed concept has the potential to strengthen the relation between construction scheduling and other management functions, such as e.g. lean operations and material layout planning.

1 INTRODUCTION

All construction activities occur within their integrated environment of temporal and spatial constraints. While the time aspect has been thoroughly explored in construction scheduling, the linkage to the spatial dimensions has received less attention, potentially due to a lack of an integrated model that is able to jointly express these aspects mathematically, while adequately considering their very different nature: Time is a single dimension that can only move forward, inevitably passes whether progress is made on the jobsite or not, and is germane to all activities without being influenced by them. Space, on the other hand, has additional dimensions of the workspace wherein each productive activity occurs, which can move into either direction or remain stationary, and is typically occupied exclusively by a single activity and thus represents an important resource of limited availability. Previous research (Lucko et al. 2014a) has introduced how to mathematically describe both time and space with singularity functions - spatial scheduling, as is explained in the following section – but has not yet examined the float that is generated in such schedules, which will provide valuable information to the project manager about the criticality and flexibility of activities at different locations. The model assumes that spatial height can be simplified based on a safety rule that no two activities work underneath one another. Scheduling with explicit consideration of a spatial aspect thus has potential to improve efficiency while fulfilling constraints and ensuring safety.
Relevant previous studies can be clustered into four main areas, spatial float analysis, modeling activity workspaces, spatial scheduling, and space criticality. First, studies of spatial float were performed for one-dimensional linear schedules. The application of total float and rate float concepts in linear schedule were investigated by Awwad and Ioannou (2007), Ammar (2003), and Harmelink (2001). In addition, Kallantzis and Lambropoulos (2004) developed a methodology to determine the critical path and segments within a linear schedule. Lucko and Peña Orozco (2009) formulated diverse float types (total, free, interfering, independent, and safety) in linear schedules using singularity functions. Second, studies developed formulation and conflict analysis methodologies of construction activity workspaces using 4D topological metrics (Chua et al. 2010; Su and Cai 2014a/b), GIS (Bansal 2011), CAD (Gu 2002), and taxonomies (Akinci et al. 2002). Third, spatial scheduling systems were developed to generate and track construction schedules considering their spatial needs and behaviors. Thabet and Beliveau (1994) created a system that formulates and quantifies the workspaces of construction activity to be considered in sequencing of the work. Mallasi (2009) developed a 4D optimization model in search of an optimum execution strategy to minimize the conflicts between activity workspaces. Esfahan et al. (2013) described spatio-temporal schedule tracking and updating of resource movements through an enveloping prism of maximum and minimum expected progress rates. Fourth, Winch and North (2006) were explicit in acknowledging the job site space as a resource and developed a system that reports its overloading by activity workspaces.

Despite the contributions of these diverse previous studies, no methodologies or metrics were developed to quantify float of activities in two-dimensional (2D) spatial schedules (Lucko et al. 2014b). Absence of float in spatial schedules prevents project managers and schedulers from being able to properly evaluate the impact of potential delays and interruptions within its actual physical environment. Furthermore, the newly envisioned space float metric can be used as a link between the managerial tasks of construction scheduling and job site layout planning. Accordingly, this paper presents new methodologies to quantify activity and space floats by using singularity functions. The following sections will therefore sequentially explain the application of singularity functions in spatial scheduling, the new metrics of activity floats (shift, rate, and combined), space float quantification and contours for individual positions, and the illustration of the proposed methodology by calculating the new activity and space floats of an application example.

2 SPATIAL SCHEDULING USING SINGULARITY FUNCTIONS

Singularity functions are mathematically defined so that they can specifically express singularities, which are locations of discontinuities in the value or behaviour of a function. They employ an operator that is denoted with pointed brackets ⟨ ⟩ and a shape exponent \( n \) to indicate the type of behaviour — constant, linear, quadratic, etc. — that is being modeled. Within the brackets, the activation cutoff \( a \) is compared to the input \( x \) to determine whether the entire function \( f(x) \) remains zero or yields a non-zero value. Finally, the strength factor \( s \) determines the intensity of whatever behaviour \( n \) provides. Equation 1 provides the operator for a single term. As each term only captures exactly one behaviour (from its activation onward), multiple terms are added to compose any more complex singularity function. Multiple singularity functions can be added; multiple terms can be simplified if they have an identical activation \( a \) and exponent \( n \).

\[
\begin{align*}
t(x) &= s \cdot \langle x - a \rangle^n \\
&= \begin{cases} 
0 & \text{if } x < a \\
0 & \text{if } x \geq x
\end{cases}
\end{align*}
\]

To express one activity within a linear schedule, which measures quantity of work and durations across time, the former is selected as the independent variable \( x \) and the latter as the dependent variable \( t(x) \) (Lucko et al. 2014b) as Figure 1 shows. The reason is that time is typically supposed to be minimized on construction projects, while work is a given input. For an activity with start position \( a_s \) (often zero) and finish position \( a_f \), a start time of \( t_s \) and a productivity of \( \Delta x \) work units that are produced in \( \Delta t \) time units, the singularity function is \( t(x) = t_s \cdot (x - a_s)^0 + \Delta t/\Delta x \cdot [(x - a_s)^1 - (x - a_f)^1] - \Delta t^2/(x - a_f)^2 \cdot 0 \), where \( t_s \) is an upstep on the time axis (intercept), \( \Delta t/\Delta x \) is a slope (inverse of productivity, due to charting time over work). The singularity function models the activity: 1) Its first term adds the activity start \( t_s \) to the schedule only between the its start and finish positions, 2) the second term adds its rate of progress and removes it beyond its finish position \( a_f \), else this activity would continue to produce forever; and 3) the last term
removes the activity duration $\Delta t$ beyond its finish position $a_{xF}$, which is accumulated by the second term. By evaluating such equation for any work quantity, the time when it will be completed can be determined.

$$t(x) = s \cdot (x - a)^n$$

![Nonlinear Singularity Function](image)

![Linear Singularity Function](image)

![Linear Activity as a Singularity Function](image)

**Figure 1: Singularity Functions and Their Use to Represent Linear Activities**

### 2.1 Activity Progress Representation

Previous work by the authors has broadened the definition of Equation 1 beyond its confines of a single independent variable (Lucko et al. 2014a). Since activities are located within the site, a two-dimensional plot of land, reflecting it in the planning and scheduling effort adds realism and value, because it enables that spatial interaction can be modeled and analyzed. Thus each activity can be located by its coordinates on two length axes $x$ and $y$. The third dimension – height – is beyond the scope of this research and will be addressed in future work. Activities are assumed to progress parallel to one or both axes as follows:

- Activity may be stationary and completely occupies an $x$-$y$-area for a specific period of time;
- Activity can only progress into positive, negative, or both positive and negative $x$-direction;
- Activity can only progress into positive, negative, or both positive and negative $y$-direction;
- Activity can progress into a combination of positive or negative $x$-direction and $y$-direction.

Equation 1 can only express progress in terms of the plane of time $t$ over a single length axis. Viewing a projection of the progress along both $x$ and $y$ provides a solution to the challenge of how to extend the model into the third dimension: Combining projections in the $x$-$t$-plane and $y$-$t$-plane via their common variable $t$. Each projection is a regular singularity function per Equation 1 of order $n = 0$ for a stationary activity or $n = 1$ for a directional one. Equation 2 models an activity with three dimensions, two of space and one of time. Its ranges are $[a_{xS}$ to $a_{xF}]$ on the $x$-axis and $[a_{yS}$ to $a_{yF}]$ on the $y$-axis, respectively. In this example, it grows into the positive $x$-direction as a multiplicative combination of linear behaviour in the $x$-$t$-plane and constant behaviour in the $y$-$t$-plane. All other such directions can be modeled analogously.

$$t(x,y) = t_s \cdot \left[ (x-a_{xS})^0 - (x-a_{xF})^0 \right] \cdot \left[ (y-a_{yS})^0 - (y-a_{xF})^0 \right]$$

$$+ \frac{\Delta t}{\Delta x} \cdot \left[ (y-a_{yS})^0 - (y-a_{yF})^0 \right] \cdot \left[ (x-a_{xS})^1 - (x-a_{xF})^1 \right]$$

The last terms in Equation 2 subtract slope and height at $a_{xF}$ to ensure that the activity does not continue to occupy space beyond its boundaries. If it is only evaluated for values within valid $x$- and $y$-ranges, it is not strictly necessary to subtract the duration (height on the $t$-axis) that the activity has consumed beyond $a_{xF}$ to yield correct results. Indeed, even the negative terms in the rectangular brackets could formally be omitted, and are merely used to convey the information about the upper boundary of the interval itself.
2.2 Activity Relation Types

Activities are modeled as entities with distinct boundaries on all axes. To create a complete and feasible schedule, one must define the types of relations that can exist between pairs of activities. For the model of a schedule that considers space, two main categories of relations will be distinguished in this study:

- Sequential activities are connected by finish-to-start relations due to resource or technical constraints;
- Concurrent activities can be dependent or independent and their ranges overlap along the time axis.

Figure 2 shows an example of two activities A and B in an x-y-plane (floor plan view) with their coordinate ranges between their respective start and finish and directions of progress. Three possible constellations are illustrated in their x-t-planes: (a) a sequential relation with an intermediate time buffer $\text{buff}_{AB}$ between any locations of A and B that prohibits overlap in time, (b) a relation that allows concurrency for A and B to occur partially overlapping in time, but maintain their dependency and buffer at any location, and (c) a relation that allows unlimited concurrency between independent A and B. Scheduling these activities into such constellations uses the spatial scheduling algorithm that is briefly explained in the following section.

![Diagram showing types of relations between activities in spatial scheduling]

Figure 2: Types of Relations between Activities in Spatial Scheduling

2.3 Spatial Scheduling Algorithm

The previously introduced spatial scheduling algorithm handles time and space constraints of activities to compose a feasible schedule (Lucko et al. 2014b) with heuristics to select among options in each step:

1. Activities are sorted by priority, which depends on the particular heuristic that is chosen by the user;
2. The next activity is selected and initialized by expressing it in form of a spatial singularity function;
3. One permissible progress direction of the activity is evaluated and its possible start time is calculated;
4. Repeating Step 3, the earliest (minimum) start time determines the selected actual progress direction;
5. Repeating Steps 2 through 4, successor activities are handled in the same manner until none remain;
6. Final singularity functions are written and starts, finishes, and directions of all activities are reported.

3 ACTIVITY FLOATS

Space float can take different forms, both due to the geometric constellations that activities can generate among themselves within a space schedule, subject to constraints, and due to the different ways in which it can be consumed by activities, as Figure 3 shows. In general, float is viewed as flexibility of an activity to mitigate a delay by postponing its start and/or finish. It is assumed that this occurs locally, i.e. between the current activity and its direct successor(s). This bears an analogy to the free float in CPM schedules, which is measured only between adjacent activities and is not shared along an entire path like total float. However, this is where the analogy between one-dimensional network schedules (time only) and three-dimensional space schedules ends, because CPM float are just single values of time without any spatial components, whereas space float takes a shape within the integrated temporal and spatial environment. Moreover, CPM float does not provide any information about its potential use, as opposed to space float.
3.1 Overview of Activity Float Types

Figure 3 shows an example with the predecessor A and successor B and their time buffer \( \text{buff}_{AB} \). They share an overlap zone in the \( x\)-\( y\)-plane. Assuming that they respective starts, finishes, and directions have been obtained in a previous analysis with the spatial scheduling algorithm, the questions remain if A has float and how much, of what type, and where. Therefore, the following definitions are established:

- **Shift float** (SF) is consumed by delaying both the start and finish of an activity, i.e. preserving its productivity and thus duration \( F_A - S_A \), but shifting its entire execution to a later interval on the \( t\)-axis;
- **Rate float** (RF) is consumed by delaying only the finish of an activity, i.e. modifying its productivity to a lower value and thus extending its duration by rotating its progress slope upward in the \( x\)-\( t\)-plane;
- **Combined float** (CF) can be consumed as shift or rate float, depending on need or user preference.

These float types can be determined for the previously discussed sequential or concurrent relation types. For brevity, only shift float will be discussed in detail and rate float is left to be studied in further research.

3.2 Activity Shift Float Calculation

Shift float, which has been defined in the previous section, is illustrated with an example of two activities per Figure 4. For illustration A and B progress into different directions. It is calculated in several steps:

1. Determining the overlap zone of both activities from the maximum of the activity start coordinates on both \( x\)-axis and \( y\)-axis to the minimum of the finish coordinates on both geometric axes. This example has a valid overlap zone with \( x\)-range = \{0 to 13\} and \( y\)-range = \{0 to 20\}. Activities in other examples may not overlap at all, which would end the shift float calculation for such activity pair at this step;
2. Establishing singularity functions for A and B per Equation 2, here \( f(x, y) = 6 \cdot [(x - 0)^0 - (x - 28)^0] \cdot [(y - 0)^1 - (y - 20)^1] + \frac{14}{28} \cdot [(x - 28)^0 - (x - 28)^1] \cdot [(y - 0)^0 - (y - 20)^0] \cdot [(x - 28)^0 - (y - 28)^1] \cdot [(y - 0)^0 - (y - 20)^0] \cdot [(y - 20)^1 - (y - 20)^0] \). Note that B is growing into the negative \( y\)-direction, which is mathematically expressed with a large upset followed by a negative slope into the positive \( y\)-direction. In other words, it is modeled from its finish to the start of the activity, which mathematically is equivalent to viewing it from its start to the finish, because singularity functions do not distinguish the meaning of start and finish, only cutoff points in a shape where any behaviour is activated or deactivated. Thus the successor activity is expressed as \( f(x, y) = 45 \cdot (x - 0)^0 \cdot (y - 0)^1 - 15/25 \cdot [(x - 0)^0 - (x - 13)^0] \cdot [(y - 0)^0 - (y - 25)^0] - (45 - 15) \cdot (y - 25)^0 \);
3. Modifying \( f(x, y) \) toward the equation for \( \text{buff}_{AB} \), which can be modeled with a singularity function in the same manner by setting its start to \( t_s + \text{buff}_{AB} \), which assumes that the time buffer has a constant value. A variable time buffer could be modeled in analogy to Equation 2, but is omitted for brevity;
4. Identifying the minimum of B as \( t_s + \text{buff}_{AB} = 30 \) and the maximum of \( f(x, y) \) at any location, not just corners of the overlap zone, which here is \( t_fA + \text{buff}_{AB} = 20 + 6 = 26 \). Their \( t\)-difference is \( 30 - 26 = 4 \), i.e. activity A has 4 hours for shift float (SF\(_{AB}\)) under the stricter sequential relation with activity B;
5. For the more efficient concurrent relation, while still maintaining dependency of A and B, shift float per Figure 3 is calculated as the minimum time distance between them in the overlap zone, less \( \text{buff}_{AB} \). The equation for \( \text{buff}_{AB} \) would be identical to \( f(x, y) \), except for its intercept \( S_{\text{buff}_{AB}} = 6 + 6 = 12 \). As the buffer here has a constant value, in the following calculation it will be simply subtracted from \( t_b - t_A \). The difference equation can be interpreted as expressing the volume between these two activities;
6. Evaluating this difference equation at all corner coordinates of the overlap zone and identifying shift float as their minimum (after deducting the required buffer). As listed in Table 1, the time difference between the singularity functions of A and B is calculated as \( t_{1} \) at \( \{0, 20\} \), \( t_{2} \) at \( \{13, 20\} \), \( t_{3} \) at \( \{13, 0\} \), and \( t_{4} \) at \( \{0, 0\} \). It is calculated by subtracting the required buffer (6 hours) from the minimum of the overlapping time differences (20.5 hours), which results in shift float \( SF_{AB} = 14.5 \) hours. Note that the shift float for the case of a concurrent relation is more than the float that can be realized for the more strict sequential relation. This fact should be considered in the field to encourage concurrent relations between activities to improve construction schedules in terms of increased opportunities from float;

7. Note that due to the right-continuous definition of Equation 1, finish coordinates are evaluated at an infinitesimal distance before the cutoff, at which the singularity function is already reset to zero. Note that in this example, A and B have perpendicular progress directions in their projection into the x-y-plane of Figure 4 (different from the example of Figure 3), so that at \( \{13, 20\} \) they are already in close proximity. For parallel progress directions, the concurrent shift float could potentially be even larger;

8. Shift float (shifting) is measured as duration, e.g. workdays, whereas rate float (rotating) – that future research will investigate – is measured as duration divided by length; a change in the progress rate.

Figure 4: Example of Activity Shift Float Calculations

Table 1: Activity Shift Float Calculations for the Example in Figure 4

<table>
<thead>
<tr>
<th>Corner</th>
<th>x [m]</th>
<th>y [m]</th>
<th>( f(x, y)_{A} ) [h]</th>
<th>( f(x, y)_{B} ) [h]</th>
<th>( t_{1} )</th>
<th>( t_{2} )</th>
<th>( t_{3} )</th>
<th>( t_{4} )</th>
<th>( SF_{AB} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>20</td>
<td>33</td>
<td>6</td>
<td>33 - 6 = 27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>20</td>
<td>33</td>
<td>12.5</td>
<td>33 - 12.5 = 20.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>0</td>
<td>45</td>
<td>12.5</td>
<td>45 - 12.5 = 32.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>45</td>
<td>6</td>
<td>45 - 6 = 39</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shift Float between ( SF_{AB} = \min(t_{1}, t_{2}, t_{3}, t_{4}) - \text{buffer} = \min(27, 20.5, 32.5, 39) - 6 = 14.5 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4 POSITION SPACE FLOAT

Position space float \( PF(x, y, t) \) is a new schedule float metric that is calculated for any coordinates \( \{x, y\} \) of the project jobsite at time \( t \) of the project duration. It is the amount of time that is available to use the said location at time \( t \) before it will be occupied by the earliest successor activity whose workspace includes this point also. A new algorithm is developed to calculate \( PF(x, y, t) \), which is explained by continuing the example of Section 3 as shown in Figure 5. The new position float algorithm has five steps that are illustrated by calculating it at coordinates \( P = \{6, 10\} \) and \( Q = \{28, 25\} \) for the project start \( (t = 0) \):

1. The execution times \( t(6, 10)_{A} \) and \( t(6, 10)_{B} \) of activities A and B at position P are calculated from their singularity functions. Accordingly, \( t(6, 10)_{A} \) is calculated as 9 hours, and \( t(6, 10)_{B} \) is calculated as 39;
2. The earliest execution time (EET) is defined as the minimum value of any successor activities that are scheduled at position P, which here is calculated as the minimum of t(6, 10)\textsubscript{A} and t(6, 10)\textsubscript{B} as 9 hours;

3. The position space float PF(x, y, t) is calculated as the difference between EET and the current time t that must be known. Accordingly, at position P = (6, 10) at time t = 0, here its PF(6, 10, 0)\textsubscript{P} = 9 hours;

4. If no successor activities are executed at the position that is analyzed, its PF is simply the difference between project finish and current time. Thus at Q = (28, 25) at t = 0, the PF(28, 25, 0)\textsubscript{Q} = 45 hours;

5. The previous steps can be applied to all discrete positions within the jobsite to generate position float contours for any time of interest. Figure 5 shows the position float contours for this example at t = 0. Position float contours will dynamically vary across the jobsite as time passes until the project finish.

![Figure 5: Example of Position Float Calculations](image)

5 APPLICATION EXAMPLE

Calculating the new activity and position float metrics are illustrated in an application example that follows the approach that Lucko et al. (2014a) had originally analyzed. It comprises nine construction activities of a slab-on-grade (SOG) and underground utilities (electrical and drainage) as Figure 6 shows. Its activities are one-directional (B, C, D, E, G, and H); two-directional (A and I), or stationary (F). Resource-driven relations are considered between those of the same trade, e.g. electrical (B, C, D, E, and F) or drainage activities (G, and H). SOG concrete pouring activity (I) has a finish-to-start dependency with all activities, while rebar placement (A) has a concurrent relation with its predecessors (F, G, and H). The mentioned spatial scheduling model (Lucko et al. 2014a) generated the space schedule. Its optimized total project duration is 53 hours. The final scheduled direction, start, and finish of each activity are listed in Table 2.

<table>
<thead>
<tr>
<th>Number</th>
<th>Activity Name</th>
<th>Duration [h]</th>
<th>Direction</th>
<th>S [h]</th>
<th>F [h]</th>
<th>SF [h]</th>
<th>RF [h/m]</th>
<th>CF [h.m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>16</td>
<td>Pos. x</td>
<td>6</td>
<td>26</td>
<td>0</td>
<td>0</td>
<td>750</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>24</td>
<td>Pos. x</td>
<td>25</td>
<td>28</td>
<td>0</td>
<td>0</td>
<td>375</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>14</td>
<td>Pos. y</td>
<td>31</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>6</td>
<td>Pos. x</td>
<td>28</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>375</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>14</td>
<td>Pos. y</td>
<td>33</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>450</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>6</td>
<td>Stationary</td>
<td>0</td>
<td>8</td>
<td>12</td>
<td>0</td>
<td>1400</td>
</tr>
<tr>
<td>7</td>
<td>G</td>
<td>16</td>
<td>Pos. x</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>H</td>
<td>20</td>
<td>Pos. x</td>
<td>8</td>
<td>16</td>
<td>8</td>
<td>0.8</td>
<td>437.5</td>
</tr>
<tr>
<td>9</td>
<td>I</td>
<td>10</td>
<td>Neg. y</td>
<td>37</td>
<td>53</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Spatial Scheduling Results and Activity Floats of the Application Example
Calculated floats of the activities indicate a high criticality of the generated schedule due to its assumption that activities are continuously executed without interruptions. Table 2 shows that all activities have zero shift and rate floats, except for F and H. Activity F has $S_F = 12$ hours but zero rate float, because it is a stationary activity that occupies its whole workspace during its duration (i.e. it does not have a progress rate). Its shift float is realized as the critical time difference with its concurrent successor A. On the other hand, H has both shift and rate floats, which are also determined based its concurrent successor A. Other activities have combined floats, but have zero shift and rate floats. This is due to the assumption in the new float metrics that activity interruptions are not allowed, which prevents utilizing the available spatio-temporal combined floats between the activities in the form of either shift or rate float unless it is explicitly permitted. It should be noted that activity I has zero floats because it is the finishing activity of the project.

![Figure 6: Application Example and its Spatial Schedule (after Lucko et al. 2014b)](image)

Position float contours provide a clear visual assessment of the space criticality and availability. Figures 7 and 8 depict the generated position space floats at two sampled times $t = 0$ and $t = 33$. At the project start $t = 0$, no float exists at the positions of G and F, because they are initial activities of the project (Figure 7). The entire workspace of F has zero float because of its stationary nature. On the other hand, G has zero float only at its start $x = 0$ between $y = \{10$ to 15$, \}$, because it is a one-directional activity that is scheduled to progress into the positive x-direction. At $t = 33$ (Figure 8), E has the least float, because it will start at the analyzed time ($S = 33$, as listed in Table 2). The longest position space float of 20 hours is at the edge of I ($y = 0$), because it is the final activity of the entire project, progressing into the negative y-direction.

![Figure 7: Position Float Contours of the Application Example ($t = 0$)](image)
6 CONCLUSIONS AND RECOMMENDATIONS

- This paper has provided an overview of a newly developed spatial scheduling model wherein singularity functions express the geometry and progress of each activity. However, previous research had not yet provided any metrics of space float (including criticality of activities without such flexibility). Therefore, shift, rate, and combined float have been discussed, and position float contours have been introduced. Together, they provide a detailed view of the spatio-temporal constraints and opportunities that exist within a project schedule from a spatial perspective. In summary, it is envisioned that spatial scheduling and floats can greatly support professionals in the construction industry in integrating space-aware project schedules, designing efficient site layouts, and facilitating lean execution of their construction activities.

- Future research should mathematically extend the new model with its two dimensions of space and one dimension of time to more dimensions, including height or even other aspects, such as e.g. cost, by generalizing the multiplicative approach (Lucko and Su 2014), even if it cannot be visualized completely.

References


PREDICTIVE MODELING OF PREFABRICATION FEASIBILITY FOR THE UNITED STATES ELECTRICAL CONTRACTING FIRMS

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Abstract: Electrical contractors have promoted offsite prefabrication after experiencing its potential in improving their operations. However, prefabrication is not a one solution that fits all. Accordingly, there is a need to develop better understanding of prefabrication feasibility for electrical contractors by analyzing its operational requirements and surrounding industry factors. The objective of this paper is to identify and model the determinants of electrical contractors’ prefabrication feasibility within the U.S. industry context, which can be used to predict the viability of prefabrication as a production approach for individual electrical contracting firms. The methodology of this study included four main phases. First, a qualitative analysis was performed to initially understand current prefabrication operations and practices of electrical contractors through a set of semi-structured interviews, site visits of prefabrication facilities, and prefabrication case studies. Second, a quantitative data collection task was performed by: 1) acquiring the internal business variables of a sample of electrical contractors using an online questionnaire; 2) complementing the questionnaire data with location-based economic data to represent external industry-related variables. Third, the collected data was used to develop and validate a binary logistic regression model that relates the prefabrication feasibility to its significant determinants. Fourth, a sensitivity analysis was performed for the developed model to provide a larger understanding of electrical construction prefabrication feasibility beyond the collected data. The developed predictive model provides useful insights about prefabrication feasibility dependency on union relations, labor conditions, market competition, supply chain relations, and building information modeling.

1 INTRODUCTION

Offsite prefabrication has been practiced in the construction industry for decades due to its clear benefits in reducing project duration and cost. Offsite prefabrication was identified as one of promising breakthroughs that can greatly improve the productivity of the construction industry (NRC 2009). Prefabrication can be applied with different extents for the typical systems and components of building projects. Building electrical systems provide great prefabrication opportunities due to their modular decomposition into standardized components and subsystems. For example, electrical systems are typically decomposed into panels, ducts, cables, receptacles, and rough-in supports. Due to their standardized modular structure, electrical and mechanical systems were reported to be as the most building components that can be constructed using offsite prefabrication operations (MHC 2012).
Electrical construction has been the subject of several previous research studies, but with little attention to prefabrication. Previous electrical construction research included: 1) schedule coordination between mechanical, electrical, and plumping (MEP) trades (Korman et al. 2003, Horman et al. 2006); 2) management of contract changes by electrical contracts (Hanna et al. 2004); 3) utilization of Building Information Modeling (BIM) in electrical construction (Khanzode et al. 2008, Hanna et al. 2014); 4) design-build considerations for electrical contractors (EC) (Rowings 2000); and 5) financial analysis of electrical contractors (Jaselskis et al. 2002). Few research studies were performed to analyze prefabrication practices of electrical contractors. First, Bogus et al. (2009) performed an industry study to identify the best practices of electrical construction prefabrication, through observing the prefabrication facilities of a sample of electrical contractors. Second, Mikhail (2014) performed a survey-based study of prefabrication practices of electrical contractors. The major findings of this study include: 1) the use of electrical prefabrication has increased by 9% over the period 2004 – 2014; 2) the majority of survey respondents still limit their prefab operations between 1% – 9% of their work volume (measured in labor hours); 3) electrical contractors experienced cost reductions in 97% of their projects; and 4) electrical prefabrication helped to achieve time savings in 94% of the projects.

The findings of the previous research studies documented the best practices and benefits of prefabrication, but did not analyze its determinants to be a feasible production approach for electrical contractors. Prefabrication is not a one solution that fits all electrical contractors, and its successful implementation is dependent on internal and external factors that influence its economic feasibility. A previous study (Mikhail 2014) investigated the internal and external drivers/impediments of electrical construction prefabrication. However, there is no quantitative tool that can predict for electrical contractors the feasibility of adopting prefabrication operations considering firm’s internal and external variables.

2 RESEARCH OBJECTIVE AND METHODOLOGY

The objective of this paper is to develop a data-driven predictive model of prefabrication feasibility of electrical contractors. To achieve this objective, the research methodology included four main phases. First, qualitative data of electrical construction was collected by interviewing industry professionals, visiting prefabrication facilities, and acquiring case studies of prefabrication work. Second, electrical construction prefabrication was qualitatively analyzed by interviewing a sample of electrical contractors, visiting their prefabrication facilities, and collecting case studies of prefabrication assemblies and projects. Third, the collected data is used to develop and validate a logistic regression predictive model of prefabrication feasibility that considers electrical contractor’s internal and external attributes. Fourth, the behavior of the proposed system is evaluated using multi-variable sensitivity analysis to better understand the impact of the model’s selected variables on the prediction of prefabrication feasibility.

3 QUALITATIVE ANALYSIS OF ELECTRICAL PREFABRICATION

Qualitative analysis of electrical construction prefabrication was performed using interviews, site visits, and case studies to obtain an in-depth understanding of prefabrication operations and drivers. The outcome of the qualitative analysis is the development of initial list of potential drivers/determinants of electrical prefabrication feasibility that will be considered in the next phase of collecting their quantitative values and developing the predictive model. The qualitative analysis was facilitated by a taskforce of electrical construction professional, which was formed by ELECTRI International Foundation to support this research study.

First, the taskforce members and other industry professionals were interviewed in a semi-structural setting to answer a set of open-ended questions (Patton 2002) about the impact of project supply chain stakeholders (designer, general contractor, vendor, manufacturer) on electrical construction prefabrication; as well as the impact of firm’s external environment on its prefabrication operations (i.e. union relations, labour hourly rates, etc.). The interviews were performed with 7 operation managers of different electrical construction companies, 1 vendor representative, 3 manufacturer sale managers and 1 executive director of a local chapter of the National Electrical Contractors Association (NECA). Second, the prefabrication facilities of a large and small electrical contractor were visited to observe on the ground their operations and document the interfaces between the facility, site work, and vendors. Third, case
studies were collected for electrical prefabrication coordination in construction projects, layout and equipment of prefabrication facilities, and samples of prefabricated electrical assemblies.

4 QUANTITATIVE DATA COLLECTION

Considering the observations and findings of the previous phase, prefabrication-related internal and external quantitative data of a sample of electrical contractors was collected using web-based questionnaire and available online governmental economic databases.

4.1 Web-based Questionnaire

A web-based questionnaire was designed and disseminated to NECA’s electrical contractors with the objective of identifying the level of their prefabrication operations, firm business attributes, and external industry parameters. The questionnaire included 26 questions, including the following that were utilized in this study:

1) Which of the following percentages represent the prefab facility contribution to the total work volume? (N/A, <5%, 5%-10%, 10%-20%, 20%-40%, >40%)

2) What is the annual volume of your work? (<$5M, $5M-$10M, $10M-$50M, $50M-$100M, $100M-$200M, >$200M)

3) What is the zip code of your FARTHEST project?

4) Which of the following services are provided by your company? (Engineering, BIM, Prefab, Maintenance)

5) Which of the following lean principles do you apply in your operations (either onsite or offsite)? (Last Planner System, Look-ahead schedules, Kanban, Value Stream Mapping, Kaizen, 5 S’s, none.)

6) Do you have a vendor partnership in place? (Yes, No.)

7) Which of the following value-added services have you obtained from your vendor(s)? (provided 11 possible services, like Managing material/tools inventory, Using vendor warehouse to store in-transit assemblies/material deliveries, material Packaging/kitting, and others)

8) How do you classify your vendor/distributor? (Local 1 state, Regional 4 states, National 10 states)

9) How frequent did you have your vendor involved early in an Integrated Project Delivery (IPD) setting? (>50%, 30%-50%, 10%-30%, <10%, Never)

10) Select from the following list the manufacturer’s services/programs that your firm used before, if any. (Training workshops, Products customization, Custom Packaging, Materials Logistics.)

11) What is the zip code of your main office?

12) In your opinion, how much flexibility do current electrical specification writers provide for electrical contractors to perform offsite work and achieve construction industrialization? (Very flexible, Flexible, No effect, Inflexible, Very inflexible)

13) How much resistance did/would your company experience with IBEW local for offsite work in your current/future prefab facility? (High resistance, Moderate resistance, Neutral, Encouraging, Very encouraging)

14) How much resistance did/would your company experience with IBEW local for outsourcing prefab work to either vendors or manufacturers? (same answer options of question 13)

The first question was used to identify the existence and size of the electrical contractor prefabrication operations. The second to the tenth questions were designed to collect firm-related business information related to the geographic spread of the company, type of services, adoption of lean principles, and supply chain relations with vendors and manufacturers. The last four questions (11 to 14) were included to collect relevant external industry-related attributes, such as the contractor location, union resistance to prefabrication, and flexibility of design and code requirements to prefabrication. The zip code is used to retrieve other industry economic data through available federal online databases, as explained later in section 4.2.

After a 5-month period of questionnaire online dissemination, 78 valid responses were received on a voluntary basis from a diverse sample of electrical contractors. The questionnaire was disseminated through NECA’s email list that included 2925 electrical contracting firms. 78 valid responses were
received with a response rate of 2.7%, which is similar to other previous study surveys that are based on voluntary participation (Galloway 2006, Rasdorf et al. 2010). There is no reliable source to identify the total population of electrical contractors and its ratio to the collected sample. As shown in Figure 1, the questionnaire sample is considered to be diverse and representative of the electrical construction industry. First, the sampled contractors are geographically dispersed as the responses were received from 32 states. Second, the sample included electrical contractors of diverse backgrounds in terms of company size (measured in work volume) and amount of prefabrication. For example, 54% of the respondents perform prefabrication with varying capacities (between 5% to 40% of the total work volume), which closely matches a recent industry survey (FMI 2013).

![States of Questionnaire Responses](image)

**Figure 1: Questionnaire Response Sample**

### 4.2 Industry Economic Data

The data of each questionnaire response was complementing by retrieving the values of its location-based industry economic attributes from available online federal databases. As shown in Figure 2, online databases of the U.S. Census Bureau (USCB) and Bureau of Labor Statistics (USBLS) were used to retrieve the local industry economic data of every response in two main steps. First, the zip code value of the response (provided in the eleventh question of the questionnaire) is used to identify the county of the electrical contractor and then its metropolitan area. It is proposed here that the economic metrics of the larger metropolitan areas are more accurate regional indicators of the industry-related determinants of electrical contractor prefabrication feasibility, compared to the localized metrics in the city or county levels. Second, the identified metropolitan area is used to retrieve the following data from the online databases: 1) the unemployment rate from the USBLS local area unemployment statistics (LAUS) database (USBL 2014-a); 2) the number, total annual payroll, and average employees of electrical construction firms in the metropolitan area, which are retrieved from the USCB's County and Metropolitan Areas Business Patterns database (USCB 2014-b); and 3) the number and average hourly wage of electricians in the metropolitan area, which are obtained from USBLS’s Occupational Employment Statistics (OES) database (USBLS 2014-b).

![Diagram of Economic Data](image)

**Figure 2: Complementing EC Survey Data with Local Economic Indicators**
The collected economic data was utilized as indicators of the demand for construction projects, industry competition, and supply of electrical workers. Unemployment rate was proposed as indicator of the economic growth and demand for construction services around electrical contractors. Economic data of electrical contracting firms (number, total payroll and average number of employees) was used to gauge the size and level of competition around the electrical contractor. Finally, electricians' occupational data (number and hourly wage) was used to indicate the supply and demand of electrical construction workforce. All these industry parameters (construction demand, competition, labor availability) were proposed based on the performed qualitative analysis of electrical construction prefabrication and suggestions of the study taskforce.

5 DEVELOPMENT AND VALIDATION OF PREFABRICATION FEASIBILITY BINARY LOGISTIC MODEL

Logistic binary regression analysis was utilized to model the dependency of electrical construction prefabrication feasibility on its firm-related and industry-related determinants. As shown in Equation 1, prefabrication feasibility \( PF \) is modeled as a binary dichotomous variable (Tung 1985, Kleinbaum 1994) that can be one of either values: 1 (true, meaning that prefabrication is a viable operations approach for the electrical contractor) or 0 (false, meaning that there are no enough drivers to justify the feasibility of performing prefabrication operations). The \( PF \) value is determined based on the prefabrication feasibility probability \( p \) that ranges between 0 and 1. As shown in Equation 1, prefabrication feasibility is declared \( PF = 1 \) if \( p \) is less than a threshold value of 0.5 (as suggested by previous studies, Cheung et al. 2010, Moon et al. 2011), and is declared infeasible \( PF = 0 \) if \( p \) is more than or equal to 0.5. As shown in Equation 2, prefabrication feasibility probability \( p \) has an exponential relation with its determinants \( X_1 \) to \( X_n \). A determinate \( X_i \) will be a driver of the prefabrication feasibility (i.e. increasing its probability \( p \)) if its coefficient \( C_i \) is found to be positive. Otherwise, a determinant will be impediment to prefabrication feasibility with a negative coefficient. In order to estimate these coefficients using linear regression techniques, the prefabrication feasibility probability is transformed into its logit value and with a linear relation with its determinants, as shown in Equation 3. The logit function facilitates transforming the prefabrication feasibility probability \( p \) (with exponential values between 0 and 1) into a linear variable that ranges between \(-\infty\) and \(+\infty\) (Kleinbaum 1994).

\[
PF = \begin{cases} 
0 & \text{if } p < 0.5 \\
1 & \text{if } p \geq 0.5 
\end{cases}
\]

\[
p = \frac{1}{1 + e^{-(C_0 + C_1X_1 + C_2X_2 + \ldots + C_nX_n)}}
\]

\[
\text{logit}(p) = \ln\left(\frac{p}{1-p}\right) = C_0 + C_1X_1 + C_2X_2 + \ldots + C_nX_n
\]

Twenty electrical prefabrication determinants were initially considered in the development of the logistic regression model, based on the performed qualitative analysis and collected data. The initially considered determinants included 11 firm-related variables and 9 industry related variables, which include:

1) Volume of Firm's Annual Work (workVolume, firm-related): this variable represents the EC size that may financially justify owning and running a prefabrication facility, which ranges between 1 (work volume is less than $5M) and 6 (more than $200M).

2) Business Territory Coverage Distance (coverDistance, firm-related): it is calculated as the driving distance between the firm’s main office and farthest project.

3) Engineering/Design Services (engDesign, firm-related): it is a binary variable that refers to the existence of electrical engineering/design capabilities within the company (i.e. 1) or otherwise (i.e. 0).

4) BIM Capabilities (BIM, firm-related): it is a binary variable that can take a value of 1 to refer to the existence of firm's BIM capability, or 0 for otherwise.

5) Level of Lean Operations (lean, firm-related): it represents the number of lean management principles used by the EC. The value of lean level ranges from 0 to 6.
6) **Vendor Partnership Existence** (vendorPartner, firm-related): it is a binary variable that can be 1 when a vendor partnership exists; or 0 otherwise.

7) **Strength of Vendor Relationship** (vendorRel, firm-related): it refers to the number of value-added services offered by the vendor to the electrical contractor, which can range between 0 and 11.

8) **Existence of Material Blanket Prices** (blanketPrice, firm-related): it is a binary variable to indicate the existence of material blanket prices (i.e., its value equals 1) or none (i.e., 0).

9) **Vendor Size** (vendorSize, firm-related), it is modeled to take three values: 1 for local vendors, 2 for regional, and 3 for national.

10) **Vendor Early Involvement** (vendorEarly, firm-related): it ranges from 0 to 4, where 0 refers to no involvement and 4 refers to vendor’s early involvement in more than 50% of the projects.

11) **Strength of Manufacturer Relation** (ManufRel, firm-related): it refers to the number of services and programs offered by the manufacturer to the electrical contractor, which can range between 0 and 4.

12) **Prefabrication Flexibility of Electrical Specifications** (specsFlex, industry-related): it ranges between -2 and +2, where the lowest value (-2) refers to the most inflexibility of electrical specification writers to prefabrication changes.

13) **Metropolitan Unemployment** (unemploy, industry-related): it is the ratio of unemployed workforce across all industries, which is utilized as an indicator of the overall economic progress of the metropolitan area where the electrical contractor is located.

14) **Annual Payroll of Electrical Contracting Firms** (payroll, industry-related): it is used to indicate the volume of the electrical contracting industry (in $1,000) in the local metropolitan area.

15) **Number of Electrical Contracting Firms** (nFirms, industry-related): it is utilized to indicate the volume and competition level of the local electrical contracting industry.

16) **Average Number of Employees per Firm** (nEmploy, industry-related): it is used to indicate the average size of electrical companies and competition in the local metropolitan area.

17) **Electricians Employment** (electEmploy, industry-related): it is proposed as an indicator of labor supply and availability in the metropolitan area.

18) **Electricians Average Hourly Wage** (electWage, industry-related): it is utilized to reflect the labor cost as a major driver for prefabrication, per the performed interviews.

19) **Union Acceptance of Prefabrication** (unionPrefab, industry-related): it refers to the electrician union (IBEW) position towards contractors performing offsite work in prefabrication facilities, which ranges between -2 (high resistance) to +2 (very encouraging).

20) **Union Acceptance of Outsourcing** (unionOutsource, industry-related): it refers to the electrician union position towards contractors outsourcing some of the project work to vendors and manufacturers in the form of prefabricated assemblies.

Before performing the logistic regression analysis, the proposed variables were tested for multicollinearity to remove any strongly-correlated variables that may affect the quality of developed predictive model. Multicollinearity in the collected data can be detected considering the following two tests (Pallant 2010): 1) variables are significantly correlated with a Pearson correlation factor (R) more than 0.7; and 2) variables with large Variance Inflation Factor (VIF) more than 5. As such, the Payroll and nFirms variables were found to be a source of multicollinearity in the collected data, as they were significantly correlated (R = 0.981) and they had very high VIF value, 64 for Payroll and 54 for nFirms. Accordingly, the number of variables considered for the regression analysis was reduced to be 18.

The 78 valid responses collected by the questionnaire were divided into two groups (Yiu et al. 2006, Cheung et al. 2010): 1) an estimation data group of 70 responses, which was used to estimate the logistic regression model coefficients; and 2) a validation data group of 8 responses, which was used to test the prediction accuracy of the developed model. IBM SPSS Statistics 22 package was used to apply a forward step-wise binary logistic regression analysis on the estimation data group. As shown in Table 1, only 6 variables were included in the SPSS results with their coefficient values, standard error (S.E.), Wald statistic, and its significance level p-value. The two variables with the strongest significance (i.e., smallest significance p-value) in the model were found to be BIM and unionOutsource. The other variables had a medium significance of p-values between 0.05 and 0.07. In general, the model fits the collected data with an acceptable quality that is illustrated by its very low P-value, high pseudo Nagelkerke R-squares, and high correct classification rate (CCR%). Figure 3 illustrates the histogram of the correct/incorrect classifications of prefabrication feasibility (showed as 1) and infeasibility (shown as 0), as
calculated by the developed model. Equations 4 and 5 illustrate the prefabrication feasibility probability \( p \) in its final form.

\[
[4] \quad p = \frac{1}{1 + e^{-\logit(p)}}
\]

\[
[5] \quad \logit(p) = -6.821 + 6.5916 \cdot (BIM) + 2.577 \cdot (vendorPartner) - 0.784 \cdot (unemploy) + 0.3914 \cdot (nEmploy) + 0.2407 \cdot (electWage) + 1.9687 \cdot (unionOutsouce) +
\]

Table 1: Coefficients and Statistics of the Developed Logistic Regression Model

<table>
<thead>
<tr>
<th>Variables</th>
<th>Sample Average</th>
<th>Value</th>
<th>S.E.</th>
<th>Wald</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant ( C_0 )</td>
<td>--</td>
<td>-6.821</td>
<td>5.529</td>
<td>1.5220</td>
<td>0.2173</td>
</tr>
<tr>
<td>BIM</td>
<td>0.46</td>
<td>6.5916</td>
<td>1.8075</td>
<td>13.3</td>
<td>0.0003</td>
</tr>
<tr>
<td>vendorPartner</td>
<td>0.397</td>
<td>2.577</td>
<td>1.3891</td>
<td>3.4425</td>
<td>0.0635</td>
</tr>
<tr>
<td>unemploy</td>
<td>7.16</td>
<td>-0.784</td>
<td>0.4225</td>
<td>3.4474</td>
<td>0.0633</td>
</tr>
<tr>
<td>nEmploy</td>
<td>12.77</td>
<td>0.3914</td>
<td>0.2107</td>
<td>3.4515</td>
<td>0.0632</td>
</tr>
<tr>
<td>electWage</td>
<td>26.28</td>
<td>0.2407</td>
<td>0.1247</td>
<td>3.7243</td>
<td>0.0536</td>
</tr>
<tr>
<td>unionOutsouce</td>
<td>-1.128</td>
<td>1.9687</td>
<td>0.988</td>
<td>3.9686</td>
<td>0.0464</td>
</tr>
<tr>
<td>Model Overall P-value</td>
<td>2.6E-13 (( \equiv ) 0.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nagelkerke R(^2)</td>
<td></td>
<td>0.851</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCR%</td>
<td></td>
<td>90.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The prediction accuracy of the developed modeled was validated by calculating the electrical prefabrication feasibility values of the validation group data and comparing them to the observed values. Table 2 lists the validation values of the model variables, observed prefabrication state, calculated prefabrication probability and resulting prefabrication feasibility for the 8 cases of the validation data group. The shown medium prediction accuracy (CCR\% = 75\%) is considered within the acceptable range of 50\% - 100\% correct classifications (Pampel 2000). The validity and prediction accuracy of the model can be improved by collecting a bigger sample of electrical contractors, which is planned in future research studies.
Table 2: Validation Results of the Developed Logistic Regression Model

<table>
<thead>
<tr>
<th>Variables</th>
<th>Validation Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>BIM</td>
<td>0</td>
</tr>
<tr>
<td>vendorPartner</td>
<td>0</td>
</tr>
<tr>
<td>unemploy</td>
<td>9</td>
</tr>
<tr>
<td>nEmploy</td>
<td>14.7</td>
</tr>
<tr>
<td>electWage</td>
<td>30.48</td>
</tr>
<tr>
<td>unionOutsource</td>
<td>0</td>
</tr>
<tr>
<td>Observed Prefabrication State</td>
<td>No</td>
</tr>
<tr>
<td>Calculated Probability</td>
<td>0.312</td>
</tr>
<tr>
<td>Predicted Prefabrication Feasibility</td>
<td>No</td>
</tr>
<tr>
<td>CCR%</td>
<td></td>
</tr>
</tbody>
</table>

6 SENSITIVITY ANALYSIS

The behavior of the developed model was analyzed to obtain more insights about electrical construction prefabrication beyond the collected cases and data. As shown in Figure 4, two-way sensitivity analyses (Clemen and Reilly 2001, pp. 174) were performed to study the impact magnitude of the following example variables on the prefabrication feasibility prediction output of the proposed model: BIM, vendorPartner, nEmploy, and electWage. The other variables are assumed to take the value of a base case, which is modeled as the average value of the observed variables. The sensitivity analyses provided the following useful insights about electrical prefabrication feasibility:

1) Prefabrication feasibility increases with the escalation of the average local electrician wage (electWage) as indication of scarce labor supply and the need to deliver the projects with less labor hours using offsite prefabrication;

2) Prefabrication feasibility increases with the increase of local competition in the form of average employees per electrical construction companies (nEmploy), due the need to outperform the competitors in terms of project cost and time savings achieved by prefabrication; and

3) The contribution of BIM capabilities of increasing the feasibility of electrical prefabrication operation (i.e., the difference between cases A and C) is bigger than the contribution of having a vendor partnership (i.e., the difference between cases A and B).

Figure 4: Sensitivity Analyses of the Developed Model for four of its Variables
7 CONCLUSION AND FUTURE RESEARCH

This paper presents the development of a new predictive model of the prefabrication feasibility for electrical contractors. The development of the model was accomplished through four main phases. First, a qualitative analysis of electrical construction prefabrication is performed using interviews, site visit, and case studies to develop a better understanding of the drivers and impediments of electrical prefabrication. Second, quantitative data of the proposed prefabrication determinants were collected using a web-based questionnaire and online federal economic and occupation databases. Third, a binary logistic regression model was developed and validated using the data collected of a sample of electrical contractors. The logistic regression is designed to estimate the probability of prefabrication feasibility for electrical contractors, based on six identified significant determinants: BIM, existence of vendor partnership, local unemployment rate, average number of employees in local electrical construction companies (i.e. local competition), the local hourly pay rate of electricians, and the acceptance/resistance of electrical local union to outsourcing prefabrication services. Fourth, two-way sensitivity analyses were performed to analyze the impact of some of the identified determinants on the prediction outcome of the developed model.

The developed model should prove useful to both academic researchers and electrical construction professionals. The model supports the previous research on construction prefabrication in general and electrical prefabrication in specific by assessing the dependence of construction prefabrication feasibility on the contractor’s internal and external parameters. In addition, the developed model provides a data-driven tool to assess the feasibility of adopting prefabrication operations in comparison to their peers in the industry.

This research can be expanded in future studies to: 1) collected a larger data sample of electrical contractors to further validate and improve the prediction accuracy of the developed model; 2) apply the same methodology to other building construction trades (like mechanical, plumping, etc.) and analyze their differences and unique attributes; and 3) develop a web-based tool that facilitates the dissemination and use of the developed model by both academics and practitioners.

References


BUILDING A SUSTAINABLE OCCUPANT’S PERFORMANCE BASED MODEL FOR INSTITUTIONAL BUILDINGS

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Abstract: The Sustainable buildings main objectives are to reduce, or avoid, depletion of resources like energy, water, and materials; prevent environmental degradation caused by facilities during the life cycle of the building. Lighting is one of the major energy consumption in institutional buildings. At 2012, the commercial sector, which includes commercial and institutional buildings, and Public Street and highway lighting, consumed about 274 billion kWh for lighting or about 7 % of the USA consumption. Most of the research works have focused predominantly on the environmental and physical factors and have neglected the daily activities of the occupants. This study examines the effects of environmental, physical, and daily activities on occupants’ performance in the institutional buildings as well as develops a model to predict the occupants’ performance using Regression analysis technique. The data was collected from the institutional buildings occupants and building facility experts using questionnaire. The model has been validated with 92 % Average Validity Percent (AVP) and R square of 0.83 which is a satisfactory result. The developed research /model benefits both architects and practitioners to choose the appropriate workplace design due to the occupants’ preferences to enhance performance, and energy efficiency.

1 INTRODUCTION

Buildings are one of the major energy consumers in the U.S. as shown in Fig 1. Both commercial and residential buildings account for 42% of the national U.S. energy consumption. The majority of commercial buildings energy consumption is attributed to lighting (25%), space heating and cooling (25%), and ventilation (7%) (Azar and Menassa 2011a).

Lighting and HVAC energy used in buildings are considered the main consumers of the total buildings energy consumption. Nearly lighting energy used is responsible for 23%, Heating, ventilation and cooling accounting for 38% (Guo et al. 2010). In a recent study, in US commercial building, 25-40% of the total electricity energy consumption is from electrical lighting (Ihm et. al., 2009).
Building professionals’ significant role is how to reduce energy consumption as well as considerably maintain comfort to the occupants. Artificial lighting systems are considered as a major consumer of energy in buildings and contribute significantly to building cooling load. Daylighting has two fold; contributing in determine the overall environmental quality in buildings as well as saving energy (Alashwal and Budaiwi 2011). Before 1940s, daylighting was considered the main light source in buildings design. Recently, in sustainable buildings, daylighting is considered as energy and environmental aspect (Edwards and Torcellini 2002). In case of office lighting, the switching patterns along with the outside conditions are at the core of investigation from the occupants’ behavior point of view. One of the studies has culminated into the fact that as much as 40% energy conservation can be realized if natural light is relied upon compared to the artificial one (Bourgeois, Reinhart, and Macdonald 2006).

Therefore, the scope of the present study is to investigate the lighting preferences in commercial buildings with focus on the institutional buildings and develop a framework for predicting occupant’s performance.

2 RESEARCH OBJECTIVES

The objectives of the present study is to build a sustainable occupant’s performance based model for institutional buildings which can be summarized as follows:

i. Investigate and identify the factors affect occupants usage of lighting.

ii. Data collection from a real workplace

iii. Determine the significant factors that mostly contribute to the Lighting intensity in the workplace.

iv. Determine the factors that affect the occupants’ performance

v. Develop a model / framework based on these factors.

vi. Validate the developed model / framework

3 BACKGROUND

The most significant factors that influence the energy and indoor environmental performances of buildings are outdoor/indoor climate, building characteristics, and occupant behavior. The most important factor is human behavior, followed by building design. Indeed, there is often an obvious discrepancy between real
total energy use in buildings and what is predicted. The reasons for this gap are a general need to understand the role of human behavior within the buildings (Fabi et al. 2011).

Several studies (Carrico and Riemer 2011, Dietz et al. 2009, Henryson, Håkansson, and Pyrko 2000) have taken two different approaches can typically be used to reduce buildings’ energy use: First, the technological approach deals with more energy efficient building systems and equipment. Second, the behavioral approach focuses on understanding building occupant presence and behavior to measure actual energy consumption and develop best practices to encourage conservation (Azar and Menassa 2011b).

3.1 Occupants behavior

Occupants behavior definition is; “the result of a continuous combination of several factors crossing different disciplines.” The factors effecting occupant interactions with building control systems are classified into external and internal. The external factors which related to the building science area (e.g. outdoor and indoor temperature) can be categorized in two categories: the physical environment and the context. The internal drivers concern the social science area can be defined into three categories: physiological, social and psychological.

These External and Internal factors influence occupant behavior, defined as “Drivers.” Drivers can be defined as: “the reasons leading to a reaction in the building occupant and suggesting him or her to act.

3.2 Occupants interactions with indoor environmental controls

Several studies have investigated occupants’ preferences of the windows in their workplace; window size, position in the walls, and its degree of transparency (Galasiu and Veitch 2006). Many studies investigate the occupants interact with the lighting system without providing the occupants satisfaction or performance in the workplace.

These models predict how occupants interact to the lighting system depending on the lighting intensity, the occupant’s schedules and the surrounded factors to predict the occupant’s use of lighting, and therefore predict the lighting energy consumption as a result (Reinhart 2004; Bourgeois et. al. 2006).

It can be deduced here that the previous studies investigated the occupants’ behavior inside the workplace and the interactions with the environment; otherwise, the impact of the interactions on the consumption. These studies however seem to have overlooked the effect on lighting preferences in the workplace due to the difference in environmental, physical, occupants activities and the policies on the occupant performance.

To that effect, this study proposes the occupants’ preferences in the commercial building regarding to the lighting in the workplace has a significant effect on the occupants’ performance.

4 ACTORS AFFECT OCCUPANTS USAGE OF LIGHTING INCORPORATED IN THE CURRENT RESEARCH

Based on the above review of literature and focusing on the institutional buildings, the lighting preferences in institutional buildings that affect the lighting intensity in the workplaces are identified and selected as shown in Table 1. These factors are considered in the present study. Fourteen factors are incorporated in this research, which represents the environmental, physical, activities, and policies factors. The factors that influence occupants’ usage of lighting are hard to quantify and thus a qualitative approach is followed.
The factors selected to be incorporated in Regression analysis model are clustered into four main categories and their factors, as shown in Figure 3. The four main categories include environmental, physical, users and Tasks lighting required. Each category includes several factors.

<table>
<thead>
<tr>
<th>Category</th>
<th>variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Factors</td>
<td>Orientation</td>
<td>Well-orientated buildings maximize daylighting through building facades reducing the need for artificial lighting.</td>
</tr>
<tr>
<td></td>
<td>Time of Day</td>
<td>time of the day affects the lighting intensity; ex, before noon, at noon, after noon</td>
</tr>
<tr>
<td></td>
<td>Sky Condition</td>
<td>The brightness of the sky; ex, Full Daylight, Overcast Day, Dark Day</td>
</tr>
<tr>
<td></td>
<td>View out</td>
<td>the effect of view out windows on the daylighting preferences in the workplace</td>
</tr>
<tr>
<td></td>
<td>Glare</td>
<td>Glare is difficulty seeing in the presence of bright light such as direct or reflected sunlight</td>
</tr>
<tr>
<td>Physical Factors</td>
<td>Window size to Wall Ratio</td>
<td>the window size percentage to the wall ratio</td>
</tr>
<tr>
<td></td>
<td>glazing color</td>
<td>the effect of window glazing color on the daylighting intensity in the workspace</td>
</tr>
<tr>
<td></td>
<td>Seating position regarding to the window</td>
<td>the position of the seat to the window</td>
</tr>
<tr>
<td></td>
<td>Lighting location control regarding to the seat</td>
<td>the capability of controlling the artificial lighting in the workspace</td>
</tr>
<tr>
<td>Activities</td>
<td>Non-computer based Activities</td>
<td>ex; Reading, writing, meetings</td>
</tr>
<tr>
<td></td>
<td>Computer based activities</td>
<td>ex; typing, browsing, etc.</td>
</tr>
<tr>
<td>Policies and Incentives</td>
<td>Word Of Mouth</td>
<td>(Co-workers in the same space influencing each other's preferences)</td>
</tr>
<tr>
<td></td>
<td>Energy Awareness Campaigns</td>
<td>(Campaigns that increase awareness of energy and its impacts)</td>
</tr>
<tr>
<td></td>
<td>Financial Incentives</td>
<td>(Monetary or other material incentives for reducing energy use)</td>
</tr>
<tr>
<td></td>
<td>Feedback Techniques</td>
<td>(Employers providing workers feedback on their energy use behaviors)</td>
</tr>
</tbody>
</table>

The factors selected to be incorporated in Regression analysis model are clustered into four main categories and their factors, as shown in Figure 3. The four main categories include environmental, physical, users and Tasks lighting required. Each category includes several factors.

5 RESEARCH METHODOLOGY

To achieve the objectives of the present research, several steps are accomplished as shown in the schematic diagram Figure 4. The proposed framework for this project consists of 5 main steps. It starts with a comprehensive literature followed by data collection, which in itself consists of two parts studying the lighting factors that affecting the occupants usage and a semi structured questionnaire and open ended interviews is adopted in order to identify the occupants’ artificial lighting preferences due to environmental, physical and activities. A Regression Analysis model is developed using model information data which is then underwent a verification process. The next part of the research methodology is to develop a daylighting usage scale which will guide the architects to best design their office buildings. The model is used to assess daylighting efficiency in private and two-person offices.
Then develop lighting behavioral modeling using Regression Analysis. The last step is the conclusion and future research.

Figure 3: Hierarchical factors affect occupants’ usage of lighting

![Hierarchical factors affect occupants’ usage of lighting]

Figure 4: Research methodology

![Research methodology]
6 DATA COLLECTION

After identifying the lighting preferences factors that may affect the occupants performance, a questionnaire was prepared to assess the effect of these factors on occupants performance. The data is collected via a questionnaire collected form 87 occupants in the institutional buildings at Purdue University. The questionnaire was designed to identify factors that affect lighting intensity in the workplace and then to predict the occupants performance in an abstract approach. It had two parts where the first part (1) was asking the occupants how strongly the factors contributes to the daylighting intensity as shown in Figure 5. Part (2) was asking the occupants using a specified 5 point subjective scale to represent their performance. The data collected is the weights of various factors to be incorporated in the model and the performance of each factor.

This paper presents findings from a web-based survey on the current use of in building design. The survey was administered from October 2014 to December 2014. Two hundred and thirty four individuals from 5 institutional buildings at Purdue University completed the survey. The respondents are Faculty, staff and students have an office at Purdue University. They worked in offices with or without windows in the workplace.

Among those participants 134 about 59% who have windows in their workplace. The rest of them 92 respondents has no window and skipped from the questionnaire. The total respondents who complete the questionnaire are 87 respondents about 37% of the total respondents. See Fig 5 as sample of the questionnaire and Fig 6 the Questionnaire statistics.

![Figure 5: Sample of Questionnaire questions](image)

The following table collects the relative weights of **Environmental sub-factors** impacting the daylighting intensity in the workplace. How strongly does the factor contribute to the daylighting intensity? Please use a scale from 0 to 100 such that the total of all weights equals to 100.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>0</td>
</tr>
<tr>
<td>Time of Day</td>
<td>0</td>
</tr>
<tr>
<td>Sky Condition</td>
<td>0</td>
</tr>
<tr>
<td>View out</td>
<td>0</td>
</tr>
<tr>
<td>Glare</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
</tr>
</tbody>
</table>

The following table collects the relative weights of **Physical sub-factors** impacting the daylighting intensity in the workplace. How strongly does the factor contribute to the daylighting intensity? Please use a scale from 0 to 100 such that the total of all weights equals to 100.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window size to Wall Ratio</td>
<td>0</td>
</tr>
<tr>
<td>glazing color</td>
<td>0</td>
</tr>
<tr>
<td>Seating position regarding to the window</td>
<td>0</td>
</tr>
<tr>
<td>Lighting location control regarding to the seat</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0</td>
</tr>
</tbody>
</table>
7 DEVELOPMENT OF LIGHTING PREFERENCES MODELS

Regression analysis is used to develop the prediction model for the occupants' performance in the workplace regarding to the lighting preferences. The model is developed based on the previously specified/selected lighting preferences. It is developed in order to represent the collected data.

7.1 Regression-Based Occupants Performance Model

For the implementation of the model MINITAB is utilized to develop a regression model. MINITAB is a general statistical technique that has capabilities of basic and advanced data analysis in a wide range, such as analysis of variance, basic statistics, correlation and regression, and multivariate analysis (Minitab 2006). To select the best number of variables, we used step-wise regression analysis in the model.

MINITAB is utilized to develop a regression model for occupants' performance as a function of the previously selected lighting factors in the commercial buildings. Four selection criteria are used to distinguish between different proposed models. These criteria are R-square, adjusted R-square, mean square error (S or MSE), and Mallow's Cp. The best model that can represent the collected data set is selected according to the largest R-square and adjusted R-square, the minimum mean square error (MSE), and the closest Cp to the number of independent variables. Therefore, the selected model has the highest R2 of 0.85 and adjust R2 of 0.83, the Cp value of 8.2 close to 9 (i.e. number of variables), and the minimum MSE value of 2.2524. The best obtained formula describing the organization performance as a function of CSFs is given by Equation 1.

\[ Y = 5.7 + 0.326 x_1 + 0.083 x_2 - 0.056 x_3 - 0.179 x_4 - 0.023 x_5 - 0.124 x_6 - 0.034 x_7 + 0.507 x_8 + 0.510 x_9 + 0.394 x_{10} - 0.125 x_{11} - 0.090 x_{12} - 0.120 x_{13} + 0.347 x_{14} + 0.173 x_{15} + 0.350 x_{16} \]

The dependent variable (Y) denotes the occupants' performance expressed as a percentage and Xs denote the lighting factors that shown in Table 2 and the subscript refers to their numbers in the table. For example, X5 denotes number 5 which is “Window size to Wall Ratio.” The built model is checked for its statistical validity. The main diagnostics in this regard are R square (coefficient of multiple determination), F-test, and t-test for model coefficients.
<table>
<thead>
<tr>
<th>Factor X</th>
<th>Predictor</th>
<th>Coefficient</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Orientation</td>
<td>0.326</td>
<td>0.459</td>
</tr>
<tr>
<td>2</td>
<td>Time of Day</td>
<td>0.083</td>
<td>0.839</td>
</tr>
<tr>
<td>3</td>
<td>Sky Condition</td>
<td>-0.056</td>
<td>0.900</td>
</tr>
<tr>
<td>4</td>
<td>View out</td>
<td>-0.179</td>
<td>0.668</td>
</tr>
<tr>
<td>5</td>
<td>Window size to Wall Ratio</td>
<td>-0.023</td>
<td>0.951</td>
</tr>
<tr>
<td>6</td>
<td>glazing color</td>
<td>-0.124</td>
<td>0.789</td>
</tr>
<tr>
<td>7</td>
<td>Seating position regarding to the window</td>
<td>-0.034</td>
<td>0.931</td>
</tr>
<tr>
<td>8</td>
<td>Window size is big</td>
<td>0.507</td>
<td>0.295</td>
</tr>
<tr>
<td>9</td>
<td>Window size is medium</td>
<td>0.510</td>
<td>0.279</td>
</tr>
<tr>
<td>10</td>
<td>Window size is small</td>
<td>0.394</td>
<td>0.407</td>
</tr>
<tr>
<td>11</td>
<td>Windows facing the seat</td>
<td>-0.125</td>
<td>0.599</td>
</tr>
<tr>
<td>12</td>
<td>Windows next to the seat</td>
<td>-0.090</td>
<td>0.715</td>
</tr>
<tr>
<td>13</td>
<td>Non-computer based activities</td>
<td>-0.120</td>
<td>0.510</td>
</tr>
<tr>
<td>14</td>
<td>Word of Mouth</td>
<td>0.347</td>
<td>0.414</td>
</tr>
<tr>
<td>15</td>
<td>Energy awareness campaigns</td>
<td>0.173</td>
<td>0.629</td>
</tr>
<tr>
<td>16</td>
<td>Financial Incentives</td>
<td>0.350</td>
<td>0.425</td>
</tr>
</tbody>
</table>

7.2 Validation of Developed Occupants Performance Model

The validation process is to guarantee that the developed models best fit the available data. In order to determine the efficiency of the developed model to derive real world results, the model is tested statistically, logically, and practically. The collected data are divided into two data sets, model building (80%) and validation (20%). The validation data set, that is 20%, selected randomly and kept away while modeling the regression analysis. After developing the regression analysis model, the validation data set is used to test the capability of the developed lighting factors model to predict the occupant’s performance. The developed model is validated by comparing the predicted results with the actual values of the validation data set.

\[ AIP = \frac{1}{n} \sum_{i=1}^{n} 1 - I \left( \frac{E_i}{C_i} \right) \]

\[ AVP = 100 - AIP \]

Where AIP is the Average Invalidity Percent, AVP is the Average Validity Percent, \(E_i\) is the \(i^{th}\) predicted value, \(C_i\) is the \(i^{th}\) actual value, and \(n\) is the number of observations.

Equation 2 expresses the average invalidity, which indicates the prediction error, while Equation 3 presents the average validity percent. The AVP values for the developed performance prediction models regression is 92.55%. These values indicate that the obtained results are satisfactory.

8 CONCLUSIONS AND FUTURE RESEARCH

Lighting energy consumption is considered a highly energy consumer in commercial buildings. Achieving higher energy efficiency at commercial buildings demands considering the lighting preferences to the users and their performance in their workplace. It is difficult to measure the occupant’s performance due to their diversity and complexity. The proposed framework is an effective methodology for developing an institutional building sustainable occupant’s performance based model. This model will help the decision
makers and the designers at different levels to design the work places that accomplish the required levels of visual comfort for the users, while saving energy used in lighting. A multi-dimensional study on performance of the occupants in the commercial buildings has been conducted using 87 surveys obtained from intuitional buildings. The obtained data are analyzed using regression-based performance model and predict the performance of occupants. The developed model benefit both architects and practitioners to choose the appropriate workplace design due to the occupants’ preferences to enhance performance, and energy efficiency. It also provide energy modeling professionals with the various essential factors that affect occupants performance and how it can be assessed/predicted, i.e. performance assessment/prediction tool. The model has been validated with 92 % Average Validity Percent (AVP) and R square of 0.83 that is a satisfactory result. The research study shows a room for improvement for future study like modeling and simulate the occupant’s interaction.

Acknowledgements

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References


PRINCIPLES, CHARACTERISTICS, AND METHODOLOGY TO DEVELOP A PROJECT MANAGEMENT ASSESSMENT TOOL AT THE CONSTRUCTION PROJECT LEVEL

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Abstract: This paper describes the principles, characteristics, and methodology to develop a conceptual approach and a preliminary project management assessment tool based on an integrated framework of international project management (PM) standards and construction projects success factors. Previous PM assessment tools have been designed to measure organizations’ PM practices, and individuals' knowledge of PM. After completing these assessment tools, individuals or organizations would identify their strengths, weaknesses and training needs. These tools, though powerful, do not assess what is actually implemented on a specific project. The intention is to develop an assessment tool that diagnoses an organization and an individual project manager by what was actually implemented in a specific project. By assessing what was actually implemented in a project and comparing this with the project results, it could be possible determine the strengths, weaknesses, and value of PM in a construction organization, as well as to benchmark PM best practices. Three types of questions will be used: context questions, PM implementation questions, and project results questions. Each question will have a reference to one or more of the international PM standards. Each question will evaluate the quality or the frequency of the PM implementation, which could be a competence, knowledge, tool, technique, process, or practice. This paper discusses the question design methodology for developing the tool using the resource management knowledge area as an example. Finally, the assessment tool is tested with 18 construction projects executed by different organizations.

INTRODUCTION

Over several decades, project management (PM) communities of practice have put substantial effort into defining good project practice, and these practices are codified in a number of PM standards. The ability to assess the PM practices of a project organization with respect to these best practices would provide a valuable tool for improving PM performance and benchmarking PM best practices. Furthermore, a comparison of the assessed PM levels with assessed project success can provide insight into the quantitative value that PM brings to construction projects.

The goal of this research is to develop a PM assessment tool that can benchmark PM best practices, as well as to diagnose the strengths and weaknesses of an organization's PM implementation, assess levels of project success, and explore the relationship between PM practices and project success in order to evaluate the PM value. A feature that differentiates this research from previous work is the focus on assessing PM practices at the level of individual projects, rather than assessing practices at the level of a company or of an individual manager. This paper will focus on the principles, characteristics, and methodology to develop the PM assessment tool using the resource management area as an example. In
order to design the questions of the assessment tool, it is important to determine the methodological process, which includes a planning, preparation, and testing phase.

The planning phase consists of developing an integrated framework of global standards and a ranking of critical construction success factors. The preparation phase consists of structuring and elaborating each question of the assessment tool. The questions will be based on specific PM standards and/or project success factors. The questions are intended to determine the strengths, weaknesses, and value of PM implementation. Each of the PM implementations defined in the PM standards does not contribute equally to project success. Therefore, some weighting technique should be applied to aggregate the PM assessment results into higher-level, overall PM scores. The weighting scale will be based on an average of the number of citations of the success factors in management journals and the number of projects involved in the empirical data collected either from surveys or case studies in the literature review.

Finally, this paper will test the questions included in the resource management area with 18 construction projects from different organizations and determine the correlation coefficients between the resource management implementation and project results.

1 EXISTING PROJECT MANAGEMENT ASSESSMENT TOOLS

Previous PM assessment tools have been designed to measure organizations’ PM practices, and individuals’ knowledge of PM. The Boston University Corporate Education Center (BUCEC, bucec.com), the Atlantic Management Center Inc. (AMCI, amciweb.com), the Business Improvement Architects (BIA, bia.ca), the Enterprise Information (EII, eiicorp.com), Harold Kerzner’s PM maturity model, and the PM/ROI Assessment by Ibbs Consulting are assessment tools designed to measure PM technical competencies, personal competencies, leadership and business competencies, or PM maturity levels. After completing these assessment tools, individuals or organizations would identify their strengths, weaknesses and training needs. These tools, although very powerful and reputable sources of organizational PM and individual knowledge assessment, do not assess what is actually implemented on a specific project.

The intention is to develop an assessment tool that diagnoses an organization and an individual project manager by what was actually implemented in a specific project. By assessing what was actually implemented on a specific project and comparing this with the project results, it may be possible to determine the strengths and weaknesses of the PM in a construction organization, as well as to explore the value of PM.

2 PROJECT MANAGEMENT STANDARDS

There are many standards for PM practices: A Guide to the Project Management Body of Knowledge by the Project Management Institute, the Capability Maturity Model, Prince2, ISO 9000, the standards by the International Project Management Association (ICB), the Project and Program Management (P2M) by the Engineering Advancement Association of Japan, and the C-PMBOK by the Chinese project management conference among others. This study will use an integrated framework from four international PM standards: A Guide to the Project Management Body of Knowledge (PMBOK) from the Project Management Institute, the International Project Management Association Competence Baseline Version 3.0 (ICB), PRINCE2 by the Government of UK, and the ISO 9000 family of standards. It is important to note that PRINCE2 is a methodology but it has all the components of a standard. Mapping these four global standards gives validity to the process of developing the PM assessment tool.
3 PROJECT SUCCESS FACTORS

Project success factors were identified to provide a source for the weighting scale of the questions of the assessment tool. Project success factors from previous research also give validity to the initial PM assessment tool questions.

Projects are considered successful when they meet stakeholders’ needs and expectations. Most of the time, the stakeholder’s needs and expectations are met when the project is on time, on budget and within the scope and quality planned. However, project success criteria are subjective, and most of the time, are determined by the stakeholders. There is a clear difference between project success and PM success (Wit, 1998).

In a recent study, a set of metrics were used to try to determine the link between PM practices and project success. The outcome of this study was that the better the PM practices, the better the project results, “the results suggest that the PM practices that make a difference may not be the most frequently used” (Papke-Shields, Beise, & Quan, 2010).

For the purpose of this study, critical success factors has been selected from construction projects only. So far, there has been identified 60 research papers from different scientific journals stating the number of construction projects and the critical success factors identified. Table 1 provides an example of these success factors, listing just the top ten ranked factors, based on the number of reference that identified the factor and the total number of project cases studied in identifying the factor. Each of these success factors, as well as the PM standards, will be related to one or more of the questions of the initial PM assessment tool.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Critical Success Factor Identified in Construction Projects</th>
<th>No. of Citations</th>
<th>Case Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Multidisciplinary/competent project team</td>
<td>10</td>
<td>661</td>
</tr>
<tr>
<td>2</td>
<td>Clear objectives and scope</td>
<td>9</td>
<td>542</td>
</tr>
<tr>
<td>3</td>
<td>Time performance (project schedule/plans)</td>
<td>8</td>
<td>860</td>
</tr>
<tr>
<td>4</td>
<td>Formal &amp; Structured Selection of Contractor/subcontractors</td>
<td>8</td>
<td>648</td>
</tr>
<tr>
<td>5</td>
<td>Competent project manager</td>
<td>7</td>
<td>565</td>
</tr>
<tr>
<td>6</td>
<td>Clear information and communications channels</td>
<td>6</td>
<td>619</td>
</tr>
<tr>
<td>7</td>
<td>Project team commitment</td>
<td>6</td>
<td>454</td>
</tr>
<tr>
<td>8</td>
<td>Power and Politics</td>
<td>5</td>
<td>932</td>
</tr>
<tr>
<td>9</td>
<td>Client's competencies</td>
<td>5</td>
<td>539</td>
</tr>
<tr>
<td>10</td>
<td>Continuous involvement of stakeholders in the project</td>
<td>5</td>
<td>528</td>
</tr>
</tbody>
</table>

4 ASSESSMENT TOOL METHODOLOGY

In order to design the questions of the PM assessment tool, it is important to determine the methodological process, as well as some principles and assessment tool characteristics. The process of developing the PM assessment tool includes a planning phase, a preparation phase, and a testing phase.

The planning phase consists of developing an integrated framework of global standards and the project success factors literature. The preparation phase consists of structuring and elaborating each question of the assessment tool. The questions will be based on specific PM standards and/or project success factors. This link between the questions of the assessment tool and the PM standards and success factors will give face validity to the PM assessment tool. The questions are intended to determine
strengths, weaknesses, and the value of PM, as well as to benchmark PM best practices. Thus, the questions are divided in three categories; one set of questions related to the project context, another set of questions related to the actual PM implementation in reference to one finished project, and a third set of questions related to the project results.

The testing phase consists of using a preliminary PM assessment tool to test the reliability and validity of the PM assessment tool on several pilot cases. After pilot testing and refinement, the PM assessment tool will be ready for a full scale survey.

5 DEVELOPING AN INTEGRATED FRAMEWORK OF INTERNATIONAL PROJECT MANAGEMENT STANDARDS

This study developed an integrated framework from four international PM standards: A Guide to the Project Management Body of Knowledge (PMBOK) by the Project Management Institute (PMI), the International Project Management Association Competence Baseline Version 3.0 (ICB3), PRINCE2 by the Government of UK, and the ISO 9001:2008 standard.

This framework is organized around the same structure of the PMBOK, but it consists of 11 management areas and 5 process groups. All four international standards include the following PM knowledge areas in different forms or wording: integration, scope, time, cost, quality, human resources, communication and information, risk, and procurement. For the purpose of this study and to adapt the framework to construction projects, the following two PM areas have been added: context, and safety and environmental management. Project context, and safety and environmental management are missing in the PMBOK, or included in a different set of standards. However, these management areas are specifically included in the ICB3 as contextual competences. The five process groups are clearly identified in the PMBOK and PRINCE2: initiating, planning, executing, monitoring and controlling, and closing.

The most comprehensive and elaborated standard is the PMBOK by the PMI, so some knowledge management areas such as cost, risk and procurement contain processes that are taken from the PMBOK as is. The other international standards mention these and other knowledge management areas and process groups in general term and definitions, so mappings to these standards have been made. For instance, project human resource management is also called Resources in ICB3 and Organization in PRINCE2, Table 2.

6 DESIGN OF QUESTIONS USING THE RESOURCE MANAGEMENT KNOWLEDGE AREA

The four global standards emphasize the process of planning, selecting, training, and managing the project team. Table 2 shows a mapping of the four global standards for the resource management area.

Project human resource management for the PMBOK standard is the process of organizing, managing, and leading the project team to achieve a goal. This process includes planning human resources, acquiring the project team, developing the project team, and managing the project team. The human resource plan includes the identification of roles and responsibilities, the required skills, reporting relationships and the creation of the staffing management plan. It is the most elaborated standard in the matter of human resource management, but also it misses other project resources, behavioural competences, the work environment, and the organization executing the project.

The PRINCE2 methodology defines roles and responsibilities as one of its principles, which relates directly to one of the PRINCE2 themes, the organization. The organization is defined in different levels, from project level to corporate level. The definition of roles and responsibilities in item 5.4 of this standard are very broad and more toward the internal corporate organization, as well as the definitions on the PM team, PRINCE2, item 5.3.2. However, this standard states clearly the importance of training the project team if needed. In this standard or methodology, the team plans (section 7.2.6) is the closest parallel to the human resource plan and is also vaguely defined.
Table 1. Mapping of the Four PM Standards for the Management Area of “Project Human Resource Management” (or “Resources” in ICB and “Organization” in Prince2). Each column represents one of the five PM process groups. Items marked “*” are from the ICB3 standard, those marked with a “+” are from PRINCE2, “#” from ISO9001, and the rest are from PMBOK.

<table>
<thead>
<tr>
<th>Initiating</th>
<th>Planning</th>
<th>Executing</th>
<th>Monitoring &amp; controlling</th>
<th>Closing</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Start up</td>
<td>+ Plans</td>
<td>+ Directing</td>
<td>+ Control</td>
<td>* Close-out</td>
</tr>
<tr>
<td>+ Starting up &amp; initiating</td>
<td></td>
<td></td>
<td>+ Progress</td>
<td>+ Closing</td>
</tr>
<tr>
<td># 1. Ensuring availability of resources</td>
<td>1. H.R plan + Responsibilities</td>
<td>1. Acquire project team</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 2. Project Organisation</td>
<td>2. Develop project team + Training Needs</td>
<td># 1. Competence of personnel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 3. Teamwork</td>
<td>3. Manage project team</td>
<td># 2. Work environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td># 5. Defining responsibility &amp; authority</td>
<td># 4. Acquire, deploy, maintain, &amp; dispose resources</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The international standard ICB-3 states and defines resource management, resource competence (section 1.12), as the planning, allocation, optimization, and monitoring and controlling of humans, materials, and equipment resources. In addition, project organization competence, teamwork, and project structures competence are considered part of this management area since they are related to the project environment. In terms of the latent variables of this study, project organization, teamwork, and project structures are part of the project context. Behavioural competences are considered in this area because they are relevant to PM and the project manager. However, the PM assessment tool will not include a question for each behavioral competence element, since the tool will be more focused on technical competences. It will include leadership, creativity, consultation, and ethics as part of the leadership score.

The global standard ISO 9001:2008 mentions the need to ensure the availability of resources and defining responsibilities and authority as part of the management commitment and responsibility. However, it is item 6 of the standard that states clearly resource management, not only to continually improve the management system in place, but also to achieve the satisfaction of the stakeholders by reaching their project requirements. It is a general statement of the resource management process. It does not state or mention a plan, but it includes important elements such as definitions of competence for people executing the work, the training needs, the infrastructure and equipment required, and the work environment.

The questions in the assessment tool and in the resource management knowledge area in particular are designed to address the PM implementation in one project, the context in which the project and the
organization performed during the project life cycle, and the project results. These are called the latent variables.

In addition, there are different types of PM implementation: competence, knowledge, skills, tool, technique, process, and practice. Each question fits one or more than one of these PM implementation according to their definitions (see table 3). Each question has been elaborated based on the best PM practices according to four global PM standards and construction success factors. Each question has a reference to one or more standard (see table 3), or one or more construction success factors (see ranking of construction success factors in table 1).

Finally, each question is designed to evaluate the quality of the PM implementation or the frequency of the PM implementation during the project life cycle, or both of them.

One of the key questions to assess the quality of the resource management process is the presence of the human resource plan. If the plan exists, there may be different levels of implementations from informal to a very formal process. Thus, the question of the assessment tool would be formulated towards how well the human resource plan was implemented in terms of its component elements or processes.

Table 2. Resource Management Area Questions, Latent Variables, Type of PM Implementation, Standard Reference, and Quality & Frequency Characteristics.

<table>
<thead>
<tr>
<th>Question</th>
<th>Latent Variable</th>
<th>PM Implementation</th>
<th>Standard</th>
<th>Quality &amp; Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>PM plan: identified roles/responsabilities</td>
<td>Technical</td>
<td>YES</td>
<td>9.1.3.1, 9.1.4, 9.3.1</td>
</tr>
<tr>
<td>56</td>
<td>PM of client experience in years?</td>
<td>Technical</td>
<td>YES</td>
<td>9.1.3.1</td>
</tr>
<tr>
<td>57</td>
<td>Developer/owner organization experience?</td>
<td>Technical</td>
<td>YES</td>
<td>9.1.3.1</td>
</tr>
<tr>
<td>58</td>
<td>Constructor organization experience?</td>
<td>Technical</td>
<td>YES</td>
<td>9.1.3.1</td>
</tr>
<tr>
<td>59</td>
<td>PM of constructor experience in years?</td>
<td>Technical</td>
<td>YES</td>
<td>9.1.3.1</td>
</tr>
<tr>
<td>60</td>
<td>PM highest level of education?</td>
<td>Technical</td>
<td>YES</td>
<td>1.7.1, 3.1, 4.3</td>
</tr>
<tr>
<td>61</td>
<td>How do you rate your leadership skills?</td>
<td>Behavioural</td>
<td>YES</td>
<td>9.4.2</td>
</tr>
<tr>
<td>62</td>
<td>Did you exploded into anger?</td>
<td>Behavioural</td>
<td>YES</td>
<td>9.4.2</td>
</tr>
<tr>
<td>63</td>
<td>Requested input from team member affected?</td>
<td>Behavioural</td>
<td>YES</td>
<td>9.4.2</td>
</tr>
<tr>
<td>64</td>
<td>Spent time thinking how to improve things</td>
<td>Behavioural</td>
<td>YES</td>
<td>9.4.2</td>
</tr>
<tr>
<td>65</td>
<td>Hypothetical situation/Conflict of interest?</td>
<td>Behavioural</td>
<td>YES</td>
<td>9.4.2</td>
</tr>
<tr>
<td>66</td>
<td>Extrovert or introvert?, Sensing or intuitive?</td>
<td>Behavioural</td>
<td>YES</td>
<td>9.4.2</td>
</tr>
<tr>
<td>67</td>
<td>Hours of work per day?</td>
<td>Results</td>
<td>YES</td>
<td>9.2.1</td>
</tr>
<tr>
<td>68</td>
<td>Managing more than one project?</td>
<td>Results</td>
<td>YES</td>
<td>9.2.1</td>
</tr>
<tr>
<td>69</td>
<td>Recognition and reward system?</td>
<td>Implementation</td>
<td>YES</td>
<td>9.3.2.4</td>
</tr>
<tr>
<td>70</td>
<td>How many project managers?</td>
<td>Results</td>
<td>YES</td>
<td>9.3.2.4</td>
</tr>
<tr>
<td>71</td>
<td>Acquired the necessary project team?</td>
<td>Implementation</td>
<td>YES</td>
<td>9.3.1, 3.3</td>
</tr>
<tr>
<td>72</td>
<td>Performance assessment during project life?</td>
<td>Implementation</td>
<td>YES</td>
<td>9.3.3</td>
</tr>
</tbody>
</table>

The next four questions on the resource management area are related to construction experience (owner/developer manager, construction organization, and construction manager). The PMBOK and ICB standard do not mention specifically this element within their standards. PRINCE2 states it in the standard 5.3.2.1 which is referring more towards the PM team structure than to the experience itself. ISO 9001-2008 6.2.1 states the importance of experience in the general definition of human resources, table 3. However, experience is what makes a competent project manager, which is ranked at the top five on critical construction success factors by the number of citation in journal articles. Seven citations with a total of 565 project cases concluded that the project manager competence is key to project success. Table 1 shows the ranking of the construction success factors. The type of answer for these questions are open ended.

The next question of the assessment tool in the resource management area is the level of education of the project manager of the construction organization. This question is related to the project manager knowledge. It is referred in the PMBOK standard on item 1.7.1 and 9.1.3.1 as knowledge and competence. ICB3 refers to the knowledge and the professional PM in item 1.2. The only standard that refers to the competence on the basis of the appropriate education is ISO 9001:2008, 6.2.1, see Table 3. In addition, the top construction success factor according to number of citations from journals and 661 case studies within those citations is multidisciplinary, competent project team, table 1.
The next nine questions in the resource management area are related to the leadership skills and personality types. It is difficult to fully assess the leadership and personality type of a project manager. These two interpersonal skills could easily be two separate assessment tools themselves. The leadership skills is assessed based on five questions. One is a self-assessment of the leadership by the tool user, how would you rate your leadership skills from excellent to poor. The other ones are based on the very definition of the leadership skills by the PMBOK “Leadership is the ability to get things done through others by establishing and maintaining the vision, strategy, and communication; fostering trust and team building; influencing, mentoring, and monitoring; and evaluating the performance of the team and the project.” Table 3 shows the references to their specific standards on questions 61 to 65.

The personality type is based on the Myers and Briggs type indicator assessment. It is a summary of the Myers and Briggs assessment. The first question is related to the individual preference for energy (introvert or extrovert), the second is related to the individual preference for information gathering (sensing or intuitive), the third one is about the individual preference for decision making (thinking or feeling), and the last one is related to the individual preference for lifestyle (judging or perceiving). The PMBOK standard mentions personality types on the required skills as part of the human resource plan, 9.1.3.1 and appendix X3 (interpersonal skills). PRINCE2 methodology states personality types in 5.3.3.1. Research suggest that a large majority of all managers have personality either Introvert-Sensing-Thinking-Judging or Extrovert-Sensing-Thinking-Judging, Noe et al.2003. Table 3 shows the references to their specific standards on questions 66a to 66d.

The last six questions in the resource management area are related to acquiring and developing the project team. The questions are intended to triangulate or corroborate the existence of the necessary project team, question 71. So, if there is an adequate project team then the hours of work should be around the normal working hours (question 67), working in one project most of the time (question 68), with a performance, recognition and reward system (questions 69 and 72) that allows the organization to reduce the employees’ turnovers. See table 3 for the questions with reference to their specific standards, their PM implementation types, and their quality of frequency characteristics. Acquiring the project team could also be extended to the proper selection of the subcontractors, which is ranked as the fourth construction success factor; formal and structured selection of subcontractors, table 1.

7 SCORING CRITERIA

After elaborating the questions, the next step is the scoring criteria for each question. There were several calibration processes in order to weight the score of each question; from assigning 1 point for each question to separating the questions according to the latent variables in the following groups: context questions, PM implementation questions, and project results questions. Finally, a scoring criteria based on the construction success factors was chosen. Questions within the top ranking of construction success factors were given more weight. For instance, resource management questions related to roles and responsibilities, the staffing management plan, experience, leadership, knowledge related to construction, acquiring the necessary project team, performance assessment plan are being scored with 10 points, as these questions are closely related to the following construction success factors: multidisciplinary project team(1), formal structured selection of subcontractors (4), competent project manager (5), project team commitment (7), client competencies (9), leadership (26), employee enhancement (38), and availability of resources (52).

The total scoring for resource management area on the planning group is 132 points in PM implementation, for the executing process group is 13 points for PM implementation and 14 for project results, and finally the monitoring and controlling process group has a maximum score of 4 points for PM implementation. In total, the resource management area account for 149 points out of 591 (25.2%) of the total possible PM implementation, as well as 14 points out of 220 (6.3%) of the total possible project results. The low percentage in project results in this area can be explained in the sense that this management area can be considered more of an input than a project result, and also because the project results are measured and located more in other management areas such as the project time, cost, scope, and quality.
8 TESTING PHASE AND ANALYSIS

The assessment tool has been tested with 18 construction projects from different organizations, with different types of projects, sizes, and context. In order to test and analyze the results in the resource management area, the projects are separated according to these differences. At the end, the results are compared among all projects to draw some general conclusions.

8.1 Residential Projects from the Same Organization

The first selection are high-rise residential projects from the same organization. The projects range from $19 million to $70 million, with an average of $44 million Canadian dollars. All these project are located and built in lower mainland BC. The project managers taking the assessment tool rated these project with complexity level 3 or 4, where 5 is very complex (e.g. demanding stakeholders, complex design, etc.) and 1 is very simple project (e.g. similar to previous type of project). Table 4 shows the resource management implementation for the specific project in HR column, the total PM implementation in all management areas, and the total project results.

<table>
<thead>
<tr>
<th>Project ID</th>
<th>Human Resource Management Score</th>
<th>Overall PM Score</th>
<th>Project Result Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>128</td>
<td>452</td>
<td>180</td>
</tr>
<tr>
<td>CR2</td>
<td>87</td>
<td>348</td>
<td>157</td>
</tr>
<tr>
<td>CR3</td>
<td>85</td>
<td>297</td>
<td>136</td>
</tr>
<tr>
<td>CR4</td>
<td>99</td>
<td>442</td>
<td>149</td>
</tr>
</tbody>
</table>

The correlation coefficient is 0.878 between human resource management implementation and project results. The correlation coefficient is 0.812 between human resource management implementation and total PM implementation. Finally, the correlation coefficient is 0.704 between PM implementation and total project results. Although these coefficients are lower than the critical values of the Pearson correlation coefficient for n=4, r = 0.95, the results show that there is a strong association between the three data sets. The better the resource management implementation, the better the project results in terms of time, cost, quality, and customer satisfaction. In addition, the better the resource management area implementation, the better the overall project PM implementation.

8.2 Institutional Projects from the Same Organization

The second selection consists of 11 institutional projects from the same organization. The projects range from $3 million to $20 million, with an average of $7 million. All project are located in different islands of British Columbia. Most projects are new schools or additions to existing schools for different First Nation communities. The project level complexity range from 3 to 5. For these projects, the correlation coefficient is 0.012 between resource management implementation and project results. The correlation coefficient is -0.013 between resource management implementation and total PM implementation. These two correlation coefficients show that there is no correlation between the two data sets. Interestingly, there is a statistical correlation between PM implementation and total project results for n= 11 and the Pearson correlation coefficient r = 0.602. The correlation coefficient is 0.739 between PM implementation and total project results.

8.3 All Projects Combined

The remaining three project are a $1.6 billion highway, a $32.5-million high-rise residential, and a $4.4-million institutional, all of them from different organizations. In this particular situation, n=18, the Pearson correlation coefficient is r = 0.468. There is a coefficient correlation of 0.280 between resource management and total project results, so there is no statistical correlation. There is a coefficient correlation of 0.167 between resource management area and the total PM implementation including all
management areas, so there is no statistical correlation between these two data set as well. Figure 1 shows the trend line, the equation that relates the two variables, and the R-squared value.

![Resource Management Implementation vs. Project Results](image.png)

Figure 1. Resource Management Implementation vs. Project Results

9 CONCLUSIONS

This paper explains the process, principles, and methodology to build the assessment tool using the resource management area as a demonstration. The questions are divided in three groups: context, implementation, and results, which are the latent variables. The questions are based on a finished project and are oriented to test the quality or frequency of the PM implementation, which could be a competence, knowledge, skill, tool, technique, process or practice. Some of these PM implementation may involve more than one of these elements.

The PM assessment tool was tested with 18 construction projects. For analysis purpose, the cases were separated based on the type of project and the organization. At the end the cases are combined to analyze the overall statistical correlation between the variables and data set in question.

The results and analysis show that there is a strong association between resource management implementation and project results for the four high-rise residential projects. The better the resource management implementation, the better the overall PM implementation and project results. Furthermore, the results for the eleven institutional projects shows that although there is no correlation between resource management and project results, there is a strong statistical correlation between the overall PM implementation and project results. Finally, when all eighteen cases are combined, there is no statistical correlation between resource management implementation and project results.

In conjunction with the other management knowledge areas and process groups as well as using an integrated framework among four global PM standards, a PM assessment tool may be used to determine the strengths, weaknesses, and the value of PM. It can also be used to benchmark PM best practices.
REFERENCES


ULTIMATE AND FATIGUE STRENGTH OF GFRP-REINFORCED, FULL-DEPTH, PRECAST BRIDGE DECK PANELS WITH ZIGZAG-SHAPE TRANSVERSE JOINTS FILLED WITH UHPFRC

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Abstract: One of the prefabricated bridge system used to accelerate bridge construction is the precast full-depth deck panel (FDDP) with transverse joint placed over steel or concrete girders. In this system, grouted pockets are provided to accommodate clusters of shear connectors connected to steel or concrete girders. In this research, ultra-high performance fibre-reinforced concrete (UHPFRC) and high-modulus glass fibre reinforced polymer (GFRP) bars are utilized in the closure strip between the adjacent precast FDDPs for enhanced strength and durability. Two actual-size, GFRP-reinforced, precast FDDPs were erected to perform fatigue tests using the footprint of the truck wheel loading specified in the Canadian Highway Bridge Design Code (CHBDC). Each FDDP had 200-mm thickness, 2500-mm width and 3700-mm length in the direction of traffic and rest over braced twin-steel girder system. The transverse closure strip between connected precast FDDPs has a width of 100-mm with zigzag-shape from each side of the joint to increase moment capacity along the interface between the UHPFRC and the precast FDDP along the joint. GFRP bars in the precast FDDPs project into the closure strip with a development length of 175-mm. Two types of fatigue tests were performed, namely: (i) high-cyclic constant amplitude fatigue loading followed by monotonically loading to-collapse; and (ii) low-cyclic accelerated variable amplitude fatigue loading. Overall, the test results demonstrated the excellent fatigue performance of the developed closure strip details. In addition, the ultimate load carrying capacity of the FDDP was far greater than the factored design wheel load specified in CHBDC.

1 INTRODUCTION

Precast full depth deck panels (FDDPs) have recently used in new accelerated bridge construction (ABC) or for the rapid bridge replacement (RBR) of existing deteriorated bridge decks. FDDPs are produced off-site, quickly assembled on-site, reduce construction time, minimize lane closure and are considered to a good solution to minimize traffic disruption (Clumo, 2011). FDDPs are placed side by side as shown in Fig. 1, then the closure strips between them are filled with bonding material. FDDP closure strips should take the advantage of high quality concrete and non-corrosive reinforcement as glass fiber reinforced polymer (GFRP) bars for enhanced strength and durability. GFRP reinforcement is a composite material made of polymer matrix reinforced with fibers. It has high strength-to-weight ratio, is free of corrosion and lasts longer. Although the Canadian Highway Bridge Design Code, CHBDC (CSA, 2006) allows the use of GFRP-reinforced FDDPs in bridge construction, there is no code provisions on the joint details between such precast system. The behaviour of the FDDP monolithic concrete joint (MCJ), also known as moment resisting connection (MRC), accounts for the state of bond of the projected longitudinal bars anchored through the cast-field joints. The Ultra-High Performance Fiber Reinforced Concrete (UHPFRC)
is a relatively new class of cementitious matrix with steel fiber content that has high compressive strength (in order of 140 MPa) and relatively large tensile strength (in order of 8 MPa), with strain hardening behavior in tension that ensure crack opening remain very small (Russell and Graybeal, 2013). The use of UHPFRC as a filling material of the closure strip between connected FDDPs have numerous benefits, including reduction of joint size, improving durability, speed of construction and prolonging usage life.

Fig. 1. Isometric view of a precast full-depth, full width, deck panels placed transversally over girders

Deflection and vibration play an important role on the serviceability of bridges. The current AASHTO-LRFD Bridge Design Specification (AASHTO, 2012) specifies the bridge deflection limits at L/800 for vehicular bridges and L/1000 for pedestrian bridges as optional criteria where L is the span of the structural element. Traditionally bridges are designed using static loads that include the dynamic load allowance (DLA) due to passing trucks at the ultimate, serviceability and fatigue limit states. It is important to examine the structural behaviour of the jointed precast FDDPs under different fatigue loading conditions which lead to progressive, internal and permanent structural changes in the materials. After the crack initiation and propagation, failure is caused by the deterioration of the bond between coarse aggregate, reinforced bars and the binding matrix. Two types of fatigue loading are considered in testing, namely: constant amplitude fatigue loading (CAF) and variable amplitude fatigue loading (VAF). Fatigue loading is known to reduce the life span for the bridge deck (Karunananda et al., 2010). The constant amplitude fatigue (CAF) is the classical method for fatigue analysis of the materials to obtain the three fatigue resistance components and structures, namely: stress-life (S-N) known as Wöhler curve, strain-life (ԑ-N) and fatigue crack growth (FCG). CAF limit is the safe stress level under elastic deformation for design that can take a very large number of cycles, longer than one-million cycles. The variable amplitude fatigue (VAF) limit is based on the same concepts with addition of cycle counting and damage summation due to increasing step loading. However, the resulting stresses are high enough for plastic deformation to occur within the number of cycles very much less than one-million cycles.

The use of the precast FDDPs in bridge construction started in United States in early 1960s, with the purpose to shorten the deck construction in areas with high traffic volumes. The deck-girder system was primarily non-composite, and the panel-to-panel connections exhibit partial failures. By 1974, FDDPs were made composite with the superstructure by extending the steel shear stud into the deck. The spacing of the shear pockets ranged from 457 mm to 610 mm and the number of studs per pocket ranged from 4 to 12. Two sizes of steel studs are typically used, namely: 19 mm and 22 mm. FDDP were supported on girders and secured to it using the shear studs embedded in the shear pockets that are normally filled with non-shrink grout to eliminate stress concentrations in the panels (Badie and Tadros, 2008). The transverse panel-to-panel connection is provided with shear keys to protect adjacent panels from relative vertical movement due to traffic load. This type of joint has two types of forces, namely: (i) vertical shear force between the panel and the field-casted joint; and (ii) bending moment that puts the top half of the joint in compression and the bottom half in tension. The panel-to-panel connection has several
shapes available in the literature including male-female (tongue/groove) shear key. However cracking, spalling and leakage were observed in such joints in practise. Other panel-to-panel connections included female-to-female shear key which comes into bulb shape, and diamond shape. Splicing longitudinal reinforcement was introduced into overlapping U-bars or using HS spirals, or using open or closed steel tubes (PCI, 2011a and 2011b). Grouting materials to fill the shear pockets and transverse joints have common properties as: (i) high strength at young age, (ii) small shrinkage deformation, (iii) superior bonding and (iv) low permeability (Badie et al., 2006). The steel reinforcement lap-splice joints exploit bonding performance with the joint-field materials made of UHPFRC (Hwang and Park, 2014). The direct tension of GFRP bars were pulled out from UHPFRC blocks to determine the development length (Sayed-Ahmed and Sennah, 2014c). This led to developing few precast panel connection details that were considered for qualifying tests. Three developed female-to-female connections for the GFRP-reinforced precast FDDPs with lap-spliced bars were constructed in full scale in the laboratory to examine their strength and serviceability under increasing static loading with the use of normal strength concrete (Sayed-Ahmed and Sennah, 2014a) and high-performance concrete (Sayed-Ahmed and Sennah, 2014b) in the precast deck slabs. This paper reports the experimental program to test one of these developed joints in real-world situation. Two precast FDDPs were constructed over twin-steel girder system, with one of them tested under CAF loading followed by loading it monotonically to-collapse, and the other one was tested under VAF loading directly to-collapse. Test results are analyzed to examine the fatigue performance and the ultimate load carrying capacity of the developed jointed precast slabs.

2 NEW CONNECTION DETAILS

Figure 2 depicts the trapezoidal zigzag-shape panel-to-panel connection with vertical female-to-female shear key. The slab thickness of 200 mm is divided vertically into equally four layers. The clear joint width between the ends of the jointed panels is 100 mm, while the zigzag-shape (i.e. trapezoidal tooth-shape) allows for an extension of the joint width of other 100 mm into the precast panel. So a projecting GFRP bar from the end of one panel at its wide width of the trapezoidal shape will project into the joint with a length of 175 mm in 200 mm joint width in the same bar direction (i.e. 100 into the closure strip and 75 mm into the grooved trapezoidal shape in the adjacent panel). The pullout strength of the embedded GFRP in the joint will be resisted by the bond between its surface and the surrounding UHPFRC filling in addition to the bearing pressure between the UHPFRC filling and the precast concrete at the included surface of the trapezoidal shape at the interface between the two concretes. Such bearing pressure expects to be resisted by the concrete surface normal to the joint at the narrow end of the trapezoidal shape and the GFRP bar projecting through it from the adjacent panel. A vertical shear key is introduced along the side of the precast panel as depicted in Fig. 2(a). The slope of the inner side of the shear key has a slope of 1vertical to 5 horizontal.

3 EXPERIMENTAL PROGRAM

The experimental program included testing two laterally restrained precast FDDPs supported over /twin-steel girder bridge system, using the available force-control hydraulic actuator system. The width of the cast slab is 2500 mm so that it can be supported over the twin girders to produce slab span of 2000 mm as depicted in Fig. 3(a). The precast slabs were of 200 mm thickness and were made of 35 MPa normal strength concrete (NSC) with 10 mm nominal size aggregate, 150 mm slump with added super plasticizer, and no air-entrant. Straight-ended, 16M ribbed-surface, high-modulus GFRP bars was used to reinforce the precast slab per CHBDC requirements. The bottom and top transverse reinforcement of the slab was taken 16M@140 mm and 16M@200 mm respectively. While the slab was reinforced with 16M@200 mm GFRP bars in the bottom and top longitudinal direction (i.e. parallel to the girder). The specified modulus of elasticity and ultimate tensile strength of the GFRP bars were 64 GPa and 1188 MPa, respectively (Schoeck, 2012). To form the joint between the precast FDDPs, two precast FDDPs were formed first. The first FDDP was of 200 mm thickness, 2400 mm length in girder direction and 2500 mm, while the second FDDP was of 200 mm thickness, 1000 mm length in girder direction and 2500 width. This made the final dimensions of the jointed slab of 3700 mm in the direction of traffic as depicted in Fig. 3(a). It should be noted that the short precast slab of 1000 mm was introduced beside the large precast slab to ensure deck slab continuity beyond the joint. Figures 3(b) and 3(c) show views of the formwork, GFRP
bar arrangement and Styrofoam used to form the joints and the shear pockets before casting concrete. The panel-to-girder connection was made using shear pockets to achieve the full composite action. Shear studs were used to establish such full composite action between the girder and the precast panel every 1200 mm. High tensile headed shear studs (structural bolts) of 25 mm diameter were used. The UHPFRC (Ductal Joint Fill JS1000) was used for the cast-in-place of the panel-to-panel connection. The ultimate strengths of the UHPFRC were 140 MPa, 30 MPa and 8 MPa in compression, flexural and direct tension, respectively, while its modulus of elasticity was 50 GPa. More details about the experimental program can be found elsewhere (Sayed-Ahmed, 2014).

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The experimental program included testing two precast FDDPs supported over twin-steel girder bridge system, using the available force-control hydraulic actuator system. The steel I-girders were 7500 mm in length and made of W610x241. They were placed over 330x330x25 mm elastomeric pads that were supported over steel pedestals, making the clear spacing of the girder equal 7000 mm. Transverse cross-type bracings were installed at the two ends of the steel girders to provide lateral restraints to the deck slab as specified into the CHBDC empirical design method. The spacing of the twin girders was 2000 mm measured center-to-center of the girders. The first slab system was tested under high-cycle constant-amplitude fatigue (CAF) loading followed by increasing monotonic loading to-collapse, while the second slab system was tested under low-cycle incremental step fatigue loading of variable amplitude (VAF) to collapse. The actuator system generates sinusoidal harmonic force,

\[ p_t = p_{avg} + p_a \sin(2\pi f t) \geq 15 \]

where \( p_{avg} \) is the average between the maximum and minimum loads, \( p_a \) is the amplitude of applied load, \( f \) is the frequency and \( t \) is the time. Before performing fatigue tests, a crack was initiated in the tested slab by applying monotonic loading equal to 3 times the applied wheel load for fatigue limit state design per CHBDC. This applied wheel load equals the heaviest wheel load in the specified CHBDC truck, multiplied with the 1.4 to include the dynamic load allowance (DLA) and 0.9 as the load factor.(i.e. \( 87.5 \times 1.4 \times 0.9 \times 3 = 330.75 \text{kN} \)). The footprint of the applied wheel load on top of the tested slab measures 600 mm wide by 250 mm long as depicted in Fig. 3(a). It was decided to locate it just beside the joint as depicted in Fig. 3(a).

The constant amplitude fatigue (CAF) loading was applied under force control with sinusoidal shape to represent the FLS load specified into the CHBDC as \( 87.5 \times 1.4 \times 1.0 = 122.5 \text{kN} \) at the frequency of 4 Hz for 4 million cycles. To prevent rattling of the test setup under cyclic loading, the loading cycle started with 15 kN applied load that increased by 122.5 kN. Thus, the sinusoidal cyclic CAF ended up with loading range of upper and lower absolute values of 137.5 kN and 15 kN, respectively with sample rate of 20.013 Hz. Monotonic test at 1.5 time the applied FLS load (i.e. \( 122.5 \text{kN} \times 1.5 = 183.75 \text{kN} \)) was conducted.
after each 250,000 cycles to assess the degradation of the FDDP system due to fatigue loading. The force-control monotonic test had a ramp segment shape at loading and unloading rate of 5 kN/min. and 10 kN/min., respectively, with collecting data points every 0.049967 sec. After the end of the 4 million cycles, the FDDP system was monotonically loaded to-collapse using a hydraulic jack with 1,300 kN capacity. The incremental step variable amplitude fatigue (VAF) loading was applied under force control with sinusoidal shape to different 7 absolute peak levels of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 times the FLS load of 122.5 kN plus 15 kN as the absolute load lower level. The corresponding peak loads of the 7 incremental step VAF loadings were 137.5, 198.75, 260, 321.25, 382.5, 443.75 and 505 kN. Each load level was applied for 100,000 cycles at the range of 2 Hz to 0.5 Hz depending on the stiffness of the FDDP system, and the steel loading frame system, with lowest frequency when approaching failure of the slab. Data was collected at a sample rate of 20.013 Hz. Monotonic test was performed after each 100,000 cycles with the same setting of the CAF monotonic test. After finishing with 7 absolute peak levels mentioned earlier, the VAF loading testing continued with the highest peak value up to the failure of the specimen. Figure 4 shows view of the test setup during fatigue testing, while Fig. 5 shows view of the test setup during the monotonic testing.

4 TEST RESULTS

This section discusses the structural behavior of the tested specimens in the form of slab vertical deflection, and crack pattern. As mentioned earlier, fatigue precracking was conducted under force control. The first hair flexural crack was observed at 2.5 times the FLS loading (275.625 kN) underneath the wheel footprint area at the mid-span in the longitudinal direction (parallel to the supporting girders). Load was increased to 3 times the FLS load (330.75 kN) to increase the crack propagation beyond the wheel footprint area. The flexural crack width was found to be 80 µm at that monotonic load. CHBDC specifies that design factored load of the deck slab is the multiplication of CHBDC truck wheel load of 87.5 kN, load factor of 1.7 and DLA of 0.40. This makes the factored design applied load 87.5 x 1.4 x 1.7 = 208.25 kN. It is interesting to mention that at the precracking monotonic load of 330.75 kN, at which a minor flexural crack propagated, is about 59% greater that the CHBDC factored design load.
4.1 Constant Amplitude Fatigue Loading

For the tested specimen under CAF loading, the compressive strength of the concrete cylinders taken from the concrete mix were 41.16, 35.32 and 35.028 MPa, with an average value of 37 MPa. The tested cylinders for the UHPFRC, that were cast 10 days before the start of the fatigue testing, resulted in compressive strengths of 130.90, 136.43, 114.96 MPa, with an average value of 127 MPa. The splitting tensile tests for the NSC resulted in tensile strength of concrete of 3.37, 2.72, and 3.61 MPa, with an average value of 3.23 MPa. During the initiation of fatigue precracking procedure, at a static load of 220.5 kN, flexural crack propagated from underneath the mid-point of wheel footprint about 100 mm towards the middle shear pockets shown at the middle of the precast slab segment shown in Fig. 3(a). When the applied load increased to 275.625 kN, the flexural crack propagated further another 300 mm. However, when the applied load reached 330.75 kN, the flexural crack propagated diagonally from the mid-point of the wheel footprint to the closest corner of the middle shear pocket. The maximum recorded flexural crack width at that point measured 80 µm. No more flexural cracks were observed during the CAF test that last over 16 days. After each 500,000 cycles, the slab was subjected to monotonic loading to observe the change in slab flexural stiffness through deflection measurements. Figure 6(a) depicts the load-deflection
relationship for the slab at the centre of the footprint of the wheel load. It can be observed that the slope of the curves after each group of fatigue cycles appeared unchanged and maintained linear. After the 4-million fatigue cycles, the slab was subjected to monotonic load to-collapse. The precast FDDP failed due to punching shear at a jacking load of 931 kN. It is interesting to mention that such failure load is about 4.47 times the CHBDC factored design wheel load. Figure 7(a) shows top view of the slab showing punching shear failure at the footprint of the wheel load. While Fig. 7(b) shows bottom view of the slab showing crack pattern after failure. One may observe the radial cracks starting from the location of the footprint of the wheel load and propagating towards the support line in a fan shape. At failure, concrete spalling appeared in some parts of the bottom side of the slabs as signs for punching shear failure. Figure 6(b) depicts the load-deflection relationship for the tested slab under static loading to-collapse. Deflections values were recorded at the mid-length of the free edge of the short slab shown in Fig. 3(a), noted as “Free Eng” curve in Fig. 6(b). Such deflection reached 1.78 mm at failure. On the other hand, the deflections under the wheel footprint, denoted as “Under Load 1 and Under Load 2” in Fig. 6(b) were recorded as 30.29 and 28.94 mm at failure. The deflection at the centre of the long precast slab, denoted as “Mid-span” in Fig. 6(b) was recorded as 19.30 mm. The maximum deflection of the long precast slab at the mid length of the edge joint, denoted as “Fixed End” in Fig. 6(b) was recorded as 2.65 mm at failure.

![Load-deflection curves under static load after each 500,000 fatigue cycles](image1)

![Load-deflection curves under static load to-collapse](image2)

**Figure 6.** Monotonic load-deflection history for the first specimen tested under CAF loading

![Top view of the slab showing punching shear failure at the footprint of the wheel load](image3)

![Bottom view of the slab showing crack pattern after failure](image4)

**Figure 7.** Crack pattern after failure of the first slab tested under CAF loading
4.2 Variable Amplitude Fatigue

The second precast FDDP specimen underwent sinusoidal waveform fatigue load cycles with incremental step low cycle fatigue loading. The compressive strengths of concrete cylinders for the NSC used to cast this slab were 43.26, 68.16, 64.99, 65.74 MPa, with an average value of 60 MPa. The compressive strengths of the concrete cylinder for the UHPFRC used to fill the joints were 163.35, 183.31, 153.28 MPa, with an average value of 167 MPa. The splitting tensile test for the UHPFRC resulted in tensile strength of 18.30, 20.47 and 21.69 MPa, with an average value of 20 MPa. The first 895,000 fatigue load cycles were performed at a frequency of 2 Hz, then followed by 21,736 cycles at 1 Hz, and finally followed by 44,804 cycles at 0.5 Hz leading to punching shear failure at a total number of cycles of 961,540. Figure 8 depicts the punching shear failure at wheel footprint on top of the slab. While Fig. 9(a) depicts the crack pattern at the bottom surface of the slab at failure. A fan-shape crack pattern was observed at the bottom surface similar to those developed for the slab tested to collapse after passing the CAF loading. However, Fig. 9(a) shows greater concrete spalling along the perimeter on the punching shear plane at the bottom of the slab but only from one side of the closure strip. This precast FDDP failed at a jacking load of 488.43 kN and a maximum slab deflection of 37.03 mm. It is interesting to mention that such failure load is about 2.35 times the CHBDC factored design wheel load. Figure 9(b) depicts the monotonic load-deflection relationship of the slab after each 100,000 fatigue load cycles. It can be observed the slope of the curve decreased, leading to a reduction in slab flexural stiffness, with increase in number of VAF load cycles.

Figure 8. Views of punching shear failure of the slab tested under VAF loading

Figure 9. Crack pattern and monotonic load-deflection history for the slab tested under VAF loading
4.3 Stiffness degradation

The stiffness degradation of slabs under flexural loading was calculated in the form of spring stiffness \( k \). \( k \) is considered as the ratio between the applied monotonic load, \( F \), in kN and corresponding slab deflection, \( d \), in mm. Table 1 summarizes the results for the CAF loading (high cycle fatigue, HCF) and for the VAF loading (low cycle fatigue, LCF). Figures 10(a) and 10(b) depict the relationship between the spring stiffness and the number of fatigue cycles and slab deflection, respectively. One may observe that the first specimen’s stiffness degraded by about 21.9% after 4 million cycles of constant amplitude fatigue (CAF) loading. On the other hand, the second specimen’s stiffness degraded by 71.32% when subjected to variable amplitude fatigue (VAF) loading before complete collapse.

Table 1. Stiffness degradation of the precast FDDP slabs

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<th>Load, kN</th>
<th>Deflection, mm</th>
<th>( k = \frac{F}{d} )</th>
<th>Cumulative Cycles</th>
<th>Load, kN</th>
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<th>( k = \frac{F}{d} )</th>
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5 CONCLUSIONS

This paper investigates the fatigue behavior and ultimate load carrying capacity for laterally restrained precast FDDP reinforced with high-modulus GFRP bars with developed trapezoidal-zigzag transverse joint combined with vertical shear key filled with UHPFRC and subjected to CHBDC wheel loading. Based on the experimental results, it can be concluded that the developed transverse panel-to-panel connection with projecting straight-ended high-modulus GFRP bars can provide a continuous force transfer in the transverse joints for the FDDPs. Experimental results also indicated that precast FDDP reinforced with high-modulus GFRP ribbed-surface bars showed high fatigue performance and there was no fatigue
damage when subjected to 4,000,000 cycles under high-cyclic CAF loading of 122.5 kN specified in CHDBC. The tested precast FDDP under high-cyclic CAF loading sustained a failure load about 4.47 times the CHBDCC factored design wheel load of 208.25 kN. While the tested precast FDDP under low-cyclic incremental step VAF loading sustained a failure load about 2.35 times the CHBDCC factored design wheel load. The two laterally restrained precast FDDPs failed in punching shear mode. Finally, the first precast FDDP specimen’s stiffness degraded by about 21.9% after 4 million cycles of constant amplitude fatigue (CAF) loading. On the other hand, the second precast FDDP specimen’s stiffness degraded by 71.32% when subjected to low-cyclic variable amplitude fatigue (VAF) loading before complete collapse.

6 ACKNOWLEDGEMENTS

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APPLICATION OF FUZZY LOGIC INTEGRATED WITH SYSTEM DYNAMICS IN CONSTRUCTION MODELING

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Abstract: Construction projects are complex systems and their behaviors are extremely dynamic throughout their life cycles. This complexity and dynamism makes them perfect candidates for system dynamics modeling for management purposes. However, ill-known variables, a lack of historical data, uncertainties, subjectivity, and the use of linguistic terms in defining construction variables all complicate the application of system dynamics in construction. Fuzzy logic is an artificial intelligence technique that has the ability to model vague, incomplete, linguistically-expressed, and subjective data in a precise way. Since the quality of system dynamics modeling relies significantly on the accuracy of the data, integrating system dynamics with fuzzy logic makes for a powerful construction project simulation tool. Integrated fuzzy system dynamics models can effectively capture the dynamic characteristics of construction projects and simulate them more precisely by using fuzzy logic to capture subjective and linguistically-expressed information. In this paper, we illustrate how fuzzy logic and system dynamics can be integrated for use in construction project simulation. Moreover, we present a review of potential applications of integrated fuzzy system dynamics models in construction. Finally, we compare the performance of system dynamics with integrated fuzzy system dynamics for a construction-related problem adopted from the literature, and discuss how integrating fuzzy logic can enhance system dynamics capabilities for construction modeling.

1 INTRODUCTION

Construction projects always involve uncertainties and complexity, which makes construction management a critical task in the industry. During the last century, several managerial tools and approaches have been developed in construction or adopted to this area from other industries to help managers plan and control their projects effectively. Simulation models—such a managerial tool—help managers to observe the conditions and performance of their projects prior to the execution phase. Simulation models are powerful planning tools that can help managers to identify the key factors affecting their projects in order to proactively manage problems before they arise. Among simulation models, the system dynamics (SD) approach, developed by Forrester (1961) for the analysis of complex industrial systems, has unique characteristics that make it well-suited to construction planning purposes. SD
models can effectively capture the dynamism of the systems where the state of the system can continuously change. This characteristic of SD models suits construction modeling, since construction projects are always changing under the effects of various factors. Moreover, SD models describe interrelationships between the elements of the systems with cause and effect loops (Ford 1995), which also makes these models an ideal choice for the construction context, where there are often numerous interactions between elements in a project.

Previous research by Lyneis and Ford (2007) shows SD models have been successfully applied in project management. Sterman (1992) asserts that project management is one of the most poorly performing areas of management and SD modeling can help the managers of large scale engineering projects. There are several applications of SD models in construction project management by researchers as well. Mowdesley and Al-Jibouri (2009) developed a SD model for construction productivity at the project level, Park (2005) used SD models for resource management, and Lee et al. (2006) used SD modeling for dynamic planning in construction. However, despite the extensive use of SD models in construction project management, SD models are limited in their ability to capture qualitative and linguistic variables in simulation (Levary 1990). In order to address this deficiency, Levary (1990) introduced the use of fuzzy logic in SD modeling.

Fuzzy logic, developed by Zadeh (1965), gives the human cognitive process mathematical precision. Fuzzy logic is a tool for modeling subjective and imprecise variables or variables that are expressed in linguistic terms. Fuzzy logic is a powerful modeling technique well suited to construction, since construction projects are unique in terms of their characteristics, and lack of historical data is one of the biggest challenges that researchers and practitioners face when modeling construction problems. Fuzzy logic has been implemented to solve construction-related problems successfully many times before (see Chan et al. 2009 for a review).

In this paper, we illustrate how fuzzy logic and SD can be integrated for use in construction project simulation. Moreover, we present a review of potential applications of integrated fuzzy SD models in construction. Finally, we compare the performance of SD with integrated fuzzy SD for a construction-related problem adopted from the literature, and discuss how integrating fuzzy logic can enhance SD capabilities for construction modeling. For the remainder of this paper, system dynamics (SD) integrated with fuzzy logic will be referred to as fuzzy system dynamics (FSD).

This paper is organized as follows; first a brief literature review of FSD is presented, followed by applications of SD and FSD models in construction. Secondly, different methods of integrating SD and fuzzy logic are discussed. Then, a comparison is made between SD and FSD models in a construction-related problem, followed by a discussion of how the integration of SD with fuzzy logic can enhance the capabilities of SD in construction modeling. Finally, future extension to the current research is discussed.

2 LITERATURE REVIEW

2.1 Fuzzy System Dynamics

Levary (1990) introduced the idea of integrating SD with fuzzy logic in order to enhance the capability of SD models for simulation of real-life systems. Common approaches of SD modeling use crisp numbers to define the variables, and the relationships between the variables are defined by either mathematical or table functions. However, there are subjective variables in real-life systems which are better expressed in linguistic terms than crisp numeric values (e.g., good weather). Therefore, as Levary (1990) discussed, integrating SD and fuzzy logic solves a major problem associated with quantitative variables modeling. Integration of these two methods has two requirements: (1) defining subjective variables by fuzzy membership functions and (2) defining the interrelationships between the fuzzy variables either by using fuzzy arithmetic in mathematical equations or fuzzy rule-based systems.

Ghazanfari et al. (2003) presented a review of the literature of different approaches for integrating fuzzy logic and SD modeling. Polat and Bozdag (2001), Nasirzadeh et al. (2008), and Khanzadi et al. (2012) provide some examples of applications of FSD models in different disciplines. Tessem and Davidsen
(1994) developed a simple FSD model with three fuzzy variables for population estimation using fuzzy arithmetic in mathematical equations. They pointed out that the use of fuzzy arithmetic in their system caused fast growth of the support of the fuzzy output (i.e., population) and the output of the system contained too much uncertainty. Sabounchi et al. (2011) developed a FSD model for product diffusion based on customer-based propagation of product (i.e., word of mouth) using two fuzzy variables in a SD molecule. They replaced the equation that contained fuzzy variables with a fuzzy rule-based system to avoid the growth of the support of fuzzy outputs. In the FSD model proposed by Sabounchi et al. (2011), in each time step the output of the fuzzy rule-based system is defuzzified and used as a crisp input in other equations.

2.2 System Dynamics in Construction

Lyneis and Ford (2007) conducted an extensive review of applications of SD models in all disciplines of project management (software development projects, manufacturing, etc.). There have also been some recent applications of SD models for project management specifically in construction. Mowdesley and Al-Jibouri (2009) developed a SD model for simulation of construction productivity at the project level. Mowdesley and Al-Jibouri (2009) refer to the large number of the factors that affect productivity in construction projects and the complex relationships between the variables and conclude that SD models are good candidates for modeling productivity. Nasirzadeh and Nojedehi (2013) developed a SD model for the simulation of labour productivity in construction projects. Their model was composed of four sub-models, each with different levels of the factors affecting labour productivity. Nasirzadeh and Nojedehi (2013) assert that the factors that affect labour productivity are rarely independent from each other and that therefore, SD models are the best options for the simulation of labour productivity. Park (2005) referred to the dynamism of construction projects and proposed a SD model for resource management. The dynamic simulation of construction projects Park (2005) proposed minimizes the idle time of resources and decreases project costs. Despite the widespread use of SD models in construction contexts, some recent studies (e.g., Khanzadi et al. 2012) refer to some deficits of this modeling tool for construction modeling. Khanzadi et al. (2012) assert that because of the subjectivity of some variables in construction, integrating SD models with fuzzy logic can improve this modeling tool for the construction domain.

2.3 Fuzzy System Dynamics in Construction

Most applications of FSD models have been developed in business and the social sciences until recently. The FSD model for construction risk assessment proposed by Nasirzadeh et al. (2008) is one of the first applications of FSD models in construction. Nasirzadeh et al. (2008) adapted the SD model for risk management developed by Ford and Sterman (1998) for production projects to suit the construction context. They proposed the use of fuzzy numbers to represent the risks’ magnitudes and possibilities due to subjectivity and lack of historical data for probabilistic representation of construction risks. Fuzzy arithmetic, based on alpha-cuts (α-cuts) and interval analysis, was used to calculate the risk consequences. In the application presented by Nasirzadeh et al. (2008) there are only five major risks affecting the project, and the model has not been tested for more risk factors.

Khanzadi et al. (2012) proposed a FSD model to estimate the concession period of BOT projects. In their model, the concession period is estimated based on the magnitude of the project’s risks. The relationships between the fuzzy variables are defined using fuzzy rule-based systems and the results are defuzzified for further calculations. Nasirzadeh et al. (2013) developed a FSD model for quality management in construction projects. In their model, the variables affecting the quality management process are estimated as fuzzy numbers and entered as fuzzy inputs to a FSD model which uses mathematical equations and fuzzy arithmetic. Nasirzadeh et al. (2013) use fuzzy arithmetic based on α-cuts and interval calculations; however, they do not discuss their system’s problem of growing support in fuzzy results as previously pointed out by Tessem and Davidsen (1994).
3 METHODS OF INTEGRATION OF FUZZY LOGIC WITH SYSTEM DYNAMICS

As previously discussed in Section 2.1, integration of the SD modeling approach with fuzzy logic enhances the performance of SD for modeling real-life systems. Fuzzy logic can contribute SD modeling by defining linguistic and subjective variables and relationships for simulation of real-life systems. Moreover, fuzzy logic can model uncertain variables when sufficient historical data are not available for probabilistic distribution fitting. Integration of fuzzy logic with SD should be implemented in two steps: fuzzy variable definition and fuzzy relationship definition. The process of integrating the two methods is explained below:

1. Variable definition: The subjective variables that need to be defined with fuzzy membership functions should be selected first. Then, membership functions for defining the variables should be developed. Membership functions can be defined with one of several different approaches proposed by the literature, using expert judgment or historical data. Fuzzy c-means (FCM) clustering, for use when historical data is available, is one example (Bezdek 1981; Pedrycz and Reformat 2006).

2. Relationships definition: Once the subjective variables of the system have been defined with fuzzy membership functions, the relationships between these variables must be modeled using fuzzy logic techniques. For defining the relationships between the system fuzzy variables, there two alternatives:

   - Fuzzy arithmetic and mathematical equations: In this method, as in SD models, the relationships between the system’s variables are defined by mathematical equations. However, here the classical arithmetic is substituted with fuzzy arithmetic where some variables of the equations are fuzzy numbers. This method provides a quick approach for developing FSD models, as it is mostly based on pre-developed SD models but with the slight modification that some of the crisp variables are changed to fuzzy variables. However, the main deficiency of this method is the fast growth of the support of the fuzzy results of the system (Tessem and Davidsen 1994).

   - Fuzzy rule-based systems: In this method, the relationships between the fuzzy variables of the systems are defined by fuzzy rule-based systems. Fuzzy rule-based systems can be defined using a few different approaches. FCM clustering (Bezdek 1981) is an alternative for defining fuzzy rule-based systems where historical data is available. Khanzadi et al. (2012) used expert judgments for developing a fuzzy rule-based system in their FSD model where historical data was unavailable. Usually, the outputs of a fuzzy rule-based system have irregularly shaped membership functions. Therefore, the results must be either defuzzified or approximated by a regular membership function for further calculations. Defuzzification is the process of converting the fuzzy memberships to a single crisp value. The most common defuzzification method is the center of area (CoA) method.

The flowchart presented in Figure 1 summarizes the steps for developing a FSD model as discussed in this section.
4 APPLICATION OF FSD MODELS IN CONSTRUCTION

4.1 FSD Model for Crew-Related Factors Influencing Construction Productivity

In this section, we develop a construction-related SD model to illustrate how fuzzy logic can contribute to SD modeling for construction applications. In this model the effect of crew and labour characteristics on construction labour productivity at the crew level. Tsehaye and Fayek (2014) conducted extensive research on identification of the key parameters that influence construction labour productivity in different levels. They categorize the factors influencing construction labour productivity into 18 groups based on their sources. For the model developed in this study uses only one of these categories: crew and labour characteristics. Next, the factors that change on a daily basis and affect labour productivity at the crew level are extracted for modeling and are modified to some extent to fit the SD modeling approach. For developing the model, we studied three concrete construction projects and collected a total of 32 data points for the selected factors for analysis purposes.

For qualitative model development, each factor is analyzed to find which factors affect it (i.e., feature selection is performed). For this purpose, the correlation-based feature selection (CFS) method is used for its simplicity. Hall (1999) introduces CFS as a simple filter algorithm which ranks the features through a heuristic evaluation function. The CFS algorithm uses historical data and identifies the features that have the greatest effect on each variable. Table 1 shows the variables of the system and the attributes selected for each factor that are used for developing causal loops. Then, based on the results of CFS, the
causal loops for each variable of the system can be identified. Finally, the qualitative model is developed as presented in Figure 2.

Table 1: Qualitative model variables and their selected attributes for causal loops

<table>
<thead>
<tr>
<th>Variable</th>
<th>Selected Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discontinuity in crew makeup</td>
<td>Crew size</td>
</tr>
<tr>
<td>Crew composition</td>
<td>Crew size</td>
</tr>
<tr>
<td>Crew size</td>
<td>-</td>
</tr>
<tr>
<td>Co-operation among craftspeople</td>
<td>Crew composition, fairness of work assignment</td>
</tr>
<tr>
<td>Fairness of work assignment</td>
<td>-</td>
</tr>
<tr>
<td>Motivation valence</td>
<td>Fairness of work assignment</td>
</tr>
<tr>
<td>Motivation expectancy</td>
<td>Fairness of work assignment, labour productivity</td>
</tr>
<tr>
<td>Motivation instrumentality</td>
<td>Fairness of work assignment, labour productivity</td>
</tr>
<tr>
<td>Labour productivity</td>
<td>Crew composition, crew size, co-operation among craftspeople,</td>
</tr>
<tr>
<td></td>
<td>fairness of work assignment, motivation valence, motivation</td>
</tr>
<tr>
<td></td>
<td>expectancy, motivation instrumentality</td>
</tr>
<tr>
<td>Production rate</td>
<td>Labour productivity, crew size, working hours</td>
</tr>
<tr>
<td>Working hours</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2: Qualitative FSD model for crew-related factors influencing construction labour productivity

Like the SD model, the FSD model is based on the qualitative model presented in Figure 2. However, the difference between the two approaches lies in their method of quantification (i.e. definition of the variables and their relationships). For quantification purposes, the SD model considers all the variables as crisp variables and the relationships are defined by mathematical equations using statistical extrapolation. To define the relationships between the variables in this model using statistical extrapolation, this model uses
the linear regression method. Two of the model's equations are presented in Table 2: (1) labour productivity, the measurement of which is the main objective of the model, and (2) production rate, which is used to compare the results of the SD model with those of the FSD model. The equation for calculating the production rate is selected for further comparison with the FSD to show that FSD models can also accept crisp values in their equations. Based on the equations presented in Table 2, the accuracy of the two models in defining the relationships between their variables is discussed. Once the relationships between the system variables are defined by mathematical equations, quantification of the SD model is complete.

For quantification in the FSD model, first, the subjective variables (i.e., cooperation among craftspeople, fairness of work assignment, motivation valence, motivation expectancy, and motivation instrumentality) of the system are defined by fuzzy membership functions. Since labour productivity is a function of both these fuzzy variables and other crisp variables (i.e., crew composition and crew size), it is also defined by membership functions. As discussed in Section 3, the resulting membership function for labour productivity can be defuzzified to find the crisp value for labour productivity. FCM clustering is an approach for defining of the fuzzy membership functions when historical data are available. In this model, triangular membership functions are selected while they are simple and widely used. Therefore, all variables of the system are defined by triangular membership functions using FCM clustering method. The membership functions which define labour productivity are presented in Figure 3 as an example. The next step for quantification of the FSD model is defining the relationships between the fuzzy variables as mentioned in Section 3. For defining the relationships between the fuzzy variables, fuzzy rule-based systems are selected. Where the historical data is available, FCM clustering is used for development of the fuzzy rule-based systems. The fuzzy rule-based system developed for estimating labour productivity is presented in Table 2.

![Figure 3: Labour productivity membership functions developed by FCM clustering](image)

The results of the fuzzy rule-based system can be defuzzified and used in further calculations of the system. In the example shown in Figure 2 and Table 2, labour productivity is defuzzified using the center of area (CoA) method and used to calculate the production rate.

Once quantification is complete, the accuracy of the two models is tested for predicting labour productivity using the historical data. While the performance of the models strictly depends on how well the variables and their relationships have been defined, the model with the more precise estimate for the variables potentially performs better for simulation. Results of the analysis show that in this case, the FSD model with the fuzzy variables and fuzzy rule-based system predicts a labour productivity value with a root mean square error (RMSE) of 0.19. However, the SD model with the mathematical equation as presented in Table 2 predicts a labour productivity value with a RMSE of 0.24.
### Table 2: Relationships between variables of the FSD and SD models

<table>
<thead>
<tr>
<th>Model</th>
<th>Relationship</th>
<th>Unit</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>$\text{Productivity} = 0.30 - 0.15 \times \text{crew size} + 0.10 \times \text{crew composition} + 0.09 \times \text{cooperation among craftspeople} - 0.30 \times \text{fairness of work assignment} + 0.09 \times \text{motivation expectancy} + 0.09 \times \text{motivation instrumentality}$</td>
<td>$(\frac{m^3}{mhr})$</td>
<td>$0.24$</td>
</tr>
<tr>
<td></td>
<td>$\text{Production rate} = \text{Working hours} \times \text{labour productivity} \times \text{crew size}$</td>
<td>$(\frac{m^3}{day})$</td>
<td></td>
</tr>
<tr>
<td>FSD</td>
<td>1. If (crew size is high) and (crew composition is low) and (cooperation among craftspeople is low) and (fairness of work assignment is low) and (motivation expectancy is low) and (motivation instrumentality is low) then (labour productivity is low)</td>
<td>$(\frac{m^3}{mhr})$</td>
<td>$0.19$</td>
</tr>
<tr>
<td></td>
<td>2. If (crew size is average) and (crew composition is average) and (cooperation among craftspeople is average) and (fairness of work assignment is average) and (motivation expectancy is average) and (motivation instrumentality is average) then (labour productivity is average)</td>
<td>$(\frac{m^3}{mhr})$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. If (crew size is average) and (crew composition is high) and (cooperation among craftspeople is high) and (fairness of work assignment is high) and (motivation expectancy is high) and (motivation instrumentality is high) then (labour productivity is high)</td>
<td>$(\frac{m^3}{mhr})$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\text{Production rate} = \text{Working hours} \times \text{labour productivity} \times \text{crew size}$</td>
<td>$(\frac{m^3}{day})$</td>
<td></td>
</tr>
</tbody>
</table>

The results of analysis of the SD and FSD models shows that the integration of fuzzy logic with system dynamics can increase the accuracy of the resultant model when there are subjective variables in the system. In this study, historical data were available and used for the definition of the fuzzy variables' membership functions and the fuzzy rule-based system for the FSD model. In cases where historical data are unavailable, other methods of defining the fuzzy variables and fuzzy rule-based system—such as expert judgment and consensus methods—can be used.

### 5 CONCLUSION

Integration of the system dynamics (SD) modeling approach with fuzzy logic develops a powerful tool for construction modeling which captures the subjectivity and complexity of construction projects at once. In this study, integration of SD modeling with fuzzy logic is illustrated and some applications of these models in construction are presented. Moreover, an application of SD and fuzzy SD (FSD) approaches for modeling the effect of crew characteristics on construction labour productivity at the crew level is presented. The comparisons between the two models (i.e., the SD model and the FSD model) verified that the FSD model is more accurate in predicting construction labour productivity at the crew level based on the sample model. However, this study only develops sub-models for the purpose of testing and comparing their performances in a construction context. To extend this research, a comprehensive model for simulating construction labour productivity can be developed. Moreover, in this study, a fuzzy rule-based system is used to define the relationship between the system variables, which results in a better performance than when linear regression is used for this purpose. The relationships between the system variables are usually defined by extrapolation methods. However, the mathematical equations that are used in SD models can also be substituted with artificial intelligence tools (e.g., neural networks). Investigating which options for defining the system variable relationships in SD models might serve as the best substitutes for statistical extrapolation is another area of extension to this study.
Acknowledgements

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References


A NEURAL NETWORK BASED MODEL FOR COST ESTIMATION OF INDUSTRIAL BUILDING AT THE PROJECT’S DEFINITION PHASE

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Abstract: Annually there are many small-scale industry projects implemented in Iran, most of which are financed by local financial institutes. The financing agreements between project owners and financial institutes are usually formed and finalized during the initiation phase and are based on feasibility studies done at the early stages; before project design and construction begin. However, in many cases actual costs of projects exceed the costs estimated in feasibility studies which have been approved by financial institutes. Limited financial resources in the country, from one side, and the lengthy process of increasing the project financing limit, from another side, cause delays in the project completion. In many cases the cost increase and the delay make the entire project unfeasible; projects stop forever; a big waste of money is the result. To respond to this issue and improve accuracy of cost estimation prior to the design and construction phases, in this research we have developed a new cost estimation model based on neural network method. At this stage of the research the model is implemented and tested for the main industrial building, which usually has a portal frame structure. Results indicate a reasonable improvement in accuracy for the estimated costs.

1 INTRODUCTION

Small-scale industry projects constitute a considerable part of industrial construction projects in Iran. Statistics for 2014 show that small industries account for 92% of the industries in the country, and that 40% of the total industrial employment is in small industries. (Fars News Agency 2015). Owners of small-scale industry projects generally own smaller industries and workshops and they are completely familiar with their target market. They feel the need to expand and develop their industries and want to increase their production power. So, they take steps to introduce industry projects, but generally they lack suitable project management knowledge. Funds needed to meet the costs of these projects in the country are provided jointly through project owner investments and financing banks. The initial capital required for carrying out projects is one of main factors contributing to the economic justification of building them. However, in many small-scale industry projects in Iran it is observed that the actual costs exceed the estimated capital. This causes many projects to face problems in providing funds during the construction phase. Moreover, many owners of such projects have limited assets and cannot meet the increased costs. On the other hand, increasing bank loan ceilings requires complicated processes and is time consuming; and, in many cases, banks no longer agree to raise their loan ceilings for the projects since elevated costs pull the projects out of their profitability margins.
Compared to large industries, small-scale industry projects generally include limited production lines; a greater part of construction costs in these industries are related to buildings and civil works required. Studies conducted on 30 industrial projects showed that construction expenditure in industrial projects with costs of less than 20 million dollars (small-scale industry projects) constituted 20% of the total costs, while in industrial projects with costs of over 20 million dollars this figure declined to 12%. Moreover, studies have shown the main industrial building accounts for the main part (58%) of the total buildings and civil works in the projects. Furthermore, most owners of these projects need to make sure banks will finance their projects before they start the design and building phases. Therefore, signing a contract with the bank for financing the project usually takes place before the detailed design and based on the initial feasibility studies. Moreover, it is difficult to estimate accurately the costs of constructing civil engineering facilities just by knowing specifications regarding their initial dimensions, and this will reduce estimation accuracy and lead to errors in cost estimation of these facilities. Study of 30 industry projects mentioned above suggested the mean deviation from the allocated budgets for industrial projects was 16% while this figure rose to 30% for the building and civil work parts. Higher variations in cost estimation of civil works compared to production line in small-scale industries originate from the fact that manufacturers of these production lines are usually specialized and have many past experiences in making specific types of machineries required; they already have design of production line machineries and can provide accurate estimations in the early stages. Therefore, what actually causes costs of small-scale industry projects to deviate from the predicted values is inaccurate cost estimation in buildings construction and civil works which need to be custom designed and built. This is also the case for main industrial buildings in which the costs deviate 28% from the allocated budgets.

Inaccurate cost estimation is accompanied by the possibility of increased construction costs because it will cause delays in paying construction contractors, and it will increase the possibility of contractual disputes. The time-consuming process of bank approval in raising loan ceilings, and the loss of economic feasibility of the projects due to increased costs, cause work stoppages in industrial projects or lead to their annulment and termination, as confirmed by the fact that there are 2900 unfinished small-scale industry projects in the country (ISNA press 2014). The importance of initial estimation and its tangible effect on success or failure of a project to the end led us to develop an estimation model based on neural networks in this research. This model is going to receive preliminary specifications of the project, which are determined in the early stages of the project prior to the project design, as the main input and return relatively accurate cost estimation of the project as its output. Though, because of its significant cost contribution and cost estimation variations, in this part of the research our main focus is on the main industrial buildings. Almost in all small-scale industrial projects we studied, including the above mentioned 30 cases, the main industrial buildings were constructed based on portal frame steel structure. So, the model was specifically developed for steel portal frame buildings. With the cooperation of the specialist group for designing and constructing steel portal frame structures for industrial buildings, we designed and used 324 portal frames with various specifications and dimensions based on geographical and environmental features of Tehran province to develop our model, to increase its accuracy, and to train the developed model. Results of validation of the model by using it in actual small-scale industry projects in Tehran province showed a high accuracy in cost estimation.

2 LITERATURE REVIEW

Ellis and Turner in 1986, and Proctor, Brown, et al. in 1993 showed that cost proposals offered by construction contractors were usually higher than the initial estimates and predictions of employers. In recent years, in an effort to narrow this gap, and with the advances made in information technology, new cost modeling approaches based on preliminary project parameters using computer software have been introduced. In 1996, Fortune and Lee compared the reliability and value of these new methods of modeling with those of the conventional ones and demonstrated the new models were more valuable than the conventional ones. Since then, extensive studies were conducted on cost estimation in the early stages of projects by using the new methods developed by computer software.

In 2006, Lowe et al. used multiple regression methods on 286 datasets collected on construction projects carried out in England to predict costs of building construction. They based their cost estimation model on
cost per square meter, cost logarithm, and cost per meter logarithm, and introduced six models by performing the two kinds of forward and backward stepwise regression analysis. Finally, the back propagation algorithm cost model showed the best result with a correlation coefficient of 0.661 and mean absolute percentage error of 19.3 percent. These results were comparable with those of previous studies that reported the mean absolute percentage error of cost estimation using conventional methods was about 25 percent. The data Lowe et al. (2006) used for modeling in 2002 was employed by Emsley et al. to develop a neural network model for estimating the total construction cost. Comparing the results of these two studies showed that the performance of the neural network model was a little better than that of the regression model. Sonmez (2004) also studied the use of regression methods and neural networks in conceptual cost estimation models (predesign cost estimation models) in construction projects. He used 30 datasets related to costs of building projects (houses, treatment centers, and public buildings) belonging to the Social Security Administration in 14 different states of the United States built during 1975-1995, and employed the range estimation method to determine cost ranges. The regression model and the neural network models were compared with respect to goodness of fit and prediction performance using the two criteria of mean square error and mean absolute percentage error. Results indicated the neural network models fit the data better.

Superiority of the artificial neural network method in estimating construction costs in the early stages of projects, and comparison of its results with those of other methods, have been the subject of many other studies as well. For example, Garza and Rouhana in 1995, Bode in 2000, Park et al. in 2002, Gunaydin and Dogan in 2004, Kim et al. in 2007, Arafa and Alqedra in 2011, Petroutsatou et al in 2012, and Kim et al in 2013 conducted similar studies in this regard. In most of these studies, the researchers concluded that artificial neural networks were more useful for cost estimation in the early stages of construction projects and yielded better results. Under conditions of great uncertainty, back propagation neural networks are more suitable for estimating the cost of the finished product, and are a useful tool for cost estimation and for dealing with nonlinear questions. These models do not have the limitations of regression analysis models such as assuming a specific type of equation (e.g., polynomial) for project costs and its related variables, or the limitations of the conventional cost breakdown methods such as the need for accurate costs and detailed quantity information. Of course, one of the challenges faced in using neural networks is that a relatively large number of samples are required for training the model and for testing its efficiency and accuracy.

Although many studies have been conducted on estimating construction costs in the predesign stage, estimation of the initial costs of production buildings in industrial projects has not received much attention. Production buildings have different structures, construction methods, applications, parameters influencing costs, and manner of calculating costs from residential buildings which have mainly been address in previous estimation models. Therefore, this research studied the development of a new model based on using neural networks to meet the need for cost estimation and calculation related for portal frame industrial buildings in the predesign stage.

3 THE COST ESTIMATION MODEL

The cost of steel structure of industrial buildings depends on various factors such as the required workforce, price of steel in the market, transportation cost, etc. One of the main factors influencing costs of steel structures is the weight of steel used or more commonly called the steel structure weight. Therefore, an accurate estimate of the weight of steel to be used must be made before estimating costs. That is why this study was divided into two main phases. In the first phase, a model was built for estimation of the portal frame steel structure weight based on initial specifications. The output of this model, and other parameters influencing costs of steel structures, were then used in the second phase as the input of the second model to estimate construction cost of the steel structure so that a suitable estimate can be made of the costs of the main production building or the steel structure. Figure 1 shows the conceptual cost estimation and calculation model for the production building. The part marked by dotted lines represents the first modeling phase (which is the subject of this article).
3.1 Factors influencing the weight of portal frame steel structure

Portal frame industrial buildings are mostly one-floor structures with pitched roofs and vertical members (e.g., columns), sloping member (e.g., rafter), and diagonal members (e.g., wind braces) which are used to cover large spaces. One of the most important criteria determining the cost of a portal frame steel structure is the weight of the steel used, which itself is a function of various geometric and non-geometric specifications of the project. That is why sessions were held with experts in the design and construction of steel structures to ask their views on factors influencing the weights of steel structures. A joint research group including experts, designers, and builders of portal frame steel structures was formed to identify and evaluate importance of factors affecting the weight of portal frame in industrial buildings. These factors and their effects on the steel structure are briefly described below.

1. Building width: Increase of the building width or building span increases the length of rafters. Therefore, the bending moment resulting from the dead weight of the roof, snow and wind loads is also increased, which will naturally increase the weight of the structure.

2. Height of the hall (from the ground to the apex): With increases in the height of the steel structure, the effects of wind load on the columns and on the rafters will be intensified, and these effects in the moment diagrams of the rafters and the columns will include changes in the second degree. Another important factor in this case is the increase in the tenderness ratio and, consequently, the decrease in permissible compressive stress. These factors together necessitate the use of heavier sections.

3. Hall length: increases in the length of the steel structure will increase its weight, which in fact is the deciding factor in determining how much force an earthquake impacts on the steel structure. This will even more increase the weight of the steel structure.

4. Snow load of the region.

5. Other loads such as the crane, the indoor floors, the false ceiling.

6. The number of spans or the sharing of the base with side steel structures: although increases in the number of spans raise the reliability coefficient of the structure against collapse resulting from wind and earthquakes, the added members increase the weight of the steel structure.
Therefore, the input parameters of the model were selected from these factors to build the neural network model. The reason was that they are not only the most important factors influencing the weight, and hence the cost of the steel structure, but are also among the preliminary specifications of the main industrial building that are determined before the design process in the early stages of project definition.

3.2 Designing various types of portal frame steel structure

Results of research conducted by Gunaydin and Dogan in 2004 showed that the performance of the artificial neural networks in cost estimation strongly depended on the quality and quantity of the samples because neural networks are trained by data related to samples. Prediction error decreases with increases in the number of samples. Therefore, reliable, high quality, and full-scale data concerning costs of various types of buildings under different conditions is required to study modeling methods and to predict and build an accurate cost estimation model. To obtain such data, it was decided to ask the expert design team to design the required samples needed for building the neural network model by changing factors that influence the weight of a portal frame steel structure. In changing these effective factors, it was taken into account that the samples used to train the neural network had to be able to cover the range of values related to steel structure specifications that may actually be used in designs related to small-scale industry projects. Therefore, small-scale industry projects were studied and the opinions of the builders and designers of structures used in these projects were asked to identify the range of changes in factors that influence the weight of the steel structures, and to use this range in selecting samples that formed the input of the neural network. In all, the design specialist team identified 324 steel structures through changing the factors that influence the weight of the steel structure so that we could conduct our research.

The types of loading structures vary in different regions of the country, and so do the snow, wind, and earthquake loads. Therefore, in this stage of the research, structure designs in Tehran Province were studied. The same dead load, live load, and earthquake load were considered for all models, and the geometric specifications of the structures and the snow and wind loads in Tehran were taken into account in considering the base snow, wind, and crane loads. Furthermore, the maximum difference in stress ratios of the main members similar in the structures of various models was considered 10% in order to extract output results with suitable accuracy. Moreover, the standard stress ratio of the main members of the structures was considered 0.9%; and, considering this ratio, we can say that the design process was carried out optimally. The steel materials commonly used in building steel structures in the country are of the ST-37 and ST-52 types. However, taking into account the industrial structures commonly built, considering the consultations we had with design consultants, and as the needed samples were to be used in small industries, the ST-37 type was selected in designing the samples. Furthermore, given the variety in soil resistance in different places, and considering Tehran is located on the southern slopes of the Alborz mountain range, it was deemed suitable to consider soil type to be grade 2 in calculating earthquake coefficient.

Study of changes in the dimensions of the spans in steel structures without ceiling cranes showed that snow load (as expected) was the dominant load combination in large-span structures because of the large area of the ceiling. However, in small- and medium-size structures the snow and the wind loads were of equal importance in the dominant load combination. Changes in the overall length of the structures did not change the dominant load and section specifications. Changes made in the height of the crown also yielded the expected results, and it was found that wind load was the dominant load in structures with great heights because of the large area of the structure, while the snow load was the dominant load in structures with medium and low heights. Changes in the number of spans indicated that the load combination consisting of the snow load and the earthquake load was the dominant load in the middle columns of these structures, while the load combination including the snow load and the dead load was the deciding load in the lateral columns.

All built models were then studied with the presence of ceiling cranes having 10, 20, and 30-ton capacities under the previous modeling conditions. After examining the output of the V16SAP2000 software, it was found that in all of the built models, except for structures with great heights, the load
combination consisting of the crane load and the snow load, and the load combination consisting of the dead weight and the snow load, were the deciding load combinations to similar degrees. In structures with great heights, the load combination consisting of the wind load and the snow load was the only critical load combination. Study and comparison of the models showed the minimum changes in the weight of the structures resulting from increases in the weight of the cranes were those of the structures with great heights because the wind load became the dominant load when the weight of the cranes was added. Moreover, weight changes were not significant in structures with large spans compared to other geometric changes because the snow load was the dominant load. It is worth mentioning that when a crane is added to the structure, the weight of the crane supporting beams must also be included in the weight of the structures and be taken into account in calculations regarding the weight of structures that have cranes.

3.3 Training the neural network of project cost estimation model

In building the neural network model, the data designed in the previous section was used. Creation of network architecture requires the determination of its various components such as the number of intermediate layers, the number of neurons in each layer, and the activation function. This proposed model has five processing elements (neurons) in the input layer and one processing element (neuron) in the output layer. The trial and error method was used in developing the intermediate component of the neural network to obtain a network with the best performance. In the end, the intermediate component with one layer and six processing elements (neurons) was selected for the model because its performance was more desirable compared to other networks.

![Figure 2: The architecture of a neural network model](image)

Table 1 lists the input parameters of the network. These are the same parameters that influence the weight of the pitched roof portal frame and were introduced in section 3.1. Their specifications are presented in Table 1. Considering the explanations offered in section 3.2, and since the proposed model is for Tehran Province, soil type and geographical characteristics are considered constant in this stage and are not included among the model inputs.
Table 1: Parameters used in designing the model

<table>
<thead>
<tr>
<th>Design parameter (1)</th>
<th>Definition (2)</th>
<th>Range (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>Width</td>
<td>6-30 m</td>
</tr>
<tr>
<td>X2</td>
<td>Length of the hall</td>
<td>18-72 m</td>
</tr>
<tr>
<td>X3</td>
<td>Height</td>
<td>6-24 m</td>
</tr>
<tr>
<td>X4</td>
<td>Number of bays</td>
<td>1-5 m</td>
</tr>
<tr>
<td>X5</td>
<td>Crane load</td>
<td>Without crane (0), 10-ton crane (1), 20-ton crane (2), 30-ton crane (3)</td>
</tr>
</tbody>
</table>

Three hundred and twenty four designed samples were used to train the neural network. The data was divided at random into three groups. The first group with 70% of the data (the equivalent of 227 data items) for training the neural network, the second group with 10% of the data (or 32 data items) for validation, and the third group with 20% of the data (the equivalent of 65 data items) for examining model efficiency and for testing the model. All the stages of building, training, and testing the model were carried out by using Matlab R2014b. The activation function determines network behavior and is of great importance. After comparing the efficiencies of the various functions, the hyperbolic tangent sigmoid function was used for the intermediate layer (equation 1), and the linear activation model was used for the output layer.

\[ \text{Hyperbolic tangent sigmoid} (x) = \frac{1 - e^{-2x}}{1 + e^{-2x}} \]

One of the important points in creating a neural network model is the determination of the algorithm for training the network. Various algorithms have been developed and introduced so far for training neural networks. Based on a study conducted by Rumelhart (1986) et al., the back propagation algorithm, which follows supervised teaching practice, is very efficient for building nonlinear models and is widely used. We also used this method for training the neural network in our research. Accordingly, the method is used in the current research for training Neural Network is forward training of Neural Network relied on Marquardt algorithm and employed the function of minimum squared error (MSE) for correcting weights during the training of the network (Hagan et al. 1994). The network was thus trained and a trained model with \( R = 0.9974 \) was obtained for the training data. After training the model with the 227 samples, its efficiency was evaluated using testing data. In this stage, the weights of steel used in 65 samples were first estimated by employing the neural network model, and the calculated weights were then compared with the actual ones (obtained from detailed design). Figure 3 shows results of the comparison.
Figure 3: Comparison of the actual values with those estimated by the neural network model for testing data

The percentage relative error was used to evaluate the accuracy of the model in estimating the data. The percentage relative error of the testing data was calculated using equation 2. Study of the accuracy of the estimates made by the model in the testing data showed that the proposed model had a suitable performance with 95% accuracy and could well be used in the early and pre-design stages in small industrial projects.

\[
\text{Percentage Error} = \left( \frac{\text{Estimated Weight}(i) - \text{Actual Weight}(i)}{\text{Actual Weight}(i)} \right) \times 100\%
\]

4 CONCLUSION

In this research, a model based on neural networks was developed for estimating the cost of main industrial buildings for small industry projects in the pre-design stage. In the first part of the research a model was developed for estimating the weight of steel used in portal frame industrial building. Coordination was made with the professional group that designed the portal frame and 324 portal frame steel structures were designed by changing values of factors influencing the weight of these frames to increase the accuracy of the calculations. The neural network model was then trained and evaluated using the above-mentioned data and, finally, a model was obtained with the accuracy of 95%. The weight and cost estimation model of the portal frames developed is based on preliminary dimensional characteristics of the structure which helps consultant engineering companies to increase accuracy of their estimates in their feasibility studies. It also enables them to better evaluate the prices offered by contractors. More accurate estimations during initial phase also accelerate the preparation of bidding documents, increase reliability of prices offered, and decrease the probability of deviating from the allocated budgets with the consequent fines falling behind schedule or for delays in the project due to insufficient budget. Moreover, financing banks will be able to use similar models and software to increase their accuracy and reduce their risks. Although the introduced model was developed based on geographical specification of Tehran, it can be easily expanded to other regions by proving the geographical specification of the desire location as inputs to the model. Results obtained from the model will be presented to those active in small-scale
industries including owners of projects, banks, consultant engineers, and builders to make more improve their projects construction phase.

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A TIME-COST-QUALITY TRADE-OFF MODEL FOR NUCLEAR-TYPE PROJECTS

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Abstract: The purpose of this paper is to introduce a generalized multi-dimensional joint confidence level model for nuclear refurbishment planning, using the Darlington retube and feeder replacement (RFR) project (which is a multi-billion dollar effort) as a research platform. The intentions of this model are twofold: (1) determining the best set(s) of cost, schedule, and proxies for quality such as radiation expenditures by incorporating the variations of work-shift models on both the activity duration distributions and the logic of the work flow, (2) improve the expected reliability and predictability involved in the resource allocation system (schedule), by “efficiently” integrating the influential project factors, constraints, and labour shift models associated with the schedule. An effective Monte Carlo based time-cost-quality trade-off model is contributed for examining the performance and risk impacts of various work-shift designs and thus supports the choice of an optimal work-shift design.

1 INTRODUCTION

1.1 Background

The four CANDU nuclear reactors at the Darlington Nuclear Generating Station supply about 20 % of Ontario’s power needs. These reactors require a multi-billion dollar Retube and Feeder Replacement (RFR) Project that will begin in 2016 and will continue for approximately 12 years. Research has clearly established that the greatest driver of success in such megaprojects is project definition, which includes engineering, project management, quality, schedule, target costs, and safety plans. This process should optimize productivity and manage resource allocation effectively so that the RFR project is successful in terms of cost, schedule, safety, quality, predictability, and participant satisfaction. In this project, a unique full-scale mock-up of the reactor’s fuel channels and feeders has been constructed and used for testing the functionality of tools, for training personnel, and for optimizing processes to achieve the stated objectives. With 960 calandria tubes, fuel channels, and inlet and outlet feeders, the RFR processes will be repeated cyclically in a manner that challenges conventional concepts of construction project scheduling and resource allocation. Unique constraints abound: radiation dosage limits, number of people allowed in the vault, and schedule milestones are among them. The varying impact on labour productivity of round-the-clock work-shift designs is only one of many additional challenges involved.

The main question that will be addressed in this paper is the optimal allocation and scheduling of resources in such a situation. The primary objective is thus to develop a tool that will support determination of the best strategies based on cost, schedule, and proxies for quality for allocating
resources for nuclear retube and feeder replacement projects by: (1) identifying and including relevant constraints, such as the number of people allowed in the vault and the labour turnover that results from reaching radiation limits; (2) incorporating parameters such as estimated craft productivity and variations in process time; (3) addressing conflicting project objectives; (4) examining "what-if" shift-work designs and discovering possible systematic improvements; (5) estimating the impact of changes; and (6) providing an understandable and practical approach. The full-scale mock-up and training facility constructed in May 2014 helps enable the validation of this tool.

The methodology for this study will build on advances made by colleagues in the construction and industrial engineering and management fields in the area of hybrid models for construction trade-off problems (AbouRizk et al., 2011, El-Rayes & Moselhi 2001, Froese 2010, and Nasir et al., 2003). For example, commercial software exists for incorporating stochastic modelling into critical path method (CPM) schedules for Monte Carlo type simulations and analysis, however the cyclical nature of much of the RFR work lends itself naturally to the logical branching capabilities of discrete event simulation systems. Finding the most efficacious combination of these approaches considering the very unique objectives will be the focus of the next few sections of this paper.

1.2 Planning, Scheduling, and Estimating Complex Refurbishment Projects

Managing a well-structured schedule involves satisfying project objectives, optimizing resource allocation, and mitigating uncertainties. This is in general the problem encountered in this study. Some related insights and challenges are discussed below.

1.2.1 Association for the Advancement of Cost Engineering (AACE) Scheduling and Estimating Classification System

As a recommended practice of AACE International, the Cost Estimate Classification System provides guidelines for applying the general principles of estimate classification to project cost estimates. As noted by the Recommended Practice No. 18-R (2005), the Cost Estimate Classification System maps the phases and stages of project cost estimating together with a generic maturity and quality matrix, which can be applied across a wide variety of industries. The Cost Classification System consists of five estimate classes which are defined based on the level of project definition (known as the primary characteristic). Secondary characteristics on the other hand include: typical estimate purpose, typical estimating method, and typical accuracy range are correlated to the level of project definition. Class 5 represents the lowest level of project definition (with a low range of -20% to -50% and a high range of +30% to +100%) and the Class 1 estimate (with a low range of -3% to -10% and a high range of +3% to +15%) represents the closest to complete project definition (100%). These Class estimates will be used in this study as mentioned below.

1.2.2 Project Operations and Modelling Structures

Modelling project operations is one way to increase predictability and improve visualization prior to project execution (Russell et al., 2009, Mohamed et al., 2007, Zayed & Halpin 2004). Examples of modelling tools in construction are serious gaming environments, 3D and 4D visualization techniques, and discrete event simulation (DES) tools such as CYCLONE, COSYE, and STROBOSCOPE (AbouRizk et al., 2011). DES tools provide intuitive environments and functional elements that can accurately model and simulate construction operations (Puri & Martinez, 2012). However, validation of DES models is challenging. Challenges include: insufficient data causing high variance of output, project managers required to be knowledgeable about simulation tools and their workability, and the assumption that operations and time-slots involved with activities are independent and discrete, meaning that incorporating stochastic modelling for continuous sets of data results in further errors (Puri & Martinez, 2012; Rekapalli & Martinez, 2011). Scheduling and project operations modelling tools are often used for optimization of conflicting project objectives such as time and cost (Al-Hussein et al., 2005, El-Rayes & Moselhi 2001). Approaches used tend to be heuristic or based on advanced algorithms such as genetic algorithms. Linear and integer programming are almost never used for these problems because of the number of decision variables involved.
1.2.3 Uncertainty and Project Scheduling

Critical Path Method (CPM) scheduling is useful for effective completion of most construction projects. Although CPM calculations have proven to be simple and straightforward, CPM-based scheduling is a challenging process, and it may fit reporting and documentation purposes more than decision support systems that reflect reality (Hegazy & Menesi, 2010). Some of these challenges include: problems with interference of constraints in a multi-constrained schedule, problems with multiple complex relationships, and inaccurate schedule calculations. While many studies have been conducted to tackle some of these problems, in 2010 Hegazy and Menesi argued that previous methods led to analysis at rough levels of detail that cause errors in calculations (Hegazy & Menesi, 2010). In addition, most schedules are developed using a deterministic approach. Methods such as PERT are meant to address this problem by providing statistical distributions for activity durations that reflect uncertainty. Unfortunately, these methods have limitations. They assume that activities are independent, more effort is required to provide estimated values, and there is no recognition of critical path variations (Nasir et al., 2003).

One common assumption of scheduling theory is a static environment which may lead to no formal justification for unexpected events. The result is deviation from the project plan (Ahmed at al., 2003), therefore, identifying and classifying uncertainty to model and later reduce it to an acceptable level is an important aspect of project planning (Song et al., 2005). Many models have been developed to classify, model, and reduce uncertainty using artificial neural networks, simulation models, heuristic approaches, and logic work flows. These methods are claimed to be more accurate compared to traditional scheduling approaches such as CPM and PERT (Shaheen et al., 2009; Song et al., 2005; AbouRizk et al., 2011) yet the gap between virtual and actual project schedule environments (i.e. simulated uncertainties versus actual uncertainties) requires more investigation.

1.2.4 Integration of Stochastic Modelling and Project Scheduling Techniques

Capturing the impact of probabilistic project input (e.g., activity durations and cost) on the project output (e.g., total cost and completion duration) can help project managers to execute a more reliable and predictable project. Many tools have been developed to map the stochastic nature of project objectives with the schedule. Among these tools, well-known ones are @Risk™ (Palisade Corporation), Oracle and Primavera project portfolio management products such as Oracle Crystal Ball™ and Oracle Primavera Risk Analysis™ package. As @Risk™ for MS Project™ is used for this study, details follow. The @Risk™ software is an add-on to MS Excel/Project™ and suggests ways to use probabilistic analysis and Monte Carlo Simulation to visualize and quantify the uncertainty in projects and have more accurate cost and schedule predictions. This tool is also used for cost contingency. The approach of this planning method starts by creating a three point estimate (minimum, most-likely, and maximum) or defining a distribution based on historical data for both duration and cost of every activity within the schedule. After subsequent steps including Monte Carlo simulation output in the form of histograms of simulated results, a cumulative probability density graph illustrating schedule variation and exposure analysis graphs must be interpreted. However, such tools are primarily applicable to high level schedule estimation and do not provide complete and descriptive accurate results for intense (e.g. cyclic operations) and complex (e.g. multi-constraint) projects.

1.2.5 Radiation Limits and Impact on Labour

The estimation of radiation expenditures is one of the most important elements and the key constraint in this study, for the following reasons: (1) it has a direct impact on the health of the labourers while they are working at the reactor face, (2) reductions in the radiation expenditures can be achieved by altering the type of clothing (comfo, plastics, etc.) and through shielding in specific work areas which affects productivity; however, it cannot be eliminated, (3) the Canadian Nuclear Safety Commission (CNSC) Radiation Protection Regulations require the implementation of a managed system at nuclear sites in order to keep the amount of radiation absorbed by labourers (and members of the public) from radiation exposure as low as is reasonably achievable (ALARA). Radiation is measured in Roentgen Equivalent Man (REM) which is known as the dosage that will cause the same amount of biological injury as one rad of X rays or gamma rays. This requirement translates into specific radiation limits that are currently determined for each labourer for one-year (1 Rem-person) and five-year (5 Rem-person) time windows.
Once labourers reach either the one- or the five-year limit, they are assigned to non-radiated work areas, (4) while the initial cost and schedule estimations prior to project execution are set to zero, in this case, labourers do not walk in with a zero radiation dose but are expected to start the job with a "pre-existing" radiation rate that can be established and modelled as frequency distribution for a population of labourers, (5) the dose rate absorbed per labourer is reset on January 1st of each year. In this case, “reset” is defined as a radiation rate estimated for each labourer based on the average dose rate over a five-year time window, and (6) different activities are associated with different radiation rates because of varying distances from radiation sources.

1.2.6 Factors Associated with Labour Productivity

To obtain a good level of accuracy with respect to cost and schedule estimated, two items should be considered: (1) identification of factors that drive labour productivity, such as: shift length, temperature, and congestion, and (2) definition of the baseline. The baseline is defined as the neutral work condition, meaning that no additional effort is required from labourers beyond that necessary for them to complete their work during a standard shift (i.e., 5-8s). For this specific project, if a multiplier of one is considered for the neutral work condition (i.e., based on assessed hours), multipliers (i.e., weights) for work conditions other than neutral are assessed. For the proposed JCL model, factors are identified based on the Productivity handbook produced by CII (2014), which synthesizes over 50 years of quantitative research (CII 252-2d, 2014) and are assessed based on documents compiled by the Mechanical Contractors Association of America, Inc. (MCAA).

1.3 Joint Confidence Limit (JCL) Model

A JCL is an integrated uncertainty analysis for cost and schedule estimation, first introduced by NASA HQ-Program Analysis and Evaluation Cost Analysis Division (2009). This model combines the cost, schedule, and uncertainty (using Monte Carlo analysis) associated with a project in order to identify the relative probability that the cost and schedule “jointly” fall within the targeted budget and schedule dates. This process helps update management with respect to the likelihood of the programmatic success of a project. A JCL can be constructed from either of two types of input: parametric models or probabilistic resource-loaded schedule (PRLS) estimates. If a JCL is constructed in the early estimation phase, parametric models can be used, and then as the project estimation phase advances, PRLS can come into play. Information required as part of the input for the JCL includes the recent cost data and project schedule. A final requirement is that statistics such as the mean and standard deviation of the cost and schedule be available (NASA HQ, 2009).

The multi-dimensional JCL introduced in this paper is an extension to the described 2 dimensional JCL model with the third dimension being the quality proxy (i.e., radiation expenditures). This section will be later discussed in section 3.

1.4 Scope of Analysis

As vehicles for identifying the primary characteristics and interdependency of the three objectives (i.e., cost, schedule, quality proxy) within the RFR project, a work package known as the “feeder removal series” has been studied in detail. The rationale behind choosing this work package among many others include: (1) relatively high rates of radiation exposure at the workface; feeders are highly contaminated with toxic particles and labourers will be exposed to significant rates of radiation while removing the feeders from the reactor in the vault, and (2) labour-intensive work; feeders will be removed manually, leading to both expected and unexpected performance and productivity variations. To note that the combination of these two points creates a more challenging trade-off problem. Due to the wide range of variations that may possibly be caused by the two points, as a result of various work shift patterns and their interdependency, it becomes very interesting to explore the impact of these variations on the results of the Monte Carlo analysis and the MD-JCL model.
1.4.1 Feeder Description

Feeders are an integral part of the primary heat transport system (PHTS). The function of a feeder is to transport the D\textsubscript{2}O coolant from the inlet feeders to the fuel channels (FCs) and from the FCs to the outlet headers. There are 960 feeders: one inlet and one outlet feeder for each of the 480 FCs. Feeders must be replaced when significant thinning of the outlet feeders occurs. Removing the feeders is expected to have the added benefit of reducing the overall radiation rates in the vault, which will expedite the fuel channel removal and installation series.

2 MODEL OBJECTIVES

This section defines six interconnected sub-objectives related to finding good sets of solutions (defined mostly in this paper by crew arrangements) with an acceptable joint confidence limit for a complex schedule with the key objectives of minimizing variance while maximizing productivity. This is done through reasonable quantification and modelling of shift models, productivity factors, project constraints, and variations in the duration and cost of activities. The proposed multi-dimensional JCL model developed for the nuclear retube and feeder replacement and other similar projects must provide the following functions:

1. Identify and include relevant time and spatially dependent constraints such as the number of people allowed at the workface (i.e., vault), scheduling milestones, certified craft professionals available, etc.
2. Incorporate estimated probability distributions for craft productivity and process times.
3. Capture the impact of the uncertainty associated with activity durations and cost.
4. Define a quality proxy by measuring and reducing the impact of labour turn-over caused by labourers reaching radiation limits defined by radiation safety practices while being exposed to radiation sources at workface.
5. Address multiple objectives such as cost, schedule, and quality by developing a new multi-dimensional joint confidence level approach.
6. Be understandable, practical, and useful, with the potential to be adapted and applied broadly.

3 MODEL OVERVIEW

3.1 Duration and Cost

In order to produce a more transparent and traceable set of outputs, it is crucial to assess uncertainty which is inherited in the duration of each planned activity. Uncertainty primarily refers to the variability in duration of the schedule activities and the values of the base cost estimates, with the amount of variability dependent on the degree of ambiguity and accuracy in the schedule and cost estimate data utilized. Uncertainty is embedded in the duration/cost values and transforms deterministic values into distributions. Examples of sources of uncertainty include: cost and schedule estimating assumptions, variable productivity rates, variable material costs, and mobilization problems.

For this study, factors such as variable skill sets and levels of experience, inconsistencies between individual workers at different times, lack of knowledge of/or failure to understand the scope definition of project specifications, and inaccurate assumptions made about “unknown unknowns” are considered and incorporated in the determination of ranges during construction estimations.

Currently the RFR project is within the Class 3 estimate. Based on the Recommended Practice No. 18R-97 (2010) the expected accuracy range for the majority of Class 3 estimates is -20 % to +30 % (AACE International, 2010). This range is referenced and assumed in the “Darlington Nuclear Generating Station (DNGS) RFR Project – Project Estimate Plan.” AACEi warns that the range is heavily dependent on the nature of the uncertainties and the technological complexity involved in a project. For this study, the accuracy range suggested by AACEi was modified for the development of the duration distributions for individual activities included in the JCL model.
In order to provide unbiased uncertainty ranges for cost lines and schedule durations, the following requirements have been deemed important for the development of the MD-JCL model.

1. A high-quality project schedule
2. An estimate without contingency

3.2 Quality Proxy (Radiation Expenditures)

Quality is an objective that can be defined and measured through different channels (e.g., process, procurements, and results) (Takim & Akintoye, 2002). Since labourers have an enormous influence on the quality of the work being executed, it is critical to determine the specifications of factors that impact the quality of their production. In this project, being exposed to radiation plays a crucial role in terms of advanced resource training programs (assurance of overlap between current and future set of labourers), learning curves, number of certified labourers, etc. For these reasons, the linkage between labourers and their exposure to radiation is used as a proxy to represent quality.

The preliminary estimation of the radiation rate is based on task duration, scope of work, and comprehensive work package documentation and incorporates as input the resource requirements as well as the time the labourers remain in the radiated work areas. Current radiation expenditure estimates are derived from historical measurements taken when the unit fuel channel contained fuel and the systems were full of D₂O. For this study, the radiation rate per hour per person is used for calculations involving the feeder removal process. A rolled-up radiation rate is used for activities prior to feeder removal, and 25% of the yearly limit (i.e., 0.25 Rem/person) represents the pre-existing radiation expenditure rate. To obtain more accurate results, the pre-existing radiation rate for all labourers over a five-year timeslot is based on a distribution of possible pre-existing dose rates rather than on a single-point estimate (i.e., the average).

The collective radiation expenditure (pre-existing dose rate + hourly dose uptake) determines the number of labourers that reach the radiation limit as the project progresses. This measurement enables further advance evaluation that incorporates a determination of the number of labourers/resources who require training, which can take up to 2 weeks. This calculation is important because failure to train additional resources before the current resources reach radiation limits can create delays and lead to additional costs.

4 INITIAL STUDIES

For demonstration purposes, eight different cases have been considered. The variation between these cases is a result of variation in productivity rates caused by factors such as including different work-shift designs per worker, which are the following: (A) 40 hours a week, (B) 50 hours a week, and (C) 60 hours a week, and different crew arrangements. The basis of shifts A and B are on a 24/7 schedule and the base of shift C is on work continuum from Monday to Saturday, and Sunday considered as the non-working day. This is shown in the Calendar column of Table 1, with Y being a working and N being a non-working day. The number of crew available in the vault is constant for every shift, however various arrangements of labourers at the workface has been considered and represented by three options: I (i.e., 3 workers remove one feeder), II (i.e., 2 workers remove one feeder), and III (2+1/2 workers remove one feeder) for the feeder removal package specifically. As shown in Table 1, the last row is the deterministic estimation of duration, cost, and proxy for quality (radiation expenditures), based on 50 hours of work per worker and crew arrangement I. In the next step, the deterministic estimations were used as the basis for the Monte Carlo analysis and uncertainty was then incorporated by various probability density functions using @Risk. The output of the Monte Carlo analysis using both MS project and @Risk are presented in Table 1 after 1000 simulation runs for each case. As shown in Table 1, case 1 is the most suited option to be explored in detail.
Table 1: @ Risk Results for Eight Different Sets of Ranges

<table>
<thead>
<tr>
<th>Case #</th>
<th>Crew Arrangement</th>
<th>Shift</th>
<th>Duration (Days) (mean)</th>
<th>Cost ($) (mean)</th>
<th>Quality (Rem) (mean)</th>
<th>Calendar Sunday (Y/N)</th>
<th>Finish Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>I</td>
<td>A</td>
<td>33</td>
<td>$3,857,778</td>
<td>539</td>
<td>Y</td>
<td>11/6/16</td>
</tr>
<tr>
<td>Case 2</td>
<td>I</td>
<td>C</td>
<td>43</td>
<td>$4,629,333</td>
<td>711</td>
<td>N</td>
<td>11/21/16</td>
</tr>
<tr>
<td>Case 3</td>
<td>II</td>
<td>A</td>
<td>46.5</td>
<td>$4,667,911</td>
<td>770</td>
<td>Y</td>
<td>11/20/16</td>
</tr>
<tr>
<td>Case 4</td>
<td>II</td>
<td>B</td>
<td>36</td>
<td>$5,516,622</td>
<td>593</td>
<td>Y</td>
<td>11/9/16</td>
</tr>
<tr>
<td>Case 5</td>
<td>II</td>
<td>C</td>
<td>51</td>
<td>$4,629,333</td>
<td>840</td>
<td>N</td>
<td>11/30/16</td>
</tr>
<tr>
<td>Case 6</td>
<td>III</td>
<td>A</td>
<td>39</td>
<td>$5,516,621</td>
<td>652</td>
<td>Y</td>
<td>11/12/16</td>
</tr>
<tr>
<td>Case 7</td>
<td>III</td>
<td>B</td>
<td>39</td>
<td>$4,629,333</td>
<td>646</td>
<td>Y</td>
<td>11/16/16</td>
</tr>
<tr>
<td>Case 8</td>
<td>III</td>
<td>C</td>
<td>42</td>
<td>$5,015,111</td>
<td>700</td>
<td>N</td>
<td>11/15/16</td>
</tr>
</tbody>
</table>

Deterministic (Start day: 10/3/16)
Case 1
<table>
<thead>
<tr>
<th>Crew Arrangement</th>
<th>Shift</th>
<th>Duration (Days) (mean)</th>
<th>Cost ($) (mean)</th>
<th>Quality (Rem) (mean)</th>
<th>Calendar Sunday (Y/N)</th>
<th>Finish Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>B</td>
<td>30</td>
<td>$3,500,000</td>
<td>400</td>
<td>Y</td>
<td>11/3/16</td>
</tr>
</tbody>
</table>

Figure 1 represents the input distributions for duration and cost for the first two crew arrangements and the magnified figure shows the input distributions for the first case. The minimum, maximum, mean, 5th percentile, and 95th percentile of the distributions are also shown in this chart. The advantages of including the mentioned point estimates are twofold: (1) to comprehend and compare the variations of the outputs as the result of (defined) variations of the input sets, and (2) the ability to estimate the variance between the probabilistic objective values for a certain percentile (confidence level) and the deterministic estimates.

Figure 1: Output Results (Distributions) from the Monte Carlo Analysis using @Risk and MS Project
Based on the results, as the level of confidence increases, the gap between the deterministic objective estimation and the @Risk output becomes wider. As shown in Figure 2, there is a difference of 206 Rem between the deterministic estimation and an 80% confidence level for case 1.

![Figure 2: Cumulative Distribution Function: Quality Proxy-Case 1](image)

Each simulation trial of the proposed model produced a quantified range of parameters that impact project schedule objectives. The combined results of all of the simulation trials enables the development of the joint confidence level for cost, schedule, and quality proxy (radiation expenditures), which contributes to the determination of the best of many sets of parameter values and outcomes, thus achieving the research objectives. Figure below demonstrates the multi-dimensional joint confidence limit for all eight possible cases (8,000 data points). In order to demonstrate the functionality of the model, an 80% confidence level has been selected as the pilot study. The yellow points represent all possible combinations of cost “and” schedule “and” quality that meet jointly the 80% confidence level. The blue point represents the deterministic values for all three objectives, and the red point is a single point estimate representing the 80th percentile for all three objectives (based on 8,000 points) with the following values: duration: 45 days, cost: $5,262,051, and quality: 794 Rem. To note that the x axis is the duration (days), y axis is cost ($), and z is quality (Rem) for the entire feeder removal series.

![Figure 3: MD-JCL for Cost, Schedule, and Radiation Expenditures](image)

As shown in both figures 3 and 4, only 145 points out of the simulated 8,000 points jointly satisfy the confidence level of 80%, which is much less than 20% of the data points. For future work, a deep-dive will be done on the points that satisfied the joint confidence level in order to identify the best possible set of solutions within every case.
5 DISCUSSION OF RESULTS

As discussed earlier, primarily the focus was to look at different “possible” work-shift designs, and by incorporating unique factors and constraints, identify the ones that may result in better sets of project objectives. Since running @Risk resulted in a prolonged schedule, the following interpretations are made: (1) a shift schedule without buffers is unachievable, therefore the expected drift (variations from @risk results) and adherence to schedule can be shown by building in the buffers, and (2) since the drift results in the change of work stage (estimated vs. actual) at every shift (i.e. start and completion), therefore the relationship between the percentage of drift and productivity loss can be identified. However, none of the items above can relate to finding suited shift patterns among many, as it is only the “constant” flow of the labourers to the workface and a generator of a labour productivity number. Looking at alternative cases for labour balance can be one of many solutions to this issue.

Although this model has proven to be advantageous, it entails some limitations which are as follows: (1) validation of models that deal with prediction of (problem) objectives is always challenging and without the availability of proper historical data often impossible or misleading, (2) excessive time is required at this point in time to manually enter all inputs for any realistic project schedule (which can consist of several thousand activities), and finally (3) the quality of the results heavily depends on the quality of the input data.

6 CONCLUSIONS

Multi-objective trade-off problems are one of many challenging areas in the construction industry with many proposed solutions. Accurate Incorporation of various factors and constraints as well as considering the uncertainty around project objectives leads to a more challenging problem to tackle. The variation of estimated and actual project outcomes leads to enormous cost overruns and excessive delays in the planning phase of mega-projects. A good initiative toward solving such trade-off problems is to accurately identify and measure uncertainty around cost, schedule, and other project objectives based on expert judgment and historical data. The functionality and contribution of the proposed multi-dimensional joint confidence limit model is to serve as a simulation platform to produce a flexible Pareto-optimal solution set for possible work shift models by incorporating various related factors such as the impact of work-shift designs on labour productivity and constraints such as radiation limits within a non-deterministic framework.
References


DEVELOPMENT OF A COST NORMALIZATION PROCEDURE FOR NATIONAL HEALTH CARE FACILITY BENCHMARKING

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Abstract: This paper presents a cost normalization framework for the National Health Care Facilities Benchmarking program developed by Construction Industry Institute (CII). Since 2009, The CII has been engaged in developing this benchmarking program with government and industry participants. In the effort, the methodology and process were developed to measure health care capital project performance in terms of cost, schedule, change, space, and best practice. Hospitals are complex building systems that are becoming more challenging with ever changing codes and regulations. Reliable comparison of hospitals built in different regions requires unique normalization approach tailored specifically for health care facilities. A single cost index had not achieved the desired results; therefore a combination of indices was employed to normalize various factors for proper benchmarking. In addition to location, time and currency, space was included for proper benchmarking and performance assessment. This paper covers the issues and challenges of normalizing the costs and spaces associated with health care capital projects, and present a practical example on how cost normalization is applied to a health care capital project. Challenges and considerations which are associated with cost indices applicable to cost normalization are also discussed. This study contributes to a better understanding of cost normalization amongst health care capital projects.

Keyword: Health Care, Benchmarking, Normalization, Capital Projects

1 INTRODUCTION

A methodology adopted for normalization for a first of its kind National Health Care Capital Facility Benchmarking program was developed at Construction Industry Institute (CII). CII has been one of the leading organizations in capital project benchmarking for the last 17 years. CII’s Performance Assessment (previously the CII Benchmarking and Metrics Program) has a database of more than 2300 projects worth over $300 billion of total installed cost (TIC) (CII, 2014). The Health care Benchmarking program is a collaborative effort amongst The University of Texas at Austin’s (UT) Construction Industry Institute (CII), the U.S. Department of Defense (DoD) / Defense Health Agency (DHA), and the U.S. Department of Veteran Affairs (VA) among other health care industry leaders. CII’s health care benchmarking program is one of the many industry specific performance assessment programs.
According to Noah (Kahn, 2009), health care construction has been less affected by economy's fluctuations than residential and non-residential construction sectors. He also mentioned, however, that recent upheaval in economy has forced everyone to re-evaluate health care system capital plans. Therefore, health care industry is looking at means to improve project delivery and process controls (Kahn, 2009). Health care costs continue to grow faster than the economy, and health care is forecasted to be 19.3 percent of Gross Domestic Product by year 2023, up from 17.4 percent in 2013 (CMMS, 2015).

Health care projects are the most complex facilities to design, construct, and operate in Architectural/Engineering/Consultants industry (Enache-Pommer et al., 2010). The proposed CII health care benchmarking research first developed a metrics framework to allow meaningful comparisons of buildings from different areas, regions, and climate/code zones. One of the key components to allow meaningful comparisons in the benchmarking program is normalization methodology. The relative metrics such as cost growth do not require cost normalization for comparison; however in order to benchmark absolute metrics (TIC per square foot) cost needs to be normalized for currency, location and time. The Health Care Facility Benchmarking program has 223 health care specific metrics including 102 absolute metrics. This paper highlights challenges associated with cost normalization for health care facility benchmarking, and describes the procedure associated with cost normalization.

2 LITERATURE REVIEW

It is essential to select appropriate indices for cost normalization in benchmarking. Previous studies have outlined various merits and demerits of published cost indices (Dai et al. 2012, McCabe et al. 2002, and Remer et al. 2008, Nasir et. al., 2014). After comprehensive literature review, two types of indices were identified and categorized as input-based cost indices and output-based price indices.

Input-based indices measure various construction process inputs, such as materials, equipment and labor hours usually referred as change in prices of a fixed basket of inputs. An input index measures the changes in the cost of resources to a contractor and it does not record the change in price to a client. It doesn’t account for technological innovations, productivity changes, contractor’s overhead and profit margins (Mohammadian and Seymour, 1997). In spite of input cost index disadvantages it can be used for identifying trends in resource costs and cost fluctuation in contracts.

Output-based price indices represent price to a client, and therefore is a direct measure of inflation. Output-based price indices are developed through model price index, hedonic price index, and bid/unit price index (Mohammadian and Seymour, 1997). The output-based indices under model price index compare the construction cost of a hypothetical structure by location and/or time (Dai et al., 2012). For example, a Producer Price Index (PPI) for an industry is a measure of changes in prices received for the industry's output sold outside the industry (Bureau of labor Statistics, 2015). Bureau of labor Statistics (BLS) producer price index for new health care building construction (NAICS code 236224) follows North American Industry Classification System (NAICS) index codes is a model price index (Bureau of labor Statistics, 2015). Model price index allows for construction heterogeneity by modeling different common building types, and is more sensitive to market change conditions.

Hedonic price index includes quality of the final product as a measure to construct an index (Mohammadian and Seymour, 1997). In United States, the hedonic price index is used to construct indices for single family homes. Hedonic price indexes may be considered a type of component pricing where the component prices are estimated from a cross-section regression. The indices based on hedonic characteristics for other construction sectors have been largely unsuccessful (Pieper, 1991). Considering the indices characteristics, the model price index under output-based price indices synchronizes well with the construction industry.

Time and location adjustment will cover for escalation and inflation adjustment. Various indices provide multiple options to accomplish time and location adjustment. According to the study on construction cost sources (Table 1) conducted by McCabe et al. (2002), the selection and use of location adjustment
indices (input or output) sometimes appears to be unreliable, resulting in significant variation in cost adjustment.

For time adjustment indices, few studies have reviewed industry specific approach for cost normalization, and in particular there are no past studies for health care facilities cost normalization. Therefore, this study reviewed and compared the existing indices to be used for health care facilities’ cost normalization including Turner Cost Index (TCI, 2015), R.S. Means (RSM-CCI, 2014) Construction Cost Index, Engineering News Record Construction Cost Index (ENR-CCI, 2014), Engineering News Record Building Cost Index (ENR-BCI, 2014) and Rider Levett Bucknall (RLB, 2014) Construction Cost Index. Table 1 summarizes the nature of indices along with process inputs considered by different indices.

<table>
<thead>
<tr>
<th>Cost Source</th>
<th>Labor Input</th>
<th>Material Input</th>
<th>Equipment Input</th>
<th>Assemblies Input</th>
<th>Location Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENR</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Input</td>
</tr>
<tr>
<td>Hanscomb</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Input and Output</td>
</tr>
<tr>
<td>RS Means</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>RLB</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Output</td>
</tr>
</tbody>
</table>

3 COST NORMALIZATION METHODOLOGY APPROACH

In CII’s experience of developing similar systems for other industry, the key to success has been participation by industry. The development of health care system followed the same principle. The industry leaders come together to develop a system that is defined by the industry for the industry (Mulva et al., 2014). The normalization process also followed the same model as shown in Figure1.
3.1 Selection of Cost Indices for Normalization

In order to choose appropriate cost indices that can be used for cost normalization of health care facilities, the cost indices reviewed in the literature review are evaluated and compared over time. All listed indices are normalized to reference year 2008 with index value of 100 to investigate the impact of late 2000’s economy downturn as shown in Figure 2. This normalization of cost indices to year 2008 helps select an appropriate index based on their sensitivity to economy changes during recession. These indices represent the spectrum of basket of inputs or most common non-residential building types in U.S.

Turner Cost Index (TCI) shows an extreme reaction to the downturn. It is free resource; however its base year is 1967 (TCI, 2015), and is limited to four observations per year. Very little is known about TCI methodology, including the location it considers for their building index. The reference year for RSMeans historical cost index is year 1993 (index value = 100) as well as the computed value of an index based on the current year. RSMeans is a composite average of material, labor and equipment. It measures variation in costs in the nine most common building types constructed in United States (Dai et al., 2012). According to McCabe et al., (2002), RSMeans cost data includes local multipliers through relative factors of material costs, installation costs as well as the weighted average for total in-place costs for each CSI MasterFormat Division. The study further explained that these multipliers allow for location adjustment across 930 cities (of which 62 are Canadian) as well as across time for the same city. The index also responded to economic slowdown in Figure 2.

Figure 2: Comparison of Normalized Cost Indices in 2008
ENR-CCI and ENR-BCI showed very little variation to economic downturn. ENR uses year 1913 as its reference year. RLB Construction Cost Index presents comparative cost of construction in 12 cities on a quarterly basis. According to RLB (2014), comparative cost index is built on bid cost comprised of labor, material, contractor/subcontractor overhead cost and profit. This index also includes sales and use tax for construction contracts (RLB, 2014). The reference year for RLB index is 2001. CII Performance Assessment (PA) committee and health care steering committee members provide their feedback and share their organization experience on the normalization methodology. In a similar exercise, steering committee participated in a study comparing the behaviour of various indices in relation to 2007-2009 economic slowdown. Based on the literature review, comparison of cost indices and industry experts’ feedback, the cost normalization procedure was developed.

The ability to adjust location to 930 cities, and a relatively recent reference year of 1993 made RSMeans a prime index for location adjustment. It was also used in past studies by CII with success. The time adjustment was preferred through RLB with a reference year of 2001. Its ability to include profit and sales tax meant market conditions were also adjusted with time.

3.2 Cost Normalization Procedure for Health Care Facilities

The comprehensive approach is outlined in a flow chart in Figure 3. The approach to a location that is not covered in the selected index is similar to Hwang et al. (2008). The closest city was chosen based on industry experience. During the data validation process the selection is verified again. The closest city approach is also recommended by RSMeans. RSMeans being an input index, using mid-point of construction for location adjustment is an appropriate approach. In other words, it moves composite average of various construction costs to the new location. RSMeans City Cost Index (RSMCCI) is used for location adjustment in health care normalization.

After the selection of RLB index by steering committee, Bureau of labor Statistics producer price index (BLS-PPI) for new health care building construction was launched. BLS-PPI was presented to the steering committee as an option since it is a health care specific index. BLS-PPI, an output-based model price index based on health care construction was immediately preferred over other methods. The steering committee agreed on BLS-PPI for health care, but PPI index had just come into existence in the year 2012. Therefore a hybrid index was created by CII research team with base year as 2012 for normalizing cost for time.

The time adjustment is done using a hybrid index of RLB Construction Cost Index and BLS-PPI for new health care building construction NAICS 236224. Among all industry experts in the steering committee, there was a consensus on hybrid approach with RLB for the years before 2012.

3.2.1 Currency Conversion

The health care benchmarking system was designed for global benchmarking for health care facilities. Owners are required to provide currency exchange rate to allow for conversion to US currency. Exchange rate is also verified during validation process. This part is designed to accommodate future expansion of health care benchmarking to include foreign health care owners and contractors. National Health Care Benchmarking program project cost is adjusted from the project location to Chicago, which is the baseline location for the health care system. The reason for selecting Chicago as the reference city for health care normalization is to maintain consistency with CII’s use of Hanscomb Means International Construction Cost index (HMICCCI) for international projects in all its previous benchmarking systems. HMICCCI also uses Chicago as its reference city. This will allow seamless expansion of health care benchmarking program to include foreign projects.
Figure 3: Health Care Normalization Method
3.2.1 Location Adjustment

The health care benchmarking system employs an online Performance Assessment System (PAS) for data entry. The mid-point of the construction phase is a mandatory data field before the data entered can be submitted. Without the mid-point of the construction phase, normalization is not possible as the system would not allow benchmarking associate to submit projects into database. However, there are exceptions to mid-point of the construction phase that are only discussed during the validation process. And such exceptions are beyond the scope of this paper. The second mandatory data field is the location of a project job-site. In the absence of a location, the costs are normalized to the combined national average of RLB/BLS-PPI construction cost indices. For a case where mid-point and location is available, RSMeans CCI is used for location adjustment.

3.2.2 Time Adjustment

As discussed earlier, the steering committee for health care benchmarking and CII decided to use RLB/BLS-PPI for time adjustment for health care normalization. The BLS-PPI for health care was launched in the year 2012, and therefore, most health care organizations are not familiar with it. The index for NAICS 236224, New Health Care Building Construction, is the latest measure developed and published by PPI as a part of its Nonresidential Building Construction (NRBC) initiative (BLS.gov, 2015). Under NRBC initiative indices yield a national weighted average of output price changes. According to BLS website, BLS-PPI includes an array of health care buildings such as hospitals, mental hospitals, infirmaries, hospital infrastructure (buildings for radiology, CT/MRI, radiation therapy, etc.), medical clinics, medical offices, medical labs, doctor and dentist offices, outpatient clinics, research labs (non-manufacturing, non-educational, or non-hospital), nursing homes, hospices, orphan homes, sanatoriums, drug clinics, rehabilitation centers, rest homes, and adult day-care centers. BLS-PPI is a type of model price index where these models represent typical health care buildings constructed in each of the four major census regions. According to BLS website, multiple health care models were developed to accommodate regional variations in building design. CII health care benchmarking program also follows the same four census regions to categorize projects geographically.

4 NORMALIZATION PROCEDURE EXAMPLE

A hypothetical example is presented for better understanding of the cost normalization procedure for health care facilities. Amongst diverse cost types, TIC is used in an example to present normalization procedure. The different types of costs such as procurement cost, management cost etc. are adjusted with different indices. The currency conversion is excluded as health care benchmarking program is focused within the U.S.

A hypothetical health care project (TIC= $50,000,000) in Indianapolis is considered for this example. Assuming the project was built in 2007, and associated costs need to be normalized to year 2014. The breakdown of the cost is presented as shown in Table 2.

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Local Currency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Installed Cost (TIC)</td>
<td>$50,000,000</td>
</tr>
<tr>
<td>Capital Medical Equipment</td>
<td>$10,000,000</td>
</tr>
<tr>
<td>Total A/E and Construction management Cost</td>
<td>$5,000,000</td>
</tr>
</tbody>
</table>

Table 2: Breakdown of Cost

Total installed cost (TIC) is defined as the total actual project cost (excluding the cost of land) from Programming/Front-end Planning through commissioning, including capitalized amounts expended for in-house salaries, overhead, travel, etc.
• Step 1: Location Adjustment (from Indianapolis to Chicago in 2007)

The procurement and management cost are subtracted from TIC before location adjustment (Table 3). The assumption is that equipment and management cost doesn’t vary with location as the equipment procured and the design teams are generally not located at the location of the construction site of health care facility.

Table 3: TIC Adjustment for Location

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Amount in 2007 Indianapolis</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIC</td>
<td>$50,000,000</td>
</tr>
<tr>
<td>Capital Medical Equipment</td>
<td>$10,000,000</td>
</tr>
<tr>
<td>Total A/E and Construction management Cost</td>
<td>$5,000,000</td>
</tr>
<tr>
<td>Net Cost to be normalized for location</td>
<td>($50,000,000-$10,000,000-$5,000,000) = $35,000,000</td>
</tr>
</tbody>
</table>

$35,000,000 out of TIC of $50,000,000 will be adjusted for location (Table 4). The rest is capital medical equipment and management cost. These cost items are only adjusted for time.

Table 4: TIC Adjustment for Location

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Amount (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Cost to be normalized for location</td>
<td>$35,000,000</td>
</tr>
<tr>
<td>(Indianapolis2007)</td>
<td></td>
</tr>
<tr>
<td>Location Index Indianapolis - 2007</td>
<td>158.5</td>
</tr>
<tr>
<td>Location Index Chicago - 2007</td>
<td>191.9</td>
</tr>
<tr>
<td>Location Adjustment</td>
<td>=35000000 x (191.9/158.5)</td>
</tr>
<tr>
<td>Adjusted TIC (Chicago 2007))</td>
<td>= $42,375,394</td>
</tr>
</tbody>
</table>

• Step 2: Time Adjustment (from 2007 to 2014 in Chicago using RLB/BLS-PPI)

With this normalization procedure, the health care project database allows for meaningful comparison among projects within the health care framework. The health care framework and algorithms attributed to selecting similar projects are essential in comparisons of health care projects constructed in different location and/or time. Time and location adjustment of various costs is also critical for comparisons. The current process has been validated by the steering committee for health care benchmarking which is comprised of industry experts. Table 5 presents three costs that need time adjustment. They are adjusted TIC (Chicago 2007), capital medical equipment and management cost which are still in Indianapolis dollars (2007).
Table 5: TIC Adjustment for Time

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Total Amount 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted TIC (Chicago 2007)</td>
<td>$42,375,394</td>
</tr>
<tr>
<td>Capital Medical Equipment (Indianapolis 2007)</td>
<td>$10,000,000</td>
</tr>
<tr>
<td>Total A/E and Construction management Cost (Indianapolis 2007)</td>
<td>$5,000,000</td>
</tr>
<tr>
<td>Total Cost to be normalized for Time</td>
<td>($42,375,394 +$10,000,000+$5,000,000) =</td>
</tr>
<tr>
<td></td>
<td>$57,375,394.32</td>
</tr>
</tbody>
</table>

Total cost $57,375,394.32 in 2007 needs to be adjusted to year 2014. The adjusted TIC (Chicago 2007), capital medical equipment and management cost can also be adjusted for time separately and added later. It will provide the same result.

Table 6: TIC Adjustment for Time

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Amount in 2007 Indianapolis</th>
<th>Amount in 2014 Chicago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Cost to be normalized for Time</td>
<td>$57,375,394.32</td>
<td></td>
</tr>
<tr>
<td>RLB/PLS-PPI Index Chicago</td>
<td>94.8</td>
<td>104.5</td>
</tr>
<tr>
<td>Time Adjustment</td>
<td>= $57,375,394.32 x (104.5/94.8)</td>
<td>$63,246,083.40</td>
</tr>
</tbody>
</table>

As shown in Table 6, $63,246,083.40 is an adjusted TIC normalized to year 2014 and city Chicago. The project’s actual TIC was $50,000,000 in the year 2007 constructed in Indianapolis.

5 CONCLUSION AND PATH FORWARD

Normalization is essential for meaningful comparison. Through literature review on existing cost indices and feedbacks from industry experts, the cost normalization procedures was designed to normalize costs associated with health care projects for the first time. Its efficacy and accuracy can only be validated over time. As stated earlier, the initial validation from health care industry experts have been positive. Health care normalization procedure is different than other industry specific benchmarking systems developed by CII. The published indices have inherent challenges based on their accuracy, compilation method, and reference years. Indices are also not able to capture cost variations due to the regulatory environment, site conditions, and change in code requirements.

Current normalization procedure is susceptible to these drawbacks. However, there are improvements over the past in the procedure developed for the health care benchmarking. The use of RLB/BLS-PPI allows for market conditions to be captured for the first time. Health care benchmarking system collects costs by Construction Specification Institute’s (CSI) divisions. It uses the RSMeans - CSI cost index. Using the CSI index, health care benchmarking system could accommodate productivity data for numerous trades. As in the past, it was a challenge and a shortcoming for normalization procedures as they lacked indices supporting productivity data. According to Goodrum (2001), the CSI index provides unit labor costs, unit equipment costs and physical output data. Labor costs are based on the average wage rates from 30 US cities and the equipment costs on rental rates plus operating costs (Goodrum, 2001).

The use of RSMeans - CSI index will allow for productivity factors in normalizing costs for the first time in CII’s history. The adjustment of space for the final metric calculations is also unique to health care
benchmarking program. As previous studies indicated that the selection of an appropriate indices are critical to valid methodology. A shift in model price index for time adjustment is a positive step in health care normalization methodology. The current scope of this paper did not cover the methodology for CSI and space based adjustment in detail. Study will next focus on challenges associated with CSI and space based adjustment for health care normalization methodology.

References


R.S. Means (RSM-CCI) 2014. Quarterly Means Construction Cost Index. Reed Construction Data. 700 Longwater Dr., Norwell, MA.

A DATA ANALYSIS FRAMEWORK FOR OPTIMIZING OCCUPANT ENERGY USE WHILE SUSTAINING INDOOR ENVIRONMENTAL QUALITY

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Abstract: Sustaining standard indoor environmental quality (IEQ) is a crucial factor in promoting occupant health and comfort, and a significant proportion of a facility’s energy use is directed toward indoor climate control. Meanwhile, because operation of facilities accounts for a large share of the world’s energy consumption, it has warranted increased interest in efforts to design facility energy management systems that reduce energy consumption. In this context, facility managers aim to achieve the optimal balance between occupant comfort and overall energy consumption. The objective of this paper is to demonstrate a framework that assists facility managers in identifying residential occupant activities that influence energy consumption and also ascertaining any correlation or sequential activities patterns and their association with respect to IEQ. This work is facilitated by the installation of various sensors in a case study, the “Stony Mountain Plaza” project in Fort McMurray, Canada. It is expected that the extracted information and strategies acquired from the framework can be implemented within the facility management system to achieve financial, environmental, and health benefits.

1 BACKGROUND

Generally speaking people spend most of their time indoors in a home or workplace (US Bureau of Labor Statistics 2006), a trend which rings especially true for cold climatic regions like Canada, where winters are cold and long (Statistics Canada 2001). A national survey on Canadian human activity patterns conducted in 2010–2011 indicates that the average Canadian spends 90% of their time indoors, most of which is at home (Matz et al. 2014; Public Health Agency of Canada 2010). Notably, these indoor spaces, which are considered to be safe and secure shelters, for many can become a cause of serious health problems because of poor indoor environmental quality (non-standard CO₂ level, RH level, and/or indoor temperature) (Sharmin et al. 2014). It is observed that, in addition to external air sources, building materials, and furnishings, one of the major influences on indoor environment is occupant activities. Studies indicate that occupant appliance usage (including faulty usage) and comfort-related choices (use of HVAC, electrical duct heating, energy recovery ventilation, window opening patterns) affect indoor environmental quality (IEQ) and may cause indoor air contamination (Building Air Quality 1991).

Meanwhile, operation of appliances and maintaining of occupants’ desired indoor temperature requires considerable energy. In 2007, Canadian households consumed a total of 1,368,955 TJ (terajoules) of energy and in 2011 there was a 4% increase to 1,425,185 (TJ) (Statistics Canada 2011). Statistics indicate that improper use of appliances (both in residential and commercial facilities) accounts for a substantial share of total energy wastage; however, a 30% reduction in energy consumption can be
achieved by eliminating wastage in facilities, which underscores the need for an effective building management system (BMS) to manage/control operational energy usage without compromising occupant comfort.

Along with technological advancements there is a growing interest in improving the intelligence of facilities by means of sensor-based building management systems capable of collecting vast amounts of building-related data. However, it should be considered that in order to take advantage of such systems, all the relevant observations need to be extracted, since less than optimal building performance may be encountered when energy use information is inadequate. Recent studies indicate that adapting different monitoring systems, using modern, energy-saving technologies and providing appropriate feedbacks to building occupants can reduce energy consumption by up to 20% (Abrahamse et al. 2005; Darby 2006; Chetty 2008; Vassileva 2012). However, very few research studies have considered examining occupant behaviour for energy management (Haas 1998). Although sustainable development require behavioural awareness (Wood 2007; Abrahamse, 2007), depending only on occupant behaviour cannot be considered an effective solution. Instead what is required is a holistic user-centric control strategy for building management (Jiang 2009).

This study aims to provide greater insight into occupant activity patterns and their effect on energy consumption and IEQ in order to equip BMS with an effective user-centric energy and IEQ management strategy. This study proposes a framework to extract useful observations pertaining to occupant energy usage patterns by means of sensor-based monitoring, using the case study of a four-storey multi-family residential facility in Fort McMurray, Alberta, Canada. Previous research by the authors has involved extract useful information by studying correlations among occupant activities. In this study, the authors investigate occupant activities to determine whether any sequential activity patterns exist, as well as to identify any correlations among activities, or between activities and IEQ. It is expected that these observations will enhance BMS through effective energy and IEQ management.

2 OBJECTIVE AND METHODOLOGICAL APPROACH

2.1 Objective

The objective of this study is to propose a methodological approach for extracting useful information from sensor-based monitoring for the purpose of user-centric energy and IEQ management of a multi-family residential facility. The study first aims to identify the most significant occupant activities affecting overall household energy consumption. Occupant energy usage patterns are also investigated for different unit types (different directional orientations and unit sizes), based upon which occupants can be categorized based on usage patterns. This study further considers identifying occupants’ sequential energy usage patterns and the correlations among them by analyzing time-ordered energy usage measurements. It is expected that these information will assist facility managers to understand occupant energy load and estimate future energy demand so they can plan accordingly. Facility managers will also be able to calculate internal heat gain from occupant activities in order to estimate optimized heating energy requirements. It is expected that this research will yield insightful observations of occupant energy usage, which may in turn be useful in shaping energy and IEQ management strategies.

2.2 Methodology

To achieve the above mentioned objective, a sensor-based monitoring system is developed to measure occupant operating energy and IEQ. In order to investigate whether occupant energy usage patterns and IEQ are affected by unit characteristics, this study measures occupant usage patterns from different unit types. At each floor of the four-storey case study building, 1 ‘one-bedroom’ unit facing north, 1 ‘one-bedroom’ unit facing south, and 1 ‘two-bedroom’ unit facing north are selected as case units. The sensor network is designed such that sensors are installed and data is collected from these 12 case study units. In order to ensure anonymity, in this study, the case study units are assigned codes (numbered 1 through 12). Figure 1 shows a schemata of the sensors used and their locations in a case ‘one-bedroom’ unit. The locations and types of sensors installed in the ‘two-bedroom’ units are similar to those of the ‘one-bedroom’ units. Table 1 shows the data collected by the installed sensors.
Figure 1: Sensor location and network

Table 1: Sensor output

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Connection</th>
<th>Sensor Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption meters</td>
<td>Using ZigBee, these sensors communicate with four EtherBee gateways (for each floor of four-storey building), and then connected to CAT5 Ethernet cable. Finally this is connected to a single-board computer through a 5-port switch.</td>
<td>Total energy so far for each load (in Watt seconds): Hot water tank (HWT), range, range hood fan, kitchen plug, bedroom plug, lighting (kitchen, bathroom, living room, and balcony), electrical duct heating (EDH), energy recovery ventilation (ERV), and refrigerator.</td>
</tr>
<tr>
<td>(Brultech ECM-1240)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MULTICAL® 601 Energy Meter</td>
<td>Communicate with an iLONsmart server, which is then connected to a single-board computer</td>
<td>Total energy (Watt hours), Total volume (L), Total mass (g), current flow (L/s), current $T_s$ and $T_r$ (°C),</td>
</tr>
<tr>
<td>Minomess 130 Water Meters:</td>
<td>Communicate with an iLONsmart server, which is then connected to a single-board computer</td>
<td>Total volume (in gallons) for each of the meters</td>
</tr>
<tr>
<td>Two in each apartment;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>monitoring total incoming</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water, output of the HWT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IAQ Point air monitoring</td>
<td>Communicate with an iLONsmart server, which is then connected to a single-board computer</td>
<td>Current values of $CO_2$ (ppm), RH (%) , and temperature (°C)</td>
</tr>
<tr>
<td>device</td>
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</table>
3 ENERGY AND IEQ MANAGEMENT FRAMEWORK

This section describes the energy and IEQ management framework (Figure 2) for observing occupant energy usage patterns by analyzing real-time data collected from case study units during regular operation of the building. The framework first identifies the activities which are the main contributors to energy consumption in the case study units. These energy usage pattern are then studied with respect to different unit types in order to identify the impact of unit size (floor space), directional orientation, and elevation (floor level) on energy usage. This study investigates occupant activity patterns in terms of (1) sequence of related activities and mining of sequential activities, (2) repetition of sequential activities over a period of time, and (3) correlation among different daily activities. Since in this study all occupant activities observed are in the same building, it is possible that they will have a direct/indirect influence on one another (Yu et al. 2011). In order to understand the relationships among different activities and to develop appropriate management strategies, this framework encompasses investigation of the associations and correlations among different activities.

![Figure 2: Energy and IEQ management framework](image)

It is expected that studying time-ordered sequential occupant energy usage patterns and correlations among them will assist in the development of a BMS that takes into account occupant energy load and that can estimate future energy demand by predicting upcoming actions using observed historical data. This energy demand information can be used to develop an appliance scheduling scheme, by taking advantage of the time-varying retail pricing. In many cases utility costs (space heating, electricity, water heating) are included in monthly rental costs of a given unit in a multi-unit facility. Thus, unlike with individual houses where occupants pay for utilities in addition to housing (mortgage or rental) costs, tenants in multi-family facilities may not have a financial incentive to reduce energy consumption (Levinson 2004). Studies indicate that tenants behave differently when they rent apartments with utilities included opposed to if they have to pay energy costs separately from rent (Sjögren, 2007). In this context the proposed framework can suggest separate utility payment for a given unit and also can set consumption limits for a given unit if any irregular occupant usage pattern is identified. The framework also allows for estimation of internal heat gain from occupant presence and activities. It is considered that
radiation from people (Wp) is 4.8 W/m², from equipment (We) is 14 W/m², and from lighting (Wl) is 11.6 W/m² (Grini et al. 2009). Estimating internal heat gain from occupant presence and activities is important for calculating optimum heating energy needed (Papakostas, 1997).

Based on this monitoring the BMS is also able to detect any non-standard IEQ. The ASHRAE guideline suggests that indoor CO₂ levels should not exceed 1,000 ppm (Quinn 2011), since occupants continuously living with elevated CO₂ levels may face health problems such as headaches, fatigue, and eye and throat irritation (Wyon and Wargocki, 2006). Also according to ASHRAE, relative humidity (RH) level should be maintained between 30% and 60% since non-standard RH can aggravate allergies and asthma by increasing the growth of mould, bacteria, and dust mites (Quinn 2011). By identifying relationships between occupant activity pattern and IEQ, the BMS can detect the cause and can take proper measures to address it. Moreover, it is expected that this framework will provide insightful information regarding occupant energy usage patterns and associated IEQ, which can be useful for enhancing energy management while maximizing occupant comfort.

3.1 Energy Usage Pattern for Different Units Types

Studies have identified that a building’s physical parameters play a significant role in the variation observed in energy consumption in different households (Branco 2004; Jeeninga, 2001). In order to determine whether energy consumption patterns vary between north-facing and south-facing units or between ‘one-bedroom’ and ‘two-bedroom’ units, electricity, heating, and water consumption patterns for three different group of units (north-facing ‘one-bedroom’ units, south-facing ‘one-bedroom’ units, and north-facing ‘two-bedroom’ units) are observed. Figure 3 shows that electricity and water consumption are comparatively low in north-facing ‘one-bedroom’ units compared to north-facing ‘two-bedroom’ and south-facing ‘one-bedroom’ units; (it should be noted that some usage data from units is unavailable due to sensor malfunction). Heating energy consumption is comparatively high in north-facing ‘two-bedroom’ units compared to ‘one-bedroom’ units (both south- and north-facing).

![Figure 3: Heating, electricity and water consumption pattern for different unit types](image-url)
Figure 4: Energy usage patterns of different activities for different unit types
Figure 4 shows that, for the above three groups, (representing both ‘one-bedroom’ units and ‘two-bedroom’ units), hot water tank (14%-35%), lighting (13%-19%), and refrigerators (10%-15%) are high energy consumers. It is observed that heating energy consumption is comparatively higher in ‘two-bedroom’ units (14%-18%) than in ‘one-bedroom’ units (2%-13%), presumably due to the larger size of these units. It is also found that south-facing units have lower heating consumption (2%-9%) than north-facing units; solar heat may be the reason for lower heating demand in the south-facing units. With the major energy consuming factors related to occupant usage patterns identified for a multi-family residential facility, it is possible for the facility manager to set energy usage limits for each unit.

3.2 Correlation and Sequential Energy Usage Pattern and their Association with IEQ

A study of the daily energy usage data shows that different sequential activity patterns can be observed among occupants. For example, it is observed that when kitchen plugs are in use (presumably for the purpose of food preparation), the range and range hood fan are found to be in operation shortly afterward (Figure 5). It is also observed that during that time kitchen lighting is also turned on. Data also shows that when bathroom lighting is on, water consumption tends to take place during the same timeframe. These sequential activity patterns for specific units can be used to develop a predictive sequential energy usage pattern model. Facility managers can use this information for estimating future-state energy load for improved energy management.

![Figure 5: Sequential activity pattern](image1)

![Figure 6: Internal heat gain associated with activity pattern](image2)
Correlations across different activities and their association with IEQ can be observed from the measured data. For instance, it is also observed that during the time the above mentioned food preparation activities are performed, the internal heat gain from kitchen appliances increases the indoor temperature even though heating consumption is low for that specific time (Figure 6). Facility managers can take into account this information regarding internal heat gain while estimating heating load. Analyzing recorded data identifies that the apartments generally show peak electricity consumption during hot water consumption (Figure 7). Furthermore, when water consumption is high in a given unit, relative humidity is also high for that unit. It is also observed that the indoor CO₂ level is significantly affected by occupant energy recovery ventilation usage patterns (Figure 8).

![Figure 7: Peak electricity consumption and IEQ associated with water usage pattern](image)

![Figure 8: IEQ associated with occupants' ERV usage pattern](image)
Occupant presence and absence patterns can also be observed by studying the data. Figure 9 shows that occupants of unit 3 were not at home for two days (January 3-5, 2013). It is also observed that three Sundays of this month show higher CO₂ concentration and heating and water consumption, which indicates higher demand during that time. This information can assist building managers to understand demand load for effective energy management.

4 CONCLUSION

The framework presented in this study demonstrates the use of real-time sensor-based data to support identification of occupant energy usage patterns and associated IEQ in order to improve energy and IEQ management. The knowledge generated from this study can be used to assess the demand load and timing of peaks loads. Aggregating the energy demand for all occupants in the multi-family building can assist with the development of an energy demand profile. Accordingly, the BMS can propose an appliance scheduling scheme based on time-varying retail pricing. This information can be used to estimate the internal heat gains (from occupants, office equipment, and lighting) in order to calculate the energy needed to maintain adequate comfort levels. Through the combination of these knowledge the BMS will be able to minimize the consumption of resources while maintaining a comfortable IEQ level.

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References


SocioBIM: BIM-TO-END USER INTERACTION FOR SUSTAINABLE BUILDING OPERATIONS AND FACILITY ASSET MANAGEMENT

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Abstract: Building and facility asset management is a strategic approach to the optimal capital and operational spending on assets to ensure control of cost and risk, asset life, performance, and stakeholder satisfaction. The decisions for sustainable building operations and infrastructure asset management ultimately rests on owners, stakeholders and building occupants. This paper introduces SocioBIM, an approach for building occupants to interact with their building and to provide valuable feedback to the building management. Our research takes advantage of the state-of-the-art and the state-of-practice Building Information Modeling (BIM) technologies, sustainability assessment techniques, advanced analytics, decision support systems, and integrator platforms. The valuable insight derived from SocioBIM can solve important issues related to model-reality performance gaps, post-occupancy evaluation, sustainability and service level assessment, sustainable building operations and facility asset management. Furthermore, SocioBIM adds value and provides improved competitive advantage to any asset management organization.

1 INTRODUCTION

There has been considerable and well-documented concern about the current state of Canada’s infrastructure (Froese & Vanier 2014), and this warning applies to many of the developed countries of the world. With respect to buildings infrastructure and their sustainable operations and management, the model-reality performance gap and failed post-occupancy and sustainability assessment techniques are the major problems with the current sustainability paradigm identified by many researchers in the field of sustainable building science (Froese 2014):

“In the current paradigm, sustainability is often achieved by assessing models of building performance during the design phase. However, these predictions often fail to agree with the facilities’ post-construction performance, and actual performance of many green buildings has been poor. Further, post-occupancy assessment techniques themselves are often weak, using inaccurate, un-validated tools and sampling strategies inconsistent with statistically significant results. The consequence is that we are currently re-tooling the built environment industry to meet sustainability goals in a way that, in many cases, is not succeeding.”

Froese and Vanier (2014) believe that the solution to the challenges associated with sustainable management of infrastructure lies in the investigation of the following three technical domains:

- Sustainability assessment for infrastructure: To build upon emerging frameworks to develop practical and meaningful techniques for evaluating the sustainability of infrastructure assets.
• Advanced analysis and decision-support for infrastructure management: To provide analysis and decision support that is compatible with—but extends beyond—the capability of current software. The focus includes performance prediction, multi-objective optimization, and data visualization.

• Integrator platform: To develop, test and validate a software system related to decision support and sustainable infrastructure that is compatible with existing commercial systems, integrates disparate data sources, and provides a platform to analyze and visualize infrastructure management data.

This paper introduces SocioBIM, an effective approach for building occupants to interact with their building and provide valuable comments and feedback to the building management, as the decisions for sustainable building operations and asset management ultimately rests on owners, stakeholders and building occupants. The paper presents a preliminary research and conceptual approach for SocioBIM that the authors are currently pursuing. Our research takes advantage of the state-of-the-art and the-state-of-practice Building Information Modeling (BIM) technologies, sustainability assessment techniques, advanced analytics, decision support systems, and integrator platforms [1].

2 BUILDING AND FACILITY ASSET MANAGEMENT

Building and facility asset management is a strategic approach to the optimal capital and operational spending on assets to ensure control of cost and risk, asset life, reliable performance, and stakeholder satisfaction (E. Teicholz 2013). “Asset and property managers are faced with many difficult decisions regarding when and how to inspect, maintain, repair and renew their existing facilities in a cost-effective manner” (Vanier 2000). To enhance making these challenging decisions at different operational, tactical and strategic levels, asset managers need to collect and run analytics on key data systematically to create business intelligence (E. Teicholz 2013). Furthermore, a Knowledge-based BIM has the capability to enhance the competitive advantage of a facility management organisation (Charlesraj 2014).

Facility management is knowledge and information intensive and relies heavily on historical information as well as operational data. To effectively collect and manage such a variety of data for sustainable asset management decision making, data support is required in all phases of the building life cycle, including assessment (sustainability audit, condition assessment, and data gathering), planning (cost/benefit analysis, scope & goal setting, and budgeting), implementation (process documentation and execution, and organizational buy-in) and management (certification, documentation and reporting, and policy management) (E. Teicholz 2013). The insight derived from such a variety of data can be used to answer the following key questions (E. Teicholz 2013):

• What investments are needed in repairs, renewals, and modernizations?
• Which investments should be made with limited funds?
• What are the risks and outcomes of investments made and not made?
• How can those risks be managed with proper investment?

Conventional building and facility management answer these questions in an unsatisfactory way. The conventional management approach would induce high risk, high costs and inferior performance such as: inability to locate the nearest shut-off valves after a water pipe break, overlooking ordering spare parts for a faulty elevator, or failure to access proper exit procedures in the time of a natural disaster or fire (Xu & Zhang 2013). Recently, Building Information Modeling (BIM) has become the preferred method for not only the design of buildings, but it is also gaining a foothold in the domain of building operations and management. BIM creates a digital database of all building assets and can serve as virtual 3D coordination of the construction and operational activities (Liao et al. 2012). Furthermore, BIM techniques are used during post-occupancy evaluation to effectively promote work efficiency of the operation organization, improve quality of service to customers, reduce emergency situations, improve safety, and reduce waste. The post-occupancy and operation phase of buildings and facilities is said to be the most important period of the building’s whole life cycle (Liao et al. 2012).

For example, Frankfurt Airport started using BIM for its operations and facilities management in 2003 to manage more than 2.4 billion Euro worth of a multitude of asset types, property, plant and equipment (Exton 2003). The Frankfurt BIM system aggregated existing documents and large and complex sets of
facility data to form a federated database that is visualized through interactive facility maps. This enabled the engineering, finance, operations, maintenance, security and emergency response teams to visualize mission critical facility information through interactive facility maps, to find relevant data more quickly, and to minimize operations downtime (Exton 2003).

Nonetheless, most BIM models utilized for facility management incorporate asset property information and building inspection data including: asset geometry, spaces, location, age, condition and scheduled maintenance. Moreover, the data is typically gathered by designers, building managers or building inspectors whose works are costly and, more often than not, do not address the concerns of building occupants.

3 SocioBIM – A NEW PARADIGM FOR SUSTAINABILITY ASSESSMENT OF THE BUILT ENVIRONMENT THROUGH INHABITANT ENGAGEMENT

Almost all applications of BIM to date have been targeted at professional users—designers, contractors, facilities managers, etc. While it is appropriate that these are the main users for BIM, this approach excludes an important segment—non-professional or general public users and, in particular, building occupants or infrastructure users. We refer to approaches that link BIM with the general public as “SocioBIM”, an approach for building occupants to interact with their building and its assets and to bring their own view of the issues on the table.

SocioBIM approaches not only strive to make information from BIM models available to the public for appropriate uses and in appropriate ways, but it also strives to obtain input from the public, largely by linking the technology of BIM with the technologies of social interaction, i.e., social networking. This approach goes beyond maintenance issues: SocioBIM provides a means for the end-user to interact with the BIM model and to provide invaluable social information necessary for the sustainable operation of the building. With reference to any particular component (asset) of the building, SocioBIM can provide the building occupant with the ability to:

- Comment on both design issues and service levels
- Comment on the usability, functionality and performance of any asset,
- Comment on the maintenance issues and asset condition,
- Comment on the decorations and visual appearance,
- Comment on indoor climate and raise concerns on socio-environmental issues,
- Express their feelings and sentiments about their living/work condition, comfort level and well-being,
- Make recommendations and propose solutions to existing problems,
- Provide their perceived value of the sustainability features,
- Make recommendations for upgrades and improvements, and
- Attach relevant photos, videos and voice memos or any other document to the comments.

This data can be input and stored for each asset in a BIM model and be accessed, viewed, and evaluated by the facility manager.

3.1 SocioBIM Benefits – Sustainability Assessment & Post Occupancy Evaluation:

SocioBIM exploits Building Information Modeling (BIM) technology to provide a holistic computational platform for integrated sustainability assessment. SocioBIM converts “occupants” (passive recipients) to “inhabitants”, who have a sense of place in, and engagement with, the building. It addresses the sustainability issues by measuring performance of the building after occupancy and the level of service as perceived by inhabitants.

The aim of SocioBIM is to exploit advances in computational sustainability and BIM to empower inhabitants to engage and participate in the operation of their facilities and take control of their management in real-time to optimize their well-being. In fact, SocioBIM shifts "snap-shot", "one-time" or
“discrete” measurement techniques (such as surveys and interviews) to “continuous” assessment techniques and “real-time” monitoring systems.

SocioBIM assists in comparing operational performance with predicted performance and identify “performance gaps”, strengthening understanding of how innovative green buildings are performing once built, assessing whether they are meeting expectations, and identifying the design lessons that can be learned from these buildings. Furthermore, SocioBIM helps with understanding the interactions between comfort factors (thermal, acoustic, lighting) with inherent trade-offs that affect occupant health, comfort and the environmental sustainability.

In fact, SocioBIM leads to more sustainable building operation and facility management, increased occupant well-being, enhanced level of service assessment, and greater community investment in sustainable solutions.

3.2 SocioBIM Benefits – Sustainable Building Operation & Facility Management:

Other valuable insight derived from SocioBIM that can solve important issues related to sustainable building operations and facility management include (Jensen 2008; Hungu 2013):

- Flexibility and ability to adapt to the changing needs of inhabitants over time;
- Enhancement in maintaining the facility and the surrounding area;
- Improvement in health, safety and security of the facility, people and assets;
- Optimization of energy and resource consumption (electricity, heating, cooling, water etc.);
- Greater assessment of socio-environmental impact;
- Enriched assessment of level of service;
- Better analysis of indoor climate and working conditions; and
- Informed decisions on facility management and procurement of new systems.

Therefore, facility managers, using the information received from the building occupants, can better plan for the maintenance of individual assets and assess the social impact of their decisions: from the type of light bulb in any particular fixture to the socially responsible investments decisions using a holistic information system.

4 SocioBIM DATA MANAGEMENT AND ANALYTICS

The SocioBIM database, containing data from building occupants can be comprehensive and include data from all other types of sources: facility inspectors and streamed data sensors, all of them feeding social, environmental, economic, condition and operation data. The analytics performed by the facility manager on this data could include descriptive analytics (what has happened), diagnostic analytics (why it happened), predictive analytics (what will happen) and prescriptive analytics (what, when and in what order are the best courses of action).

The vast potential data sources, however, need to be prepared for analysis. Although some information collected from users may be fully structured data, much of it may be unstructured. To prepare the data received from the previously described sources, we are considering employing advanced computing science techniques such as text mining and machine learning. Therefore, the design of the data-structure system to receive and store the data in the SocioBIM database is an important factor on which we are currently working on. Text comments may include many types of the occupant’s concerns mentioned above such as usability, performance, condition, visual appearance, maintenance issue, sentiments, and recommendations. Therefore, some of the design consideration for the comment analytics tool include:

- understanding the database structure,
- performing data analytics on the structured data of the database (e.g. priority rating),
• performing text analytics on the comment section (unstructured part of the database) and ability to break down the comments into different sections: e.g. usability, performance, condition, visual appearance, maintenance issue, sentiments, and recommendations, and
• performing further text analytics to present statistical inference on individual sections to answer important questions such as: what is the overall performance of an asset based on users' comments, how do users feel about a particular asset and how to adapt to their changing needs over time.

5 SocioBIM INTEROPERABILITY

Additional work is also needed to research the interoperability between different systems in SocioBIM: the BIM model, the data management system and the facility management system. As the data may not be entered into one single model, the data needs to be relayed from the upstream for downstream system use and the systems need to be updated to reflect the changes made. Our research to date has reviewed the applicability of the following multiple approaches to data integration (P. Teicholz 2013):

1. Capture the data into a spreadsheet: This option is mostly suitable for small projects and lacks formal structure. This approach may be prone to errors due to absence of a validation mechanism.

2. Use the Construction Operations Building information exchange (COBie): This option is convenient but does not provide graphic data to show where equipment is located.

3. Create two-way links between the BIM model and the facility management systems: This option is suitable for integrating graphic views with the data (e.g. EcoDomus system).

4. Have direct integration of BIM with the facility management system using APIs: In this option, graphics data is updated in BIM and the data is entered into COBie or directly into the facility management system. A cloud-based server can also be implemented to access data content from anywhere.

Our approach to interoperability between data systems, BIM model and the facility management systems is to develop a cloud-based SocioBIM application interacting with external dynamic databases for facility management systems.

6 USER- SocioBIM INTERACTION

Our research also explores user-SocioBIM interaction. We are considering today's technological advancements in mobile computing and systems (smartphones and tablets) to enhance the process. These smart devices are equipped with powerful CPUs, touch screens, and wireless communication technologies. The integration of BIM with a smart device provides time and location convenience, ease of way-finding, detailed visualization of building components, improvement with identification of issues, and fast interaction with the model (Kim et al. 2013). This in turn translates into an effective SocioBIM management system. To showcase SocioBIM, we are considering development of applications based on the Building Information Model server (BIMserver.org) platform. We have identified the following user-interface scenarios for our applications:

A. An interface for the administrators to manage users, IFC building models, and comments left by the users. The data will be dynamically exported to other facility management software for processing.

B. An interface for the building occupants to view IFC building models, select assets within the models, leave a comment for a particular asset, and view comments posted by others.

C. A dashboard for facility managers to perform and visualize analytics on the data and comments stored in the database.
7 CONCLUSION

Sustainable building and facility management is knowledge and information intensive and relies heavily on a variety of information provided by the building occupant, inspectors and sensor feeds. SocioBIM can enable the development of a knowledge management system that can effectively be used for problem solving and decision making by incorporating the valuable information provided by the building occupant. The user-interface developed for SocioBIM would facilitate user interaction with the BIM-based knowledge management system. The building or facility asset manager could run queries in SocioBIM to retrieve appropriate information provided by the building occupant and perform analysis on the data. This would lead to not only enhanced and real-time sustainability assessment, service level assessment and post-occupancy evaluation, but also identifying the design lessons and greater community investment in sustainable building solutions. Hence, SocioBIM adds value and promises improved well-being of building inhabitants and competitive advantage to sustainable operation of any building or facility management organization.

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References


SYSTEM DYNAMICS MODELLING FOR AN URBAN WATER SYSTEM: NET-ZERO WATER ANALYSIS FOR PEACHLAND (BC)

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Abstract: A Net-zero water (NZW) community limits the consumption of freshwater resources and returns water back to the same watershed, so as not to deplete the groundwater and surface water resources of that region in quantity and quality over the course of a year. A NZW study includes the analysis of various combinations of water supply sources, water conservation, and reuse over time. Such dynamics can be modelled by using system dynamics. This article aims to develop a system dynamics model (SDM) to achieve NZW at the urban community level. The SDM was developed by including all life cycle stages of urban water using STELLA® software. The developed SDM was validated using the historical data of Peachland water consumption (BC). Moreover, the model was applied to analyze NZW of the Peachland community during 2015-34 by considering six different scenarios. In the base case scenario, two thirds of the supplied water will be used for irrigation and will not be directly available to the community for reuse. As the community is in a semi-arid region, the Peachland community can only achieve NZW or even net-plus water for the initial five years by considering Peachland as a typical urban community without agriculture, and by implementing various water efficiency improvement measures. However, due to the projected increase in water demand, the NZW cannot be achieved after 2019.

1 INTRODUCTION

1.1 Urban Water Systems and Peachland

The world’s urban population is more than half (~54%) of the total population and is expected to increase rapidly (UN DESA 2014). In Canada, the urban population is very high (~ 81%) and is growing (Statistics Canada 2014a). The growing population requires a large volume of water served by the urban water supply. Urban water processes, such as water abstraction, treatment, distribution, wastewater treatment, disposal, and stormwater drainage are essential in any urban area. They are necessary for the human consumption of safe water and reduction of environmental impacts due to wastewater discharge (Termes-Rifé et al. 2013). These human regulated urban water processes constitute a human hydrologic cycle (Bagley et al. 2005), or simply an urban water system (UWS).

The District of Peachland (DoP) is located in the Okanagan Valley, British Columbia (BC), Canada. The DoP covers an area of 17.98 square kilometres (DoP 2008). The estimated population of the DoP is 6320 in 2014 with an annual population growth of 6.5% (Statistics Canada 2014b). The public water is supplied from two creeks (Trapanier Creek and Deep Creek), Okanagan Lake, and two Ponderosa wells (groundwater) (DoP 2007). Major consumers of the municipal water are residential (indoor and outdoor) buildings, agriculture, public parks, golf courses, and commercial and institutional sectors. The
wastewater generated from the water use is treated at the Westside Regional Wastewater Treatment Plant and then discharged to Okanagan Lake.

1.2 System Dynamics Model (SDM) for Urban Water Systems

System dynamics is a well-established methodology to quantify complex feedbacks in system interactions (Forrester, 1961; Forrester, 1968). The system dynamics model (SDM) is often used to quantify system behaviors with feedback loops for more accurate projections (Qi and Chang 2011). The model allows for the effective trade-off analysis of multi-scenarios and the multi-attributes of UWSs over time (Sehlke and Jacobson 2005). A SDM can help users better understand and express how complex systems function through visualization and computer simulation (Sehlke and Jacobson 2005). System dynamics involves the construction of “causal loop diagrams” or “stock and flow diagrams” to mimic a dynamic system. System dynamics has not been explored much in water demand estimation studies (Qi and Chang 2011; Zarghami and Akbariyeh 2012).

1.3 Net-Zero Water (NZW) Analysis

The concept of net-zero water (NZW) is similar to the carrying capacity of a system (Holtzhower et al. 2014). NZW refers to the balance of water demand and supply within a given areal boundary (Holtzhower et al., 2014). The US Army states that “net-zero water limits the consumption of freshwater resources and returns water back to the same watershed so not to deplete the groundwater and surface water resources of that region in quantity or quality over the course of a year” (US Army 2011). The central theme of NZW emphasizes a balance so that the sum of all input water is offset by comparable output water (Joustra and Yeh 2014). NZW presupposes that a community system can secure an adequate water supply within its boundaries, typically from surface water, groundwater, reclaimed water, and rainfall (Holtzhower et al. 2014). Achieving net-zero water similar to the natural cycle requires both the conservation of water and the creation of balanced water feedback loops (Joustra and Yeh 2014).

A recent report published by the US National Research Council showed that “The use of reclaimed water to augment potable water supplies has significant potential for helping to meet future needs, ….” and also recommended potable reuse with or without an environmental buffer as an alternative water management approach (National Research Council 2012). Similarly, water recycling for the augmentation of drinking water supplies has been promoted by the Australian government, who published guidelines for reclaimed water quality management (EPHC/NHMRC/NRMMC 2008). Also, in Canada, the provincial government of British Columbia has planned for the mandatory construction of dual water-plumbing (additional purple pipes for reclaimed water flow) in new buildings (MoE 2008). These initiatives show an increasing aspiration for reclaimed water use. This research develops a system dynamics model for the urban water system of Peachland and analyze its potentiality to achieve NZW.

2 METHODOLOGY

The system dynamics model for the UWS of Peachland was developed by using STELLA® software (Karamouz et al., 2012; Qi and Chang, 2011). The SDM includes three sub-models: population, water, and wastewater sub-models. These sub-models and NZW analysis method are described below:

a. Population Sub-model

The population dynamics of the District of Peachland was analyzed using the population growth equation as given in Equation 1 (Nasiri et al. 2013). The data required for the population sub-model, such as base population, population growth rate, and dwelling size were obtained from Statistics Canada (2014b).

\[ N_t = N_0 e^{rt} \]

where \( N_t \) = population in a month, \( N_0 \) = Base population, \( r \) = population growth rate (monthly), \( t \) = time duration in months
b. Water Sub-model

The water sub-model represents the flow of supplied water within the Peachland community. The water flow occurs through the urban water stages: abstraction, treatment, distribution, and use. The water use dynamics was modelled using Equation 2. The equation includes the water consumed by different activities of the urban sectors: residential; industrial, commercial, and institutional (ICI); agricultural; public parks; and golf courses over time.

\[ \text{(Water use)}_t = \text{(Residential water use)}_t + \text{(Agricultural water use)}_t + \text{(Institutional water use)}_t + \text{(Commercial water use)}_t + \text{(Industrial water use)}_t + \text{(Parks and golf courses water use)}_t \]

where “\( t \)” refers to a month

The rates of water consumption by different residential indoor activities were obtained from modified Mayer et al. (1999). The extensive study on the end uses of residential water also included Canadian cities. The efficiencies of conventional and efficient water fixtures and appliances were obtained from Mayer et al. (1999), ENERGY STAR (2014a), and ENERGY STAR (2014b). The rate of irrigation demand for different land covers such as agriculture, lawns, community parks, and golf courses of the Okanagan valley (OBWB 2010) was used for Peachland. The agricultural land area (121.6 ha) was estimated from the land use map of Peachland (DoP 2008). The average maximum site coverage of lot area is 48% for different types of residential buildings with an average lot size of 1178 m² in the district (DoP 1996). The site not covered by building structures or paved areas is required to be landscaped. Based on these requirements, the average lawn area per dwelling unit was considered as 50% of the average lot size. In addition, the area of community parks is 14.49 ha and new neighbourhood development is required to maintain a community park of 3.04 ha per 1000 population (DoP 2014a). Also, a golf course of 0.6 ha is located in Peachland (Ponderosa Golf 2015). The rates of commercial and institutional (CI) water use were obtained from the CI water use studies by US EPA (2009) and Dziegielewski et al. (2000). The data on the present industrial, commercial, and institutional floor space and their future growth were obtained from (DoP 2012). However, Peachland has no major industries (DoP 2012).

c. Wastewater Sub-model

The wastewater dynamic was modelled in the wastewater sub-model. This sub-model includes wastewater (WW) collection and its treatment for residential and ICI sectors.

\[ \text{(WW)}_t = \text{(Residential WW)}_t + \text{(Industrial WW)}_t + \text{(Commercial WW)}_t + \text{(Institutional WW)}_t \]

Where “\( t \)” refers to a month

d. Net-Zero Water Analysis

The potentiality of Peachland to achieve net-zero water was analyzed using the developed SDM. Equation 4 was used for the analysis.

\[ \text{(Net water)}_t = \text{(Water use)}_t - \text{(Rooftop rainwater harvested)}_t - \text{(Greywater reused)}_t - \text{(Reclaimed water use)}_t - \text{(Stormwater harvested)}_t \]

Where “\( t \)” refers to a month

The average monthly rainfall data of the past 35 years (1980 to 2014) of the nearby meteorological stations of Penticton and Kelowna (Government of Canada 2015) was used for the estimation of rooftop rainwater harvesting and stormwater harvesting potential.

Prior to the development of a complete SDM, a causal loop diagram (CLD) was developed. A CLD is a foundation of a SDM, and is used to identify relationships between individual system components and to show feedback loops that affect system regulation (Nasiri et al. 2013). The CLD of the SDM of the
Peachland UWS is given in Figure 1. In the CLD as shown in Figure 1, a “+” sign indicates a positive (reinforcing) relationship between two variables. An increase in the arrow tail variable causes an increase in the arrow head variable. A “-” sign indicates a negative (balancing) relationship between two variables. An increase in the arrow tail variable causes a decrease in the arrow head variable (Nasiri et al. 2013). Based on the CLD, a SDM was developed. The SDM was validated using the historical monthly data of municipal water consumption by Peachland from 2010 to 2014.

Figure 1: Causal loop diagram of the urban water system of Peachland

3 RESULTS AND DISCUSSION

3.1 System Dynamics Model for the Peachland UWS

The monthly water consumption of Peachland was simulated for five years from 2010 to 2014. The result was compared with the historical data of Peachland (DoP 2015) and is shown in Figure 2. The coefficient of determination ($r^2$) of the model is 0.85, which is high and is acceptable. Both historical data and SDM result showed an equal average water consumption of Peachland: 1104 L/capita/day for the five-year duration. In particular, the average residential water consumption of Peachland from 2010 to 2014 was 711 L/capita/day based on the SDM. The residential water consumption of Peachland is very high compared to the Canadian average of 343 L/capita/day (Environment Canada 2014), British Columbia average of 490 L/capita/day, and Okanagan valley average of 675 L/capita/day (OBWB 2011). The important causal factor for high residential water consumption by Peachland may be a low density residential neighbourhood with a large area of outdoor landscaping. For example, a minimum lot size of a single family residential building is $1350 \text{ m}^2$ (0-25% slope) to $4000 \text{ m}^2$ ($\geq 35\%$ slope) in an area without sewer connection and is $830 \text{ m}^2$ in an area with sewer connection and can have a maximum site coverage of 40%. Also, a site not covered by building structures or paved areas is required to be landscaped (DoP 1996). In addition, neighbourhood developments are required to maintain the standard of 4.04 ha parks per 1000 population (neighbourhood parks of 1.01 ha and community parks of 3.04 ha) (DoP 2014a).
Figure 2: Comparison of historical (real) and modelled data of monthly water consumption from January 2010 to December 2014

Furthermore, the slight variation of the peak water use in the real and modelled data (Figure 2) could be due to the difference in irrigation water demand. Due to the lack of the monthly irrigation pattern of Peachland, the SDM model used the monthly irrigation rate derived from combining the total annual irrigation rate of the Okangan valley and the monthly irrigation pattern of British Columbia (BC). The monthly irrigation pattern of Peachland may be different from that of the BC average. The accuracy of the model can be improved by using the location specific irrigation rate of Peachland. However, the model’s generalizability will be decreased.

The sectorial water consumption of Peachland from 2010 to 2014 estimated by the SDM is shown in Figure 3. As shown in the Figure, the major water consumer was the residential sector consuming about 65% of the total water supply. In this sector, approximately 37% of the total water was used for irrigating outdoor lawns. The next dominant water consumer was agriculture with about 25% of water consumption. The remaining water was used by ICI sector (5.7%) and community parks and golf courses (4.8%). The ICI sector also includes water uses such as firefighting, street sweeping, system flushing, sewer flushing, and culvert flushing.

Figure 3: Water consumption by different sectors in Peachland 2010 to 2014
3.2 Applications of the Proposed SDM

3.2.1 Prediction of Water Demand

The SDM was applied for the prediction of water demand of Peachland. The total water demand under the base case scenario was simulated for 20 years from 2015 to 2034. The result of the simulation is shown in Figure 4. The total water consumption of 2,772.5 ML/year of 2015 will be gradually increased to 8,220.8 ML/year in 2034. In particular, a high population growth rate of 6.5% per year (Statistics Canada 2014b), a large area of landscaping requirement for residential buildings even in a semi-arid region, a rapid growth rate of 8.3% per year of the commercial and institutional sectors (DoP 2012), and 121.6 ha (6.8% of total land area) of reserved agricultural land (DoP 2008) will demand increased water in the future. In this period, approximately two thirds of water (66%) will be consumed by irrigation including residential outdoor lawns (39%), agricultural land (22%), and community parks (5%). This water is not directly available to the community for reuse. Water license is a permit issued to water users by government authority. The license permits water users to withdraw a given quantity of water in a specified time period (e.g. per year) at maximum from particular water bodies such as lakes, creeks and rivers. Although the District of Peachland has a water license of 17,587.0 ML/year from local lakes and creeks (DoP 2014b), which even exceeds the water demand of 2034, water demand is greatly increasing. In addition, the licensed volume of water does not guarantee the availability of water in sources and only indicates the maximum limit of water withdrawal. In turn, the water availability in the creeks of Peachland is decreasing (Harra, Johnson, and Cohen 2011). Therefore, Peachland needs to plan for sustainable urban water management.

![Graph showing water demand from 2015 to 2035](image)

Figure 4: Water demand of Peachland from 2015 to 2034

3.2.2 Net-zero Water Analysis of Peachland

Peachland is located in a semi-arid region. The potentiality of Pechland to achieve NZW was analysed using the developed SDM. Six different scenarios were developed for the analysis. These scenarios are shown in Table 1.
Table 1: Scenarios for net-zero water analysis

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Community water features</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base case scenario</td>
<td>Future community water features similar to the present.</td>
</tr>
<tr>
<td>2</td>
<td>Scenario 1 with the</td>
<td>Efficient toilets, faucets, showers, dish washers, and cloth</td>
</tr>
<tr>
<td></td>
<td>efficient water fixtures</td>
<td>washers in all sectors with waterless urinals in CI sector.</td>
</tr>
<tr>
<td>3</td>
<td>Scenario 2 with irrigation demand reduction</td>
<td>Irrigation demand reduction by: 50% in residential lawns and 30% in agriculture and community parks/golf courses; use xeriscaping; water efficient crops, and efficient irrigation; 15% water conservation by behavioural change</td>
</tr>
<tr>
<td>4</td>
<td>Scenario 3 with rooftop rainwater harvesting and greywater recycling</td>
<td>Short term storage and use of harvested rainwater and recycled greywater</td>
</tr>
<tr>
<td>5</td>
<td>Scenario 4 with treated wastewater use</td>
<td>Use of treated wastewater (black water)</td>
</tr>
<tr>
<td>6A</td>
<td>Scenario 5 with stormwater harvesting and use</td>
<td>Stormwater harvesting of built up area (downtown, neighbourhoods, and residential areas) of 520 ha</td>
</tr>
<tr>
<td>6B</td>
<td>Typical urban setting of Scenario 6A</td>
<td>Scenario 6A without considering agricultural water use</td>
</tr>
</tbody>
</table>

The results of scenario analysis for achieving NZW from 2015 to 2034 are presented in Table 2 and Figure 5. As shown in Table 2, the average annual freshwater withdrawal of the UWS gradually decreases from Scenarios 1 to 6. The freshwater withdrawal and water use can be reduced by about 10% by using efficient water fixtures and appliances (Scenarios 1 to 2). However, water withdrawal and use can be reduced by 40% from Scenarios 1 to 3 by using efficient water fixtures and irrigation demand reduction. Peachland can reduce up to approximately 80% of freshwater withdrawal by using harvested rainwater, recycled greywater, treated wastewater (black water), and harvested stormwater (Scenario 6A compared to Scenario 1). Moreover, considering a typical urban setting without agriculture (Scenario 6B), Peachland can reduce up to 90% of water withdrawal by implementing similar measures to those of Scenario 6A.

Table 2: Average annual net water in six different scenarios for 2015 to 2034 period

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Water use (ML)</th>
<th>Freshwater withdrawal (ML)</th>
<th>Net water (ML)</th>
<th>Internal water reuses/harvesting</th>
<th>Return to env. (Treated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4974.5</td>
<td>4974.5</td>
<td>-3630.1</td>
<td>-</td>
<td>WW</td>
</tr>
<tr>
<td>2</td>
<td>4485.7 (-9.8%)</td>
<td>4485.7 (-9.8%)</td>
<td>-3537.0 (-2.6%)</td>
<td>-</td>
<td>WW</td>
</tr>
<tr>
<td>3</td>
<td>3018.8 (-39.3%)</td>
<td>3018.8 (-39.9%)</td>
<td>-2203.1 (-39.3%)</td>
<td>-</td>
<td>WW</td>
</tr>
<tr>
<td>4</td>
<td>3018.8 (-39.3%)</td>
<td>1721.8 (-65.4%)</td>
<td>-1426.5 (-60.7%)</td>
<td>GW, RW</td>
<td>WW</td>
</tr>
<tr>
<td>5</td>
<td>3018.8 (-39.3%)</td>
<td>1426.5 (-71.3%)</td>
<td>-1426.5 (-60.7%)</td>
<td>GW, RW, WW</td>
<td>-</td>
</tr>
<tr>
<td>6A</td>
<td>3018.8 (-39.3%)</td>
<td>985.9 (-80.2%)</td>
<td>-985.9 (-72.8%)</td>
<td>GW, RW, WW, SW</td>
<td>-</td>
</tr>
<tr>
<td>6B</td>
<td>2569.3 (-48.3%)</td>
<td>536.4 (-89.2%)</td>
<td>-536.4 (-85.2%)</td>
<td>GW, RW, WW, SW</td>
<td>-</td>
</tr>
</tbody>
</table>

Note:
i. GW: Greywater recycling; RW: Rain water harvesting; WW: Wastewater (black water); SW: Stormwater harvesting; env: environment
ii. Parenthesis indicates a percentage change in the value from Scenario 1
iii. Negative sign indicates a reduction
A typical urban community has no agriculture. The NZW and even net-plus water can only be achieved in Scenario 6B, a typical urban Peachland community (without considering agriculture) for the initial five years from 2015 to 2019 (Figure 5). The annual net-plus water will be approximately 246 ML, 193 ML, 137 ML, 77 ML, and 12 ML from 2015 to 2019 respectively, showing a decreasing trend due to increasing water demand. In a net-plus and NZW condition, the water withdrawal by a community is less or equal to its discharge to the same watershed. In Scenario 6B, the NZW can be achieved by taking the following measures:

- Reduction of per capita water demand by using efficient water fixtures and appliances
- Irrigation demand reduction through xeriscaping, water efficient crops, and efficient irrigation
- Residential water conservation by behavioural change
- Water supply by rooftop rainwater harvesting for portable purposes (≈149L/cap/day)
- Greywater recycling in houses and use of the recycled water for non-potable purpose and some portion for potable use if freshwater is not supplied (≈126L/cap/day)
- Wastewater (black water) recycling and use of the recycled water for non-potable purposes (≈64L/cap/day)
- Stormwater harvesting, treatment, and use for non-potable purposes (≈95L/cap/day)

4 CONCLUSIONS

The system dynamics model for the urban water system of Peachland was developed and validated using the historical data of the monthly water consumption of the Peachland community. The developed model was applied to analyze the net-zero water potentiality of the community by considering six different scenarios from 2015 to 2034. In the base case scenario, two thirds of the supplied water will be consumed by irrigation and will not be directly available to the community for reuse. Moreover, the community lies in a semi-arid region having less precipitation. For these reasons, multiple measures are required to achieve net-zero water in the community. In particular, Peachland can only achieve net-zero or even net-plus water for the initial five years when Peachland is considered as a typical urban community without agriculture (Scenario 6B). In the five-year period, the net-zero water can be achieved by using efficient water fixtures, efficient water appliances, efficient irrigation, behavioural water
conservation, reclaimed water use, rooftop rainwater harvesting, and stormwater harvesting (Scenario 6B). However, due to the projected increase in water demand, the NZW water condition cannot be achieved after 2019.

Acknowledgements

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References


MODELING EARLY PAYMENT DISCOUNTS AND LATE PAYMENT FEES WITH SINGULARITY FUNCTIONS

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\textbf{Abstract:} Cash flow management is a vital concern of construction contractors. To break its vicious cycle of ‘pay as late as possible, get paid as early as possible’ in which the project participants may engage to their mutual detriment, potential incentives and disincentives that are used in financial transactions should be systematically investigated. Both are time-dependent functions that define a discount or surcharge based on whether a transaction is performed before or after a deadline. They can thus be expressed by so-called singularity functions, which are activated on said cutoff date. The new model expands prior research on cash flows by linking early (prompt) payment discounts – for which a practical nomograph is provided – directly with their counterpart of late payment fees. The values of both can be calculated from the individual financing interest of the participants to assess different scenarios based on their relative time value of money. They thus gain the ability to make financially informed decisions on offering a discount and imposing a fee appropriately, and accepting the discount or incurring a fee, respectively.

1 INTRODUCTION

Cash flow management is crucial for the success of a project, especially from the profitability perspective. Furthermore, the timely issue of cash flow is critical for all participants in the project. However, different participants’ motivations will lead to diverse behaviours. From a viewpoint of the time value of money (TVM), the payer (participant who pays bill) has the intention to pay late and less if possible, whereas the payee (participant who sends bill) wants to receive payment earlier and more if probable (Su and Lucko 2014b). To a certain extent, the payer’s intention has been realized in construction projects. For example, due to the motivation that the owner requires satisfactory performance from the contractor, retainage and bill-to-pay delay terms are ubiquitous in contractual payment requirements. As a result “the contractor tends to act as financier until the later stages of the project” (Green 1989, p. 55). Worse, pay when/if paid terms and delayed pay seriously impede payees, e.g. first and second-tier subcontractors, and may also create negative consequences for payers: Both public and private owners faced complaints from contractors and subcontractors that they did not receive the pay in a timely manner (Sweet \textit{et al.} 2014). In public projects, according to the Federal Prompt Payment Act, “a contractor must pay its subcontractors for satisfactory performance within seven days of receiving payment from the federal agency. Failure to pay on time subjects the contractor to an interest fee owed to the subcontractor. Subcontractors have the same obligation to pay sub-subcontractors.” (Sweet \textit{et al.} 2014, p.349). In private projects, unpaid contractors and sub-contractors may even have mechanic’s liens on properties (Construction Report 2014), which could make owed payments becoming more enforceable (Sweet \textit{et al.} 2014). Fairness in both timely business transaction is important for the success of projects, which “the contractor should not be required to complete work at a loss, and the owner should not have to pay more than a reasonable amount of profit on any given item” (Gransberg and Riemer 2009, p. 1140). As a result, the fairness of the
contractual payment term should be considered from both the payer’s and payee’s perspectives. As Table 1 shows, the possible deals between payer and payee are either earlier payment with a discount or late payment with a fee, where the former term prompts the payer to pay in a less but earlier manner, while the latter requires the payer to pay more if it pays later.

Table 1: Payer and Payee Strategies (Adapted from Su and Lucko 2014b)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Timing</th>
<th>Amount</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payee</td>
<td>Earlier</td>
<td>More</td>
<td>None</td>
</tr>
<tr>
<td>Payer</td>
<td>Later</td>
<td>Less</td>
<td>None*</td>
</tr>
<tr>
<td>Payee</td>
<td>Earlier</td>
<td>Less</td>
<td>Deal (discount)</td>
</tr>
<tr>
<td>Payer</td>
<td>Later</td>
<td>More</td>
<td>Deal (fee)</td>
</tr>
</tbody>
</table>

*Result exists if considering retainage and bill-to-pay delay

2 LITERATURE REVIEW

Hill and Rien (1979) modeled a situation that a retail firm offers a discount to those customers who pay their bills earlier than others and searches its optimum discount. The model relied upon assuming that some customers wish to take a discount, while others do not. However, without a bilateral motivational explanation of the feasibility of such discount, such hypothesis of randomness does not explain why they wish to take a discount. As de la Garza and Melin (1986) noted, the construction contract should permit prepayment to mitigate inflation. Ng et al. (1999) systematically analyzed early payment discount terms across various industries, and summarized the factors ruling behind. Touran et al. (2004) researched how prompt payment provisions influence the profitability of contractors in the transportation area. Cui et al. (2010) considered early payment discount in a system dynamics model for cash flow and derived macro-level strategies, however, the micro-level was is omitted, which may encumber its application in industry. Kouvelis and Zhao (2012) explored the discount term (trade credit) between supplier and retailer by using game theory. Yet the precondition – newsvendor-like retailers – is inapplicable for a construction contract, wherein the work scope is explicitly defined. Al-Hussein et al. (2013) advocated floor and ceiling discount concepts for construction transaction, but its utilization is also hindered by lacking a theoretical foundation.

Late payment fee is the counterpart to discount, which many companies do not spell out explicitly. A reason may that the company does not wish to antagonize its customers. This is similar to charging fee for overdue payment of credit card. Another analogy is charging a fee if paying tax or filing a return after the deadline: “If you pay your taxes late, the fee is usually ½ of 1% of the unpaid amount for each month or part of a month the tax is not paid... This fee is in addition to interest charges on late payments” (IRS 2013, p. 91). For construction, the law requires that a “prime contractor who violates the law (prompt pay) is subject to licensing disciplinary action and must pay the subcontractor a fee of 2 percent per month in addition to normal interest” (Sweet et al. 2014, p.349). Su and Lucko (2014b) comprehensively explored the mechanism of prompt payment discount using a synthetic cash flow model with singularity functions, but omitted the early payment fee. A gap exists in comprehensively analyzing and unifying the financial phenomena of early payment discount and late payment fee. For this three Research Objectives are set:

1. Expand the synthetic cash flow model to suit both the early payment discount and late payment fee;
2. Explore mathematically the range of conditions for different values of the feasible late payment fee;
3. Chart graphically in form of nomographs these feasible ranges of conditions for the late payment fee.
MODEL CASH FLOW WITH SINGULARITY FUNCTIONS

A central issue in defining early payment discount and late payment fee is fairness for both sides, which “the payee wants to offer and the payer wants to take” (Su and Lucko 2014b, p. 8). It requires a method that can effectively and efficiently calculate the net cash flow for both payer and payee under different discount or fee rates on early or late pay periods. Previous methods fall short of balancing between them: A chronological approach calculated the balance of cash flow at the end of each period by treating actual simultaneous transactions (charging interest and receiving pay) sequentially by inserting an infinitesimal time $\varepsilon$ (Elazouni and Metwally 2005; Halpin and Woodhead 1998). This is accurate, but lacks efficiency, because it is not formularized. As a result, calculating ‘what if’ scenarios with this chronological method has to arduously repeat the process. Even though it can be automated with computers, vital relations among those variables cannot be easily explored, especially to identify dominant effects. On the other hand, previous studies focused on computational efficiency of numerous types of cash flow models, e.g. linear programming (Yang et al. 1993) or heuristics (Alghazi et al. 2012; Neumann and Zimmermann 2000). Their problem was opposite to the chronological method; omitting or simplifying central details of cash flow to make the model simple enough to be implemented with a computationally efficient algorithm. For example, financing interest, retainage, and periodical phenomena were omitted from some models, which impeded the reliability and realism of their output. An ideal cash flow model should reflect essential characteristics and also provide an advantage in terms of computational efficiency, following the moniker ‘as simple as possible, as complicated as necessary’ as advocated by Ockham’s razor (c. 1287-1347).

3.1 Singularity Functions

Each basic term within singularity functions per Equation [1] is symbolized distinctly by pointed brackets. It performs one case distinction by evaluating the current value of the independent variable $y$ (here time, for consistency with previous research) as to whether it is smaller than the cutoff value $a$ or not. If so, it remains at zero, otherwise it is activated by treating the pointed brackets as round brackets of traditional algebra. The independent variable $z(y)$ here is cost. The exponent $n$ determines the behavior (i.e. shape) of the curve once active; low orders often suffice in models, e.g. $n = 0$ for a step or $n = 1$ for a slope. The factor $s$ then determines the intensity (i.e. strength) and takes its exact meaning from said behavior. Equation [1] can be integrated and differentiated in analogy to traditional calculus. A complete singularity function is the summation of basic terms per Equation [2], where $i$ is a running index within their count $m$.

$$z(y)_{\text{basic}} = s \cdot (y-a)^n$$

for $y < a$

$$z(y)_{\text{basic}} = s \cdot (y-a)^n$$

for $y \geq a$

$$z(y)_{\text{ng}} = \sum_{i=1}^{m} s_i \cdot (y-a_i)^{n_i}$$

3.2 Synthetic Cash Flow Model

The arduousness of a chronological approach reduces its calculating efficiency. Yet calculating the TVM of cash flow is very important for accuracy. A particular phenomenon, periodicity, can be exploited to aid in the formalization: Since progress pay and month-end interest are initiated periodically, then the timing of month-end balances with TVM can be modeled if such repeatable cash flows are modeled by defining a ‘signal’ function. Another concept of viewing a balance, the ‘investment pool’ of engineering economics, is also helpful for the formalization, whereby the balance with TVM is equal to the difference of the future values of cost and of pay at the same time (Park 2011). This new cash flow model was called a ‘synthetic cash flow model’, to distinguish it from traditional chronological balance calculation (Su and Lucko 2014a). The synthetic cash flow model is a group of functions that formalizes variables of cash flow as parameters in equations. Figure 1 shows the steps of the synthetic cash flow model, where general input parameters at the activity level are: $z$ is the dependent variable of cost, total cost $C$, markup $M$, retainage $r$, monthly interest $i$, $y$ is the independent variable of time, duration $D$, shift $d1$ and delay $d2$, bill period $p$,
bill-to-pay delay b, planned start as and finish aF, where \[ a^*_s = a_s + d_1, \quad a^*_F = a_F + d_1 + d_2 \] (Su and Lucko 2014a).

### Figure 1: Steps of Synthetic Cash Flow Model with Singularity Functions

#### 3.2.1 Signal Functions

Signal functions can control a periodic phenomenon like receiving progress pay and charging month-end interest. They are generated by introducing round down \( \lfloor \cdot \rfloor \) and up \( \lceil \cdot \rceil \) operators into the terms with the independent variable y. They work as follows: The term \( \lfloor y \rfloor - a \) is a step function that turns on when y equals a, while the other term \( \lceil y \rceil - (a + 1) \) is also a step function, but turns on when y is just larger than a \((a + 0.000...1)\). Their difference returns a periodic signal. Figure 2 shows the case when the cutoff a is 0: Here \( \lfloor y \rfloor - 0 \) has right-continuous jump discontinuities per Figure 2(a) as represented by solid and hollow circles, whereas \( z_2 = \lfloor y \rfloor - 1 \) has left-continuous jump discontinuities per Figure 2(b). Figure 2(c) is the profile of subtracting (b) from (a), which gives a periodic. Its period, amplitude, and start and finish can be controlled with additional parameters (Su and Lucko 2014a, Su and Lucko 2013). To apply it to a pay signal and charging interest signal per Equation [7] and [8], the bill period p affects the cycle time of the pay signal, it is applied as a divisor (since interest is monthly, the divisor 1 is omitted in Equation [8]). A virtue of signal functions is that it allows the cutoff a to be any fractional number. Thus if an activity start or finish \( a^*_s \) and \( a^*_F \) are fractions of periods due to shifts and delays, Equations [7] and [8] can model fractional signals at period boundaries. This allows potential integration of signals with schedule research.

### Figure 2: Mechanism of Signal Function

### Pay Functions

Since each signal is a value between 0 and 1, multiplying it with the intensity factor performs a periodic sampling. Defining a cost intensity factor $C \cdot (1 + M) / (D + d^2)$ returns each pay per Equation [9]. Note $p$ is for both integer and non-integer bill period cases. To subtract retainage, Equation [10] calculates the retained amount at each pay time and Equation [11] is the pay with retainage, releasing the accumulated sum of the retained amount when the project is finished. Treating the result from Equation [11] as the principal, Equation [12] calculates the future value of pay at any time during the schedule.

### Cost with Interest Functions

Analogous to pay, applying an exact interest formula (Lucko 2013), the future value of cost is calculated by introducing a charge interest signal into the exponent terms per Equation [13]. Different from Equation [9], it is multiplied with an intensity factor $C / (D + d^2)$, because cost does not include markup or retainage.

### Balance Functions

After obtaining both the future values of pay and cost, and applying the aforementioned 'investment pool' concept, Equations [14] and [15] give the balance with TVM, which is the last step in Figure 1. Note that Equations [7] through [16] compose the synthetic cash flow model, whose steps have been explained. Note that all individual equations that are explained for this synthetic cash flow model can be inserted into an overall equation to ultimately return a single general balance function, which is omitted here for brevity.
4 EARLY PAYMENT DISCOUNT

An early payment discount is the first deal between payer and payee in Table 1. Its feasibility has been discussed in previous research by the authors (Su and Lucko 2014b), as is summarized in the following.

4.1 Floor Discount

The lower limit of the early payment discount is called the floor discount, which would be affected by the payer’s interest rate. No matter how generous the discount is, this is the minimum that has to be so that the payer wants to take it (otherwise no deal will be possible). Note the new parameters in the synthetic model, where \( l \) is the early pay period and \( \rho \) is the discount rate (e.g. 2 / 10, net 30, \( l = 10 \) days and \( \rho = 2\% \) base on bill). Here ‘\( \rho / l, \text{net } b \)’ means that the payer can pay the bill less a discount \( \rho \) if paid within \( l \) days, or pay the full amount within \( b \) days. The pay signal shifts leftward by \( b - l \) days. Its cost intensity factor must be \( C \cdot (1 + M) \cdot (1 - \rho) / (D + d) \). As a result, it would use the payer’s interest rate to calculate the future value of pay for both early and normal pay scenarios, to let the former be smaller than the latter per Equation 17. Only in this case it is favourable for the payer to pay earlier but less from a TVM view. The floor discount is also the payer’s indifference discount, because taking it or not has the same effect.

\[
\begin{align*}
\text{floorF} & = \text{payF} \cdot F(\text{pay disc}) \quad \Rightarrow \quad \rho_{\text{floor}} = 1 - (1 + i_{\text{payer}})^{-b} \\
\text{ceilingF} & = \text{balanceF} \cdot d(\text{disc balance}) \quad \Rightarrow \quad \rho_{\text{ceiling}} = 1 - (1 + i_{\text{payee}})^{-b}
\end{align*}
\]

4.2 Ceiling Discount

Similar to the floor, the ceiling discount is the upper limit of the early payment discount, which is defined by the payee’s interest rate. Because no matter how urgently the payer wants to accept a discount, if the payee does not want to offer it, it is still infeasible. In this case, one must compare the balance function of the payee between early and normal pay scenarios, to let the former be larger than the latter per Equation 18. It models that the payee earns more if the payer pays earlier. Since cost is not affected by taking the discount or not, Equation 18 is further simplified to comparing future pay functions for both scenarios. As a result, the ceiling discount has the same pattern as the floor discount. It is also the payee’s indifference discount, because it has the identical effect for the payee, regardless whether the payer takes it or not.

\[
\begin{align*}
\text{balance disc} & \geq \text{balance} \quad \Rightarrow \quad \rho_{\text{ceiling}} = 1 - (1 + i_{\text{payee}})^{-b}
\end{align*}
\]

4.3 Feasible Early Payment Discount Term

The condition for the feasibility of the early payment discount is that the floor discount should be lower than the ceiling discount per Equation 19. Substituting the results from Equation 17 and 18 into this condition returns a simple result: As long as the payer’s interest is lower than the payee’s interest, there exists a feasible range for the discount. Note that not only the feasible discount range can be calculated from the equation; the feasible early pay period \( l \) can also be computed. For example, assume the payer’s interest is 4\%, payee’s 8\%, and the payee wants to give a ‘\( p / 10, \text{net } 30 \)’ discount. Per Equation 20, the feasible discount range is 2.5808\% to 5.0013\%. If the payee wants to offer ‘\( 2 / l, \text{net } 30 \)’, the feasible early period per Equation 21 is any integer time between 15 and 22 days. Users who know two early payment discount variables for their particular case can thus directly calculate the third value using these formulas.
5 LATE PAYMENT FEES

A late payment fee is the second deal between payer and payee in Table 1. This lets the payer pay later but more. From the view of construction law, the term ‘fee’ paid from the owner to the contractor is similar to ‘liquidated damage’, by which the contractor compensates the owner for delaying the project finish time.

5.1 Floor of Late Payment Fee

Note the new parameters in the synthetic model, where \( l \) is the period between the time of normal pay and late pay and \( i' \) is the fee (e.g., \( b = 30 \) days, if pay is overdue, charging \( i' = 2\% \) monthly interest). From the payee’s view, the balance of the delay situation should be larger or at least equal to the normal case per Equation [22]. Solving it returns an apparent result that the late payment fee should be at least equal to the payee’s financing interest, which serves as the floor value of the fee. Moreover, from the payer’s view, a fee actually could have two effects for the payer: It is favorable for the payer to pay late rather than on time per Equation [23]. Or it is favorable for the payer to pay on time per Equation [24]. Obviously, from the payee’s view, wanting the fee can lead the payer to select the second case. Two scenarios of inequalities for \( i_{\text{payee}} \) and \( i_{\text{payer}} \) exist (assuming that the payer borrows to pay): If \( i_{\text{payee}} < i_{\text{payer}} \), then the payee requires a late payment fee between the range of \( \{i_{\text{payee}}, i_{\text{payer}}\} \), and the payer will pay late, because the fee is smaller than their own loan interest. Here the floor fee should be at least larger than \( i_{\text{payer}} \). Otherwise if \( i_{\text{payee}} > i_{\text{payer}} \), then the floor fee is applied. The floor fee is the maximum of \( i_{\text{payee}} \) and \( i_{\text{payer}} \) per Equation [25].

\[
\begin{align*}
C \cdot \left(1 + M \right) \cdot \left(1 - r \right) \cdot \left(1 + i' \right) \cdot \left(1 + i' \right) & \geq \frac{C \cdot \left(1 + M \right) \cdot \left(1 - r \right) \cdot \left(1 + i' \right) \cdot \left(1 + i' \right)}{D + d_2} \\
\end{align*}
\]

5.2 Ceiling of Late Payment Fee

A ceiling of the late payment fee must exist to guarantee fairness for both sides and because a mere punishment is not allowed by courts. However, different from the early pay case, from both payee’s and payer’s views per Equations [22] (payee’s balance of late pay should be larger than the balance of the normal pay case) and [24] (payer’s late pay should be larger than in the normal pay case), both conclude

\[
\begin{align*}
\end{align*}
\]
the same direction of the inequity (≥). As a result, both $i_{\text{payer}}$ and $i_{\text{payee}}$ define $i_{\text{floor}}$. This lacks the condition to define $i_{\text{ceiling}}$. An open-ended late payment fee will increasingly resemble a punishment, not liquidated damages. A possible solution for this is to set a ceiling fee by negotiations between payer and payee.

5.3 Nomograph for Both Discount and Fee

An early payment discount per Equations [17] and [18] has the variables $i$, $l$, and $b$, which can be plotted as nomographs to show their relationships among each other. Since $i$, $l$, and $b$ have two types of units (% from $i$ and time units from $l$ and $b$), two nomographs can be plotted: Interest-discount and time-discount. In the interest-discount nomograph per Figure 3, each line shows how discount changes with growing interest for a specific early pay period case. Since $i$ is the independent variable and exponent $l - b$ is the constant of each line; the profile of each line is essentially a power function. It monotonically increases, because the derivative of such power function is positive. To use this nomograph, first select the line for the planned $l$ value. Second, find the payer’s $i$ (4%) and payee’s $i$ (8%) on the horizontal axis. Third, find the cross on the $l = 10$ profile. Finally, draw a horizontal line crossing the vertical axis to find the floor and ceiling discounts. For the late payment fee, since $i_{\text{payee}}$ is larger than $i_{\text{payer}}$, so the $i_{\text{floor}}$ should equal $i_{\text{payee}}$.

The time-discount nomograph per Figure 4 switches the horizontal axis with time. Each profile represents how discount changes with growing early pay period for a specific interest case. Since the variable $l - b$ in the exponent is the independent variable and the base $1 + i$ is a constant, each line will be essentially an exponential function. It monotonically decreases, because its first order derivative negative.

![Figure 3: Interest – Discount Nomograph](image1)

![Figure 4: Time – Discount Nomograph](image2)

6 CONCLUSIONS

On-time pay is a serious issue for both payee and payer, which directly affects the economic success of the former and keeps project running smoothly for the latter. This paper started at two possible deals that could be made between payee and payer in the payment terms: Early payment discount defines a case that lets the payer pay promptly (before the due date) less a discount, and late payment fee regulates the
opposite case that add an extra charge to the pay if the payer pay the bill late. To analyze such situations, it has established a cash flow model that can model them effectively and efficiently. A synthetic cash flow model was presented as a group of equations with singularity functions, which was explored in previous research by the authors. Then conditions for the feasible early payment discount and late payment fee have been calculated from the cash flow model. They can also be plotted in nomographs, which provide a deeper understanding for such payment terms and helps project participants to make rational decisions.

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STRUCTURING THE ADOPTION AND IMPLEMENTATION OF BIM AND INTEGRATED APPROACHES TO PROJECT DELIVERY ACROSS THE CANADIAN AECO INDUSTRY: KEY DRIVERS FROM ABROAD

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Abstract: The architecture, engineering, construction and owners (AECO) industry plays a vital role in a country’s economy, and has a great impact on its society and on the local and global environment. Focussing on the performance and the impact of their respective AECO industries, government bodies around the world are increasingly pushing to transform current practices to maximise the value generated by this industry. Recent innovative approaches, notably building information modeling (BIM), integrated approaches (either integrated project delivery (IPD) or integrated design processes (IDP)) and Lean construction, show promise in providing many improvements. However, many challenges and obstacles are hindering the deployment of these approaches; a lack of strong client demand chiefly among them. In response to this, many countries have developed strategies to encourage and accelerate the pace of adoption of these innovative approaches. This often is prompted by requirements for suppliers to implement one or more of these innovations on all their publicly procured projects. The various levels of governments in Canada however have yet to follow suit in this regard. As a consequence, the Canadian AECO industry is seen to be lagging in its adoption of BIM and integrated approaches to project delivery. While certain projects have emerged as beacons of enlightened practice in the Canadian context, it remains that the vast majority of projects are still being delivered in a traditional fashion, with the well-known limitations this entails. This paper investigates the contextual challenges in adoption and implementation of BIM and integrated approaches in the Canadian AECO industry. The objective is to identify challenges and opportunities to create favourable context that ensures that the Canadian AECO industry remain competitive in the face of increasing global competition by leveraging the potential significant benefits of these innovative approaches. This paper is based on a review of the literature of various initiatives around the world. The paper lays out six key factors, which are seen as drivers for the adoption and implementation of BIM and integrated approaches in other countries, and discusses their implication in the Canadian context. Notably, the need for a national policy that structures the adoption and implementation BIM and integrated approaches; the need for leadership from the public sector; the importance of constituent organizations acting as a voice for industry; and the need for investments in research and development.

1 INTRODUCTION

The Canadian architecture, engineering, construction and owners (AECO) industry represented $290 G in capital expenditure in 2013, approximately 20% of the Canadian GDP (Statistics Canada, 2014). Moreover, the construction industry alone employed 1.3 million people or 7.5% of total workforce during this same period (OECD, 2014) distributed across more than 120 000 enterprises (Industry Canada,
As with most countries, the Canadian AECO industry is truly one of the pillars of the Canadian economy, generating significant value for its society. On the other hand, it must contend with many well-known obstacles, such as its fragmentation and complexity which make it a wasteful and inefficient industry. In fact, many countries have invested and put forth national frameworks and initiatives to support the reform of their respective AECO industries to improve performance, productivity and the value that is generated. Over the past two decades, innovative tools, technologies and processes for project delivery and asset lifecycle operations and maintenance, such as building information modelling (BIM), integrated project delivery (IPD), integrated design processes (IDP) and Lean construction have shown much promise in helping the industry overcome these obstacles and shortcomings. These innovative approaches have been adopted and their development made a priority in many countries around the globe. The Canadian AECO industry, however, has yet to initiate this transition. Indeed, there is a general consensus that it is lagging behind many of these other countries in the adoption and implementation of these innovative approaches (Beaudoin et al., 2011). In the current global economic context and facing increasing global competitive pressure, the Canadian AECO industry, cannot afford to stand idle and let pass the opportunities to transform itself through a structured and strategic reform. On the other hand, this relative tardiness can also been seen as a serious advantage in that the industry can learn from other countries and avoid many of the growing pains that others had to go through. In this regard, this paper seeks to answer the following questions:

1. How can the Canadian AECO industry learn from other countries’ experiences in the transition to innovative project delivery approaches?
2. In light of these lessons learned, how can the Canadian AECO industry develop a comprehensive reform strategy in order to improve its performance and efficiency to ensure its sustainability and competitiveness?

The paper first gives a brief overview of the current innovative approaches to project delivery that are being developed around the globe. It then exposes the particularities of the Canadian AECO industry context and discusses the adoption and implementation of these innovative approaches for the Canadian AECO industry across six key factors that were developed by Wong et al. (2010). A comparative analysis between Canadian initiatives (or lack thereof) and various from around the world is performed. Lastly, the paper concludes with a discussion on moving forward with a national framework for the adoption and implementation of innovative approaches to project delivery.

## 2 THE TRANSITION TO BIM AND INTEGRATED APPROACHES

The past decade has seen a rapid growth in the literature, both academic and industry oriented, pertaining to BIM implementation and the deployment of innovative project delivery approaches. These approaches are seen as a solution to target fragmentation and inefficiency of the AECO industry. BIM is perceived as both “Technology” and “Process”. BIM technologies allow to prototype a product, where a building information model is constructed with input of precise digital data to support the design, procurement, fabrication and construction (Eastman et al., 2011). This innovation changes the roles and relationships of all the stakeholders involved in the project delivery process, demanding new ways of work, thinking models and approaches to design and construction. However, BIM adds even more value to the project delivery if it is supported by the integrated design and construction approaches (Eastman et al., 2011) as well as by Lean construction approaches. These integrated approaches are “A holistic approach to building in which all project stakeholders and participants work in highly collaborative relationships throughout the complete facility life cycle to achieve effective and efficient building” (Elvin, 2007). Among the major initiatives regarding the integrated approaches, two main approaches could be distinguished: Integrated Design Process (IDP), which seeks energy optimization and sustainable design; and the Integrated Project Delivery (IPD), which focuses on the optimization of the project delivery process by reducing waste and managing project information flows in integrated way. In an integrated approach, the most important decisions are taken in the early stages of project design process. These decisions have a major impact not only on the progress of the construction phase, but also on the asset’s lifecycle. Lean Construction is a new way of managing projects that look to minimize waste and time, and to maximize value (Ballard, 2000). This approach is considered an optimal solution for managing various project delivery processes, and for taking full advantages of BIM, while maximizing their benefits. BIM is seen as a ‘tool’ to support integrated relational contracts such as Integrated Project Delivery (IPD),
alliancing or Integrated Supply Chain, enabling a tighter collaboration, where the process becomes more efficient and predictable. BIM decisions and protocols are best developed by joint decisions in IPD process that maintains the beneficial relationships between parties (AIA, 2007). Also, many researchers and studies recommended combining Lean with BIM to create a positive team synergy, which generates a great opportunity for improvement in industry (HM Government, 2012, Sacks et al., 2010). These in turn improve efficiency, knowledge dissemination, reduce errors, and enable generation of alternative solutions and expansions of market opportunities. Implementing integrated approach and collaboration with BIM brings more value to the process.

In an attempt to move towards a more efficient AECO industry, several countries have undertaken the reform of this industry by setting up initiatives which promote the adoption of one or more of these innovative approaches. Wong et al. (2010) carried out an extensive review of initiatives targeting BIM implementation from around the globe. The authors performed an overview of these initiatives in the USA, Finland, Norway, Denmark, Singapore and Hong Kong in terms of policy, process and technology. Their study identified some attributes which are seen as strategic steps taken to implement BIM in these countries: 1) The importance of the public sector as a driver for implementation of BIM in all the countries studied; 2) Establishing clear and specific governmental policy mandating BIM on all public projects; 3) Developing standards and guidelines for the deployment of BIM; 4) Clear information exchange capability requirements, and relying on open standards for data and information exchanges; 5) Designated organizations responsible for BIM implementation within a country (either an existing government department or external organization); 6) A constant and consistent reporting and promotion of BIM; 7) A focus on BIM research and the establishment of BIM research programmes. In the 5 years since the paper was published many more countries have sought to establish BIM initiatives, namely the United Kingdom (UK), Australia, New Zealand, France, Brazil and Korea. An analysis of these international initiatives reveals that the successful deployment of the innovative approaches depends largely on strong leadership from the government in the form of interventions and targeted initiatives, and commitment of governments to direct or support these initiatives. To better support this reform, some countries have rethought the structure of their industry by setting an overarching strategy which includes procurement methods, and an integration between government and industry stakeholders and promotes collaborative work, such as in the UK. Other countries have worked closely with the industry by offering financial incentives, and academic support programs such as in Singapore. The technological advancement to promote innovation was a key driver in the Scandinavian countries. While seeking performance and productivity improvement was a key driver in the US. All these countries have developed strategies, set specific milestones, and took considerable action to achieve their goals. To date, some benefits have been observed, many challenges have been encountered and there is still work to do to achieve their ultimate goals. Canada can learn from these initiatives to inform and structure its transition to innovative project delivery approaches.

3 THE CANADIAN CONTEXT

The Canadian AECO industry plays an important role in the Canadian economy, influences Canadian society and has a major impact on its environment. However, the context in which the Canadian AECO industry evolves is very particular. First, the AECO industry is based on provincial jurisdiction. As such construction projects are governed by provincial laws with the exception of federal projects (military, federal infrastructure such as certain bridges, airports, sea ports and projects for First Nations communities). These laws vary between provinces, especially in Quebec, which is subject to the Civil Code. The Canadian AECO industry is also very diverse; each province has its own professional associations, which govern all aspects related to professional accreditation and certification. Furthermore, there is a lack of industry-wide organizations to support innovation in Canada as discussed by Froese and Rankin (2009). This particular context makes it difficult to establish comprehensive initiatives that are consistent across the country, and can be endorsed by various levels of government as well as the public sector. For example, the National Benchmarking Initiative initiated by the Canadian Construction Innovation Council (CCIC) (Rankin et al., 2008) was discontinued when the CCIC was closed due to a lack of funding. The Canadian Construction Innovations (CCI) was created in 2013 to fill the void. This particular context also influences the speed of innovation, namely in adopting new technologies and approaches.
Little empirical work has looked into the adoption of integrated approaches and BIM in the Canadian AECO industry. As such, actual adoption rates in Canada are still largely unknown. However, there have been more attempts at quantifying the BIM adoption rate in Canada. In this regard, various surveys have been conducted over the past 6 years. The principal sources of data are the McGraw-Hill surveys (2009, 2012 and 2014) that showed a 49% BIM adoption rate in Canada in 2009, which grew to a 72% adoption rate in 2012. These results were on par with adoption rates in the US (McGraw Hill Construction, 2012). Recently, McGraw Hill Construction (2014) published results of a new survey presenting BIM adoption by contractors around the world. The report shows that 87% of Canadian contractors have adopted BIM, and that most report a positive return of investment. Again, this report still considers Canada and USA on par in terms of BIM maturity. The results of these studies are limited mainly due to the small sample size: 175 respondents from Canada compared to 2,053 from the US in 2009, 29 respondents from Canada compared to 553 from the US in 2012, and 39 respondents compared to 291 respondents in the US in 2014. In a similar study, carried out by NBS (2013), four countries took part in a survey measuring BIM adoption rates: Canada, UK, Finland and New Zealand. The survey indicated that 64% of Canadian respondents (78 respondents) were aware of and were using BIM, compared to 65% (more than 400 respondents) in Finland, where BIM is obligatory for public projects since 2010. The author of the study highlights the fact that for all the countries except Canada, the confidence rate was high and that the data was largely representative of the respective industries. For Canada, however, the results of the survey may have been skewed by the fact that the respondents were likely to be people that were familiar with BIM instead of an accurate statistical representation of the Canadian AECO industry. Other work looking into BIM adoption in the Canadian AECO industry has found that BIM implementation in Canada is currently being led by the industry and by looking at what is happening in the US. In this regard, Forgues and Staub-French (2011) have conducted a study comparing the adoption of BIM between early adopters in the Canadian AECO industry and BIM users in the American one. They observed important gaps between these two industries. The main gap noted was that the overall level of use of BIM tools on projects was systematically lower in the Canadian industry than in the U.S. industry. This study showed that BIM adoption in the U.S. industry was more advanced, and discussed how BIM implementation is related to market demand, particularly on the part of the client. To close the gap, the study argued that the transition to BIM would have to be endorsed by public clients, and that support from research and professional associations is critical. In other words, specific drivers were needed to provide impetus for widespread BIM adoption and implementation in the Canadian AECO industry.

4 KEY DRIVERS FOR CANADA

Specific attributes, also seen as drivers, for widespread adoption and implementation of BIM, and to a certain extent other innovative project delivery approaches, at the national level have been developed by Wong et al. (2010). Using those specific drivers, we discuss the implications for the Canadian AECO industry and compare them to what has been done elsewhere.

4.1 Public Sector As A Driver

Better satisfying client requirements and improving asset management has led various public organisms to look into the use of innovative project delivery approaches. Namely, the United States Government Services Agency (GSA), Statsbygg, the Norwegian Directorate of Public Construction and Property, and Senate Properties, the Finnish state owned enterprise responsible for real property acquisition and maintenance, and Her Majesty’s Government in UK have acted as drivers for innovation in their respective AECO industries by taking active steps in pushing for the widespread use of BIM and integrated approaches on their public projects. One of the most telling examples is that of the GSA who since 2003, has established a program to develop BIM guidelines to better meet and deliver its clients space requirements. Between 2003 and 2006, the (GSA) carried out 9 pilot projects to test and develop BIM implementation for various uses. This allowed the GSA to develop its 3D-4D BIM program and the accompanying guides. During that same period, the Danish government initiated Det Digitale Byggeri (Digital Construction) (bips, 2011), a public-private initiative, aimed at providing a number of requirements governing the use of BIM and ICT for consultants and contractors (The European e-Business Market Watch, 2005). While the Danish government does not possess a large property portfolio, its support of the
transition to innovative approaches has had a strong impact in the Danish AECO industry and can continue to do so. For instance, the report of COWI (2009) demonstrated that by developing projects in a fully digital environment, this would contribute an additional € 2.3 billion per year to the Danish economy. Lastly, the UK has a long history of questioning the practices of its AECO industry and developing programs to overcome the limitations of this industry, the most famous being the Latham and Egan reports (Latham, 1994, Egan, 1998). More recently, the government has set aggressive targets in their Construction 2025 industrial strategy: 33% lower costs, 50% faster delivery, 50% lower greenhouse gas emissions and 50% improvement in exports (HM Government, 2012). Further to these telling examples of public sector leadership, one of the main lessons learned from the exploration of innovative approaches around the globe is that successful implementation has been supported by investment from the governments either for research and development (such as in Finland and Norway) or to support the industry (such as in the UK). A specific example of this is the Singaporean government who has introduced the BIM Fund that covers training, consultancy services, purchase of software and hardware. Other investments by the public sector are illustrated in table 1.

Table 1: Investment in BIM implementation per country

<table>
<thead>
<tr>
<th>Country</th>
<th>Organization</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom</td>
<td>BIM Task Group</td>
<td>Public sector funding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mobilisation - £ 1.4 million</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operations – £ 480 000 / year (5 years)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total – £ 3.86 million ($ 6.94 million CAN)</td>
</tr>
<tr>
<td>Finland</td>
<td>Tekes</td>
<td>Public and private sector funding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pre program at RYM oy. R &amp; D – € 21.7 million (4 years between 2010 and 2014)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>($ 30.9 million CAN)</td>
</tr>
<tr>
<td>Norway</td>
<td>Statsbygg</td>
<td>Public and private sector funding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R &amp; D – € 21.7 million (4 years between 2010 and 2014) ($ 30.9 million CAN)</td>
</tr>
<tr>
<td>Singapore</td>
<td>Building Construction Authority (BCA)</td>
<td>Public sector funding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BIM fund – cover up to 50% of costs associated to BIM adoption within firms: 12 millions SGD ($ 10.4 millions CAN)</td>
</tr>
</tbody>
</table>

As mentioned, the Canadian government has put forth some initiatives targeting the AECO industry. However these have either been short lived or their impact has not been fully felt. When looking at other countries, most of these initiatives were undertaken within a specific government department and treated as a priority within this department. These countries have recognized the significant power of the public sector as a key actor in the reform of the AECO industry. In this regard, the Canadian public sector represents 22.40% of the total capital expenditures in Canada, or $ 65.18 B (Statistics Canada, 2014). These capital expenditures are distributed across three levels of government. At the national level, public bodies include: Public Works and Government Services Canada (PWGSC), the Department of National Defense (DND), and its representative Defense Construction Canada (DCC). At the provincial level, each government has a specific organization, a crown corporation, which assists other government agencies in their construction projects and asset management. Lastly, at the municipal level, most large municipalities will have departments responsible for overseeing construction projects. It is also at the municipal level that building codes and bylaws will be enforced through development applications, public consultation and plan review. The complexity inherent to this multi-layered governmental context is a core issue to the lack of national initiatives that can truly take root in the Canadian AECO industry. The authors believe that while a national initiative is relevant, the bulk of the work must happen at the provincial and municipal levels. Therefore, this national framework for innovative project delivery must be multi-tiered and consistently adopted and adapted at all three levels of government.

4.2 Governmental Policy Mandating BIM on All Public Projects

The principal way through which the countries mentioned above have driven the adoption and implementation of innovative project delivery approaches, namely BIM, has been through a national
policy mandating their use on all public projects. For example, the US, Finnish and Danish governments have all been mandating BIM on all public projects since 2007. The Norwegian government has stated its commitment to succeed in BIM adoption in 2010 (The BIM Issue, 2011). Both Hong Kong and Singapore are making BIM obligatory in 2015, while the UK government is mandating “level 2” BIM, or a “managed 3D environment held in separate discipline “BIM(M)” tools with attached data” on all its projects in 2016 (BIM Task Group, 2012). No such timeline exists in Canada either at the national, provincial or municipal level. While there exists no formal policy mandating BIM implementation on all public projects in Canada, several governmental bodies, at varying levels, have initiated pilot projects to begin framing a mandate. In this regard, the authors are aware of four separate initiatives where BIM is being looked into by a government body: The work in the field of space management and open BIM initiated by DND and DCC since 2009, the Royal Alberta Museum pilot project initiated by Alberta Infrastructure, several small pilot projects initiated by the Société Immobilière du Québec (SQI) and finally, the Moose Jaw Hospital initiated by the Government of Saskatchewan, which incorporated BIM and more importantly is one of the first IPD contracts with lean approach in Canada. These individual efforts across Canada show a willingness on the part of governmental bodies to move towards these innovative project delivery approaches. However, there is a risk that these individual efforts lead to fragmented policies across the county. There is a need for a concerted effort across all levels of government, to develop a unified mandate regarding the implementation of BIM and other approaches on public projects.

4.3 BIM Standards and Guidelines

The number of BIM standards and guidelines has grown exponentially over the past years. Representatives from both the US and the UK have mentioned that the presence of so many different standards was problematic in broadcasting a consistent message and gaining traction within the industry. In particular, the US is faced with the challenge of having many different standards, which have been produced, at the National level (GSA, US Army Corp of engineers, US Veteran, US Coastguard), at the state level, at the municipal level and from private owners (ie. universities). The presence of so many guidelines and standards has created confusion in the US industry, namely with the professionals who have to contend with these different standards. On the other hand, the Finnish, Norwegian, Danish and Singaporean examples are particularly interesting in their strategy of developing standards from a single source, with inputs from industry, academia and government. For example, Senate Properties in collaboration with buildingSMART Finland, construction companies, big cities, hospitals and consulting companies produced their BIM requirements in 2007 and updated them in 2012 (COBiM, 2012). In Denmark, bips is responsible for the producing the Digital Building Code and the Danish Building Classification System (DBK) based on buildingSMART. The Building Construction Authority (BCA) is the sole source of BIM standards in Singapore.

Canada has a big advantage to benefit from the efforts and lessons learned of other countries in developing its standards. Some guidelines have begun to appear, namely the AEC (Can) BIM Protocol published by the Canadian BIM Council (CanBIM) and modeled on the AEC(UK) BIM protocol, developed by the AEC(UK) initiative. These protocols serve as tools to generically inform model structure and the modeling process, and have not been adopted as a governing standard by either the Canadian or the UK industries. The Institute for BIM in Canada (IBC) has published a series of ‘toolkits’ aimed at supporting the implementation of BIM by Canadian firms (IBC BIM, 2014). IBC has also published a contract language document to be used as an exhibit or appendix to other contracts and spells out the roles and responsibilities as well as the uses of BIM on the project. While these documents serve to better inform the implementation of BIM in Canada, they have not yet been endorsed by any governmental bodies. There are other efforts to create national standards in Canada, notably, the Canadian Construction Documents Committee (CCDC), a national joint committee responsible for the development, production and review of standard Canadian construction contracts, forms and guides, and the National Building Code of Canada (NBCC), issued by the Institute for Research in Construction (IRC), which is part of the National Research Council of Canada (NRC). Whereas, the standard contract documents produced by CCDC are now widely used by the Canadian AECO industry, they still are used on a project basis. On the other hand, the model code produced by the IRC must be adopted by a jurisdiction to take effect. Many provincial jurisdictions have adopted the NBCC as is. Some provincial and even municipal jurisdictions have modified the NBCC, as is the case in British-Colombia, Quebec and in the city of Vancouver.
However, they possess the same structure and much of the same content. In light of these efforts, there is potential for the creation of unified standards and guidelines for the Canadian AECO industry. While these standards could be informed by existing standards such as versions 1 and 2 of the National BIM Standard, produced by the NIBS, as well as the Common BIM Requirements produced in Finland, these standards could be endorsed at all government levels, similarly to the National Building Code. Furthermore, they should be consensus based and originate from a unique organization that is comprised from members of industry, academia and government.

4.4 Clear Information Exchange Requirements and Open Standards

One of the core concepts of BIM is the seamless production and exchange of information across a project’s lifecycle (Eastman et al., 2011). In an effort to ensure this seamless information flow, open exchange standards are critical so as to not be reliant on a specific platform or proprietary mechanism. These open standards have been developed over the past two decades, namely the Industry Foundation Classes (IFC) by buildingSMART international (formerly the International Alliance for Interoperability (IAI)). Recognizing the importance of this open data exchange, the GSA, Senate Properties, Statsbygg and DECA (Denmark) signed a joint statement in 2008 to support open BIM based on IFC (Winstead et al., 2008). The question of data requirements is more complex. What information is to be produced at what time and for what use is a difficult question to answer; it is highly dependent on the stakeholder’s perspective. From a public owner’s perspective, two perspectives emerged from the various initiatives around the world. The first is for specific uses such as program validation (GSA) or code compliance checking (Singapore). The second is to ensure the reuse of information over the product lifecycle. In this case, the standards indicate how the information should be input to ensure consistency across projects, as is the case in the Finnish and Danish standards. Lastly, the question of information evolution has been addressed by the UK government who has developed COBie drops to allow public owners to validate the information received from their project team in a structured manner (The National BIM Library, 2012).

Canada can benefit from the development and work in this field performed in other countries. While the mandating of IFC compliant deliverables on public projects is relatively straightforward and the international consensus around the use of this exchange standard provides relative stability and confidence, the exchange requirements will have to be further investigated. While government bodies can look to these requirements to fulfill their business processes, they should also look to leverage these in order to prompt the reconfiguration of practice that is called for in the transition to BIM and integrated approaches. In other words, while the value of this open data for public bodies lies in its reuse over their asset’s lifecycle, in their role as catalysts for change, these public bodies should look at structuring the information requirements to push project teams to innovate and become more efficient.

4.5 Designated Organizations Responsible for BIM Implementation

Further to the development of standards and guidelines originating from a single source, an organization responsible for driving BIM adoption and implementation in Canada should be mandated. This has been the case in other countries such as the BIM Task Group, a UK Government-funded group, which plays an active role in the reform at the national level by helping the AECO industry become more efficient and to adopt collaborative work practices for all public projects. Although the group has a small number of personnel (10 people), they work on creating links between industry, government, public sector and academia around collaborative work and BIM; and on developing open standards to facilitate interoperability and data exchange to reduce barriers in this exchange (HM Government, 2012). Another example is the BCA in Singapore who is primarily responsible for the implementation of BIM and integrated approaches within the Singaporean AECO industry, more specifically, introducing BIM Fund incentives as mentioned earlier.

The role of professional associations in the deployment of BIM is very important. In the US and the UK, professional accreditation is done through national bodies such as the American Institute of Architects (AIA) and the Royal Institute of British Architects (RIBA). This results in a very large constituent base for these associations. Both the AIA and RIBA have been instrumental in advocating and developing tools for the implementation of BIM and IPD in their respective countries. The same can be said for the
Association of General Contractors (AGC) in the US. In Canada, construction being of provincial jurisdiction, professional accreditation becomes the responsibility of provincial associations. This reduces the capability to understand and support changes in the professional practices and body of knowledge at the same time. Some associations, such as the Royal Architecture Institute of Canada (RAIC), Engineers Canada (EC) and the Canadian Construction Association (CCA) operate at the national level and assist provincial bodies in terms of certification of education. However, they mainly serve as advocacy groups and hold little power over day to day practice, contrary to their American and British counterparts. This limits the impact of national initiative put forth through professional associations. To push a national mandate for BIM and integrated approaches, it will be important to get all professional associations to support and buy into the initiative. Lastly, two national advocacy groups have been founded which promote BIM in Canada: the Canadian BIM Council (CanBIM) and the Institute for BIM in Canada (IBC) of which the Canadian chapter of buildingSMART International is a council. Both these groups have put forth considerable effort to engage the industry in moving BIM forward. While these organizations are gaining traction, they largely rely on individual effort to push the Canadian BIM agenda. At the provincial level, several "grass roots" organizations or committees have emerged in recent years. These could include Alberta Center for Excellence and aceBIM chapter, the BIM BC user group, as well as BIM Quebec group. These groups work in silo, and are not integrated. Again, the presence of an organization that is backed by all professional associations and is supported and funded by all levels of government can act as a unifying front to push a coherent Canadian mandate.

4.6 Reporting and Promotion of BIM

The reporting and promoting of BIM and innovative project delivery approaches is a very important component in driving widespread adoption and implementation. Experience has shown that there is a lack of distinction between promotion of these approaches by vendors and AECO organizations serving marketing purposes and objective reporting by independent bodies. Many claims have been made that are unsubstantiated and as such creates some scepticism in the industry. As such, an independent reporting of lessons learned and outcomes is needed to foster industry wide acceptance. In many countries, this responsibility is taken on by the organizations mandated to drive the initiative such as the BCA in Singapore and the BIM Task group in the UK. Both these organizations work on developing and monitoring activities such as forums, presentations, training, workshops, etc. The BIMForum in US also represents an important resource to address multidisciplinary practice and to keep industry up to date regarding advances in BIM.

In Canada, there are several activities that promote BIM, such as trade shows, conferences and symposiums. At the national level, bSC, IBC and CanBIM promote innovative approaches through conferences and workshops. At the provincial level, some private organisations are working on promoting new technologies and approaches such as Contech in Québec. Some professionals associations are beginning to be more involved in promoting BIM through conferences and workshops by inviting researchers and pioneer adopters to exchange their experiences and practices. Although the main goal is promoting BIM, the majority of these activities do not go beyond being purely informative in purpose. At the project level, as mentioned above, most of the promotion is led by firms who have worked on innovative projects and who use these cases for marketing purposes. In light of this, a centralized resource, which supports the objective capturing of lessons learned and outcomes for the Canadian AECO industry is needed. This resource should be maintained by the organization mandated with leading the national initiative.

4.7 BIM Research Programs

Lastly, the importance of research and development in this field is vast. The countries, which have succeeded in leading the reform of their AECO industries, all have invested in research programs to develop internal competencies and develop tools and technologies to support the transition. For example, Finland is famous for its research initiatives, innovation programs and establishments of international networks. The earliest research on BIM was initiated in the 1980s. Just after the recession in the early 1990’s, the Finnish technology policy and industry leaders agreed about the need to develop the cluster [focussing on the AECO industry] and identified some key problem areas in the industry with a focus on
'information sharing and management in all processes during an asset’s lifecycle (Kiviniemi, 2006). This led to the emergence of TEKES’s technology programs and later on, in 1994, to emergence of International Alliance for Interoperability (IAI) with the focus on the development of IFC data specification internally and since 1996 at the international scale. This was followed by developments such as VERA (1997-2002) and SARA (2003-2007) (Froese, 2002, Kiviniemi, 2006). The outcomes of these programs were first BIM guidelines in 2007 in Finland. More recently the PRE project, led by RYM OY has received important funding from both the government and industry. The US also has heavily invested in R&D. For example, the National Institute of Building Science (NIBS) and the National Institute of Standards and Technology (NIST) are the two main organizations, which carry out research on BIM. Whereas NIST is a governmental agency, NIBS is a Not-for-profit, which regroups representatives from the government, industry and academia. The American chapter of buildingSMART is integrated within NIBS. NiBS oversees the development of open data exchange standards such as IFC and COBie as well as the National BIM Standards. There are other organisms that conduct research in the AECO industry in the US such as Fiatech and the Construction industry Institute (CII).

In Canada, many research groups; universities and organizations are involved in the study of BIM and integrated approaches. Research groups, such as the BIM Topics lab at the University of British Columbia; research groups at the University of Calgary, the University of Alberta, the University of Ottawa and University of Waterloo, Concordia University and the GRIDD at the École de Technologie Supérieure, work with the industry through pilot projects to develop better practices for BIM and other construction innovations based on industry needs. The Canadian government has some programs to fund these researches and to create bridges between industry and academia and research centers such as Engage Grants or Industrial Research Assistance Program (IRAP). These programs allow industry to have access and to exchange knowledge with researchers. However, many of these research projects are one off and remain fragmented and the findings are highly contextual. Another key issue that must be addressed is related to adapting educational program to current realities. According to Forgues and Farah (2013), Canada needs to swiftly update and reform its university curricula to reflect the innovation and integration. There is a need to redefine professional curricula to fit the new context of integrated approaches. Certification of these new programs must be standardized and governed by a certifying body, as is the case with other programs that lead to professional accreditation.

5 CONCLUSION
This article has outlined the various initiatives from around the world that are driving the reform of the AECO industry. Innovative approaches to project delivery and asset management, such as BIM, IPD, IDP and Lean construction, are increasingly being relied upon to improve the performance and value generated by an industry that has long been seen as inefficient and wasteful. Many countries consider that their respective AECO industries contribute significantly to the development of their society, economy and have a very big impact on their environment. By acting as a driving force, and by providing the impetus to the industry to transform itself, governments around the world are tooling their AECO industries to become better and to remain competitive in light of increased global pressures such as global competition, move towards sustainability and carbon neutrality and increasing economic pressures on governments to deliver projects on-time and on-budget.

In this regard, Canada cannot afford to remain idle. Active steps must be taken to follow suit to these other countries. This paper has discussed six attributes to successfully drive the adoption and implementation of BIM at a national scale. While the context in which the Canadian AECO industry operated is unique, there exists some mechanisms and strategies which can structure and adapt the adoption process to this particular context. Learning from abroad, a Canadian mandate can rely on international efforts to inform its initiatives, namely by adopting Open standards and developing guidelines that are inspired by best practices from elsewhere. More importantly, the Canadian initiative must share a single vision. It will need the backing from constituent organizations and professional associations across Canada as well as being endorsed by all levels of government.

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References


RESEARCH FOR GENERATING 3D MODEL FROM LASER SCANNER DATA REMOVED NOISE

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Abstract: Construction CALS/EC is introduced in public works projects over the whole life cycle for the purpose of reduction of the construction period, quality guarantee, and cost reduction. Especially recently, environmental improvement of the information-oriented construction using 3D data attracts attention for engineering works stage. In the construction site, it is expected to create 3D model from the point cloud data obtained by surveying the site with the total station or the laser scanner. However, it is necessary to solve the problem of how to handle the great amount of point cloud data obtained at the survey based on their characteristics, as well as the problem of required accuracy for the information-oriented construction. The authors have devised a technique to make 3D model of the river embankment, which satisfy the required accuracy of the information-oriented construction from a large quantity of point cloud data. This technique used the point cloud data of the river embankment measured with the laser scanner and DM data of it. Then, the boundary line (breakline) between the crown surface and the slope face of the river embankment is extracted automatically to create 3D model on CAD. However, the following problems were revealed; the freshness depending on the update cycle of DM data, and wrong extraction of a breakline due to the noise such as the vegetation between the crown surface and the slope face of the river embankment. In this research, we devised a method for automatically extracting a breakline by inferring the crown surface area of the river embankment from the point cloud data, and a method for removing any point cloud data that are the noise such as the vegetation on the crown surface of the embankment. Then we performed evaluation experiments and proved the usability of the devised solution.

1 INTRODUCTION

Public institutions in Japan are promoting measures for constructing a data circulation environment using ICT (Information and Communication Technology) over the whole life cycle for reduction of construction period, quality assurance, and cost reduction of public works. Recently, there are efforts underway by academy, industry, and government to apply this in product models in construction stages such as development of Road Alignment Data Exchange Standard, as well as advanced efforts for intelligent construction (Tanaka, 2009).
Against this background, a workshop on establishing a data circulation environment for river projects was set up in Kinki Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism for the purpose of promoting new technology development with public and academic sectors as its core (Fukumori, 2009). This workshop aims to develop technologies for generating high-precision three-dimensional (3D) models useful in construction management or maintenance using the survey data concerning the present topography of rivers. Relevant researches suggest methods of generating 3D models automatically from the point cloud data (Shaohui, 2013) (Choi, 2008) (Tanaka, 2010) measured with high-precision scanners (Ohtu, 2007). However, there are two potential problems in the 3D models created from the point cloud data collected by the laser scanner: how to handle a large amount of point cloud data, and wrong extraction of the boundary line of aspect change (hereinafter referred to as 'breakline').

To solve these problems, the existing researches propose a method to extract breaklines, leaving geometric characteristics and thinning out an enormous amount of point cloud data, through a method of using relative positions of point cloud data (Shaohui, 2013), or a method of using reflection intensity of point cloud data (Choi, 2008). However, it is impossible to uniquely identify the boundary lines between planes of the river embankment because it is a space where artifacts and natural objects coexist. Accordingly, it is difficult to create a 3D model with high precision of reproducibility. Therefore we have been working on the research on controlling wrong extraction of breaklines (Tanaka, 2010). Firstly in specific, point cloud data was superimposed on DM data developed nationwide by public survey. Next, a 3D model was automatically generated using the road alignment contained in DM data as a clue. However, there are two problems of "Freshness due to the update cycle of DM data" and "That noise such as vegetation inhabiting the top plane of a river levee (hereinafter referred to as "crown surface")".

Based on these problems, this research aims to establish a method of automatically generating a 3D model from a large amount of point cloud data in consideration of boundaries of planes of the river levee. This method assumes the outline of the crown surface estimated from the point cloud data as a candidate breakline. Furthermore, wall-shaped noise is eliminated from the point cloud data on the crown surface automatically to restraint wrong extraction of breaklines.

2 OVERVIEW OF OUR RESEARCH

This research proposes an automatic generation method of 3D models that solves two problems: "problem of freshness due to the update cycle of DM data" and "problem of wrong extraction of breaklines because the boundary between planes becomes vague due to the wall-shaped noise".

2.1 Measures against the problem of freshness due to the update cycle of DM data

This method identifies an area showing the crown surface from point cloud data. The outline of the identified area is assumed the candidate breakline. Therefore, a 3D model is constructed from point cloud data without depending on DM data.

2.2 Measures against the problem of wrong extraction of breaklines because the boundary between planes becomes vague due to the wall-shaped noise

This method estimates ambiguous ground surface from features of the shape and the noise of the river embankment.

2.3 Processing flow

Figure 1 shows the processing flow proposed in this research. This research adds a function of generating candidate breaklines and a removal processing of wall-shaped noise to the existing method (Tanaka, 2010). Thus the proposed method is comprised of three functions: candidate breakline generation, breakline extraction, and thinning out point cloud data. The processing procedure of each function is shown below.
The function of candidate breakline generation is comprised of three kinds of processing: process of dividing elevation, process of clustering density, and process of identification crown surface. Process of dividing elevation is the process of entering the point cloud data and divided them into multiple layers using elevation values. In order to distinguish the layer on which the point cloud data are concentrated, the point cloud data on each layer is clustered based on the relative distance between points, and a cluster of micro area is removed as noise. Process of identification crown surface is the process of evaluating the density of point cloud data of each layer to estimate the crown surface layer. Then the outline of the point cloud data region contained within the crown surface is obtained as a candidate breakline. Function of breaklines extraction comprises 5 kinds of processing; limiting the extraction range, generating a cross-section model, removing wall-shaped noise, identifying the cross-sectional change point, and creating breaklines. Process of limiting the extraction range limits the extraction range of the cross-sectional change points using the candidate breaklines acquired from the point cloud data and the candidate breakline acquisition function. Process of generating cross-section model acquires cross section models of the levee from the point cloud data contained in the extraction range. Wall-shaped noise removal processing removes the point cloud data with the altitude higher than the crown surface and acquires cross section models from which the influence of noise has been removed. Identification processing of cross-sectional change points acquires an intersection point of the line segments showing the crown surface and the slope from the cross section model from which wall-shaped noise has been removed as the cross-sectional change point.

Process of creating breaklines creates a breakline by connecting cross-sectional change points through process of identification acquiring cross-sectional change point. Function of thinning out point cloud data comprises process of creating a filter and process of interpolation of the point cloud data. Process of creating a filter creates a breakline filter by superimposing breaklines and a grid-like filter. Next, process of interpolation of point cloud data interpolates the point cloud data using the breakline filter. This process converts the point cloud data measured at irregular intervals to the thinned-out point cloud data in a grid-like shape with breaklines taken into consideration.

3 FUNCTION OF CANDIDATE BREAKLINE GENERATION

The function of candidate breakline generation creates candidate breaklines from the point cloud data. Here we assume the point cloud data measured by the laser scanner as \( P = \{ p_1, p_2, p_3, \ldots, p_i \} \). This function solves the aforementioned problem of freshness due to the update cycle of DM data.

3.1 Process of dividing elevation

This processing divides point cloud data into multiple layers as pre-processing to distinguish the region of the crown surface from the point cloud data. Specifically, the point cloud data \( P \) is divided at regular intervals at every height \( h \), as shown in Figure 2. The layer set acquired from this processing is assumed as \( L = \{ l_1, l_2, l_3, \ldots, l_j \} \).
3.2 Process of clustering density

In order to distinguish the layer on which point cloud data are concentrated, this processing performs clustering by the density of points over the layer and calculates the region area of each cluster. The characteristics of the point cloud data obtained by measuring a river levee with MMS shows that the density of the point cloud data of the crown surface close to the measurement vehicle tends to be high, and that the point cloud data density of those away from the measurement vehicle such as slope or foot of slope tends to be low. For this reason, this processing used DBSCAN method, which is one of the data mining methods, as a method for clustering based on density. DBSCAN is a clustering method based on the point density using two values: distance threshold $Eps$, and threshold of target numbers $MinPts$. Figure 3 shows a method of process of clustering density. First, the point cloud data contained in an arbitrary layer $l_j$, $P_{dbscan} = \{pd(j, 1), pd(j, 2), pd(j, 3), ..., pd(j, l)\}$, is clustered by DBSCAN. When arbitrary point $pd(j, l)$ in the point cloud data $P_{dbscan}$ and neighborhood point $pd(j, l+1)$ contained in the neighborhood point cloud $N_{Eps}(pd(j, l))$ within the distance $Eps$ from that point satisfy the following conditional equations [1] and [2], the neighborhood point $pd(j, l+1)$ is classified as the same cluster with the point $pd(j, l)$.

\[
\begin{align*}
[1] & \quad pd(j, l) \in N_{Eps}(pd(j, l+1)) \\
[2] & \quad |N_{Eps}(pd(j, l+1))| \geq MinPts
\end{align*}
\]

Assume the clustering result by DBSCAN from an arbitrary layer $l_j$ as $Cl_j = \{cl(j, 1), cl(j, 2), cl(j, 3), ..., cl(j, k)\}$. Then obtain the region outline of each cluster $cl(j, k)$ of the cluster set $Cl_j$ by the active contour method. In addition, assume the point cloud data applied to the active contour method as $P_{snake} = \{ps(j, 1), ps(j, 2), ps(j, 3)\}$. Figure 4 shows the outline of the active contour method used in this research. The active contour method is a method for capturing the contour of an object by repeating movement and deformation of the closed curves that contain the object. First, create a circle so that it circumscribes the target point cloud data $P_{snake}$. Second, create point-series $P_{tangent} = \{pt_1, pt_2, pt_3, ..., pt_n\}$ arranged at equal intervals on the
circumference, and a tangent line of the circle \( T = \{ t_1, t_2, t_3, \ldots, t_n \} \) passing through \( p_{tn} \). Then, translate the tangent line of the circle \( t_n \) passing through the point \( p_{tn} \) on the circumference towards the center point of the circle until it overlaps with the target point cloud data \( ps(j, m) \). Then the distance translated by \( p_{tn} \), range is calculated using equation [3]. Here \( t_n \) is a straight line formula \( ax + by + c = 0 \). \( x_t \) and \( y_t \) are assumed as \( x \) and \( y \) coordinates of the translating point \( p_{tn} \), whereas \( x_s \) and \( y_s \) as \( x \) and \( y \) coordinates of the target point cloud data \( ps(j, m) \).

\[
\text{Range} = \frac{|ax \cdot x_s + b \cdot y_s + c|}{\sqrt{a^2 + b^2}}
\]

![Diagram](image)

Figure 4: Outline of the active contour method used in this study

The set of tangent lines of point cloud data obtained by this processing is assumed as \( T' = \{ t'_1, t'_2, t'_3, \ldots, t'_n \} \). The set of intersections of a tangent line set \( T' \) is assumed as the region outline \( F = \{ f_1, f_2, f_3, \ldots, f_o \} \). Then the region area \( S_l = \{ s_1(j), s_2(j), s_3(j), \ldots, s_l(j) \} \) of the cluster set \( Cl_j \) is calculated from the region outline \( F \) of the cluster obtained by the active contour method. Region area \( S_l \) of each cluster is calculated by calculating the area of the following polygons using equation [4]. \( x_o \) and \( y_o \) in equation [4] are \( x \) and \( y \) coordinates of vertex \( f_o \) of the region outline \( F \). \( x_{o+1} \) and \( y_{o+1} \) are \( x \) and \( y \) coordinates of the point \( f_{o+1} \) adjacent to vertex \( f_o \).

\[
s_l(j, i) = \frac{1}{2} \sum_{o=1}^{l} (x_o - x_{o+1}) \cdot (y_o + y_{o+1})
\]

3.3 Process of identification crown surface

Figure 5 shows the process of identification crown surface. The process of identification crown surface identifies the layer of the crown surface in order to acquire the candidate breakline. The layer of the crown is estimated using the ratio of the region area of the point cloud data belonging to the layer to the sum total of region area of each cluster \( S_l(j) \) or the region size where there are point cloud data. Then, the region area of each layer is assumed as \( S = \{ s_1, s_2, s_3, \ldots, s_j \} \). These region areas are different from layer to layer since they depend on the result of clustering processing of each layer.

First, when it is a micro cluster of which the region area is threshold \( \text{MinSize} \) or smaller, the micro cluster is removed from any layer \( l_j \). Next, the region outline and region area of any layer \( l_j \) is calculated using the active contour method like the preceding term. Then using the region area of the layer and the region area of the cluster contained in the layer, layer \( l_j \) that is to be the crown surface is identified using equation [5]. Finally, the region outline of the layer \( l_j \) of the crown surface is obtained as the candidate breakline \( BL \).
4 EVALUATION EXPERIMENT

4.1 Experiment outline

Aiming to verify if the two problems (of freshness due to the update cycles of DM data, and of wrong extraction of breaklines because the boundary between planes becomes vague due to the wall-shaped noise) are solved, this experiment compares the precision of reproducibility of 3D models by the existing and proposed methods using the following indicators.

- Comparison using breaklines
- Comparison using a cross section drawing generated from a 3D model

The former compares and evaluates the breakline of a 3D model generated by each method with the breakline acquired by manual operation as the evaluation criteria. The latter compares and evaluates the cross section drawing created from a 3D model of each method with a measured cross section drawing used in the actual river management.

4.2 Experiment environment and experimental data

Table 1 shows the specifications of the equipment and experimental data used in this experiment. The point cloud data used in this experiment covers the area ranging from 7.2km to 8km in the distance from the river mouth (hereinafter referred to as "distance mark") divided at every 200m (approximately 40m in width and 8,000m² in area). The area to measure in this experiment was set to the right bank of a section along the Yodo River levee circled in an ellipse in Figure 6. Figure 7 shows the result of visualizing point cloud data using MMS, and Table 2 shows the details of point cloud data. In addition, the existing method (Method a) uses road alignment contained in DM data as candidate breaklines. This experiment adopted DM data of the Yodo River levee (map information level 2,500).
Table 1: Experiment environment

<table>
<thead>
<tr>
<th>Type</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>Intel® Core™2 Duo CPU 2.50Ghz</td>
</tr>
<tr>
<td>Memory</td>
<td>4.0GB</td>
</tr>
<tr>
<td>HDD</td>
<td>280GB</td>
</tr>
</tbody>
</table>

Table 2: Details of the experimental data

<table>
<thead>
<tr>
<th>Items</th>
<th>MMS data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of points</td>
<td>About 4.1million</td>
</tr>
<tr>
<td>Measuring distance</td>
<td>800m</td>
</tr>
<tr>
<td>Absolute precision</td>
<td></td>
</tr>
<tr>
<td>Horizontal direction</td>
<td>10cm</td>
</tr>
<tr>
<td>Vertical direction</td>
<td>15cm</td>
</tr>
<tr>
<td>Relative precision</td>
<td>1cm</td>
</tr>
</tbody>
</table>

4.3 Experiment description

First, three 3D models are generated by entering the point cloud data.

- Existing method (Method a) (Tanaka, 2010)
- Proposed method with a function of candidate breakline generation added to the existing method (Method b)
- Proposed method with a function of candidate breakline generation and process of removal wall-shaped noise added to the existing method (Method c)

Next, cross sections are obtained from the generated 3D model. Using the longitude and latitude of the distance marks in the measured cross sections of correct data, information on the same place is extracted as to cross sections. Finally, the cross sections is compared with their correct data for evaluating the precision.

4.4 Experimental results and discussion

This experiment evaluates the precision using the difference in elevation of each cross section by superposing the cross section of a 3D model created through each method with the measured cross section. For the measured cross sections to be used in this experiment, 5 drawings were prepared at every 200m between the distance marks of 7.2km and 8.0km points contained within the measurement area using MMS. Figure 8 shows an image of comparing cross sections. Here comparison of the difference in elevation is calculated over the evaluation points created by dividing the measured cross section at intervals 1cm. Moreover, the comparison results are classified into three sections: all, section A and section B, and totalized as shown in Figure 9.

Section A is assumed as the range including the width of the crown surface with 5cm added on both sides. This is determined with reference to the value of the work progress control standard for filling works of river earthwork providing the accidental error for the crown surface should be within 10cm.

Section B is assumed as the range not contained in Section A except the crown surface. Table 3 shows the totalized results for 3D models created using each method and the measured cross section drawing.
This experiment totalized to what degree the difference in elevation between cross sections is contained within 15cm at intervals of 5cm. This is a reason there is absolute error of 15cm (in the vertical direction) in the measurement data using MMS. Furthermore, for each totalized section, underlines were added to the values with the lowest error between the cross sections created using three methods and the measured cross section drawings. The experimental results proved the following three points.

### Table 3: Comparison results between 3D models and measured cross sections

<table>
<thead>
<tr>
<th>Measured points</th>
<th>Overall (%)</th>
<th>Section A (%)</th>
<th>Section B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method a</td>
<td>Method b</td>
<td>Method c</td>
</tr>
<tr>
<td>~ 5cm</td>
<td>22.68</td>
<td>20.45</td>
<td><strong>23.64</strong></td>
</tr>
<tr>
<td>~10cm</td>
<td>29.71</td>
<td>29.07</td>
<td><strong>37.38</strong></td>
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<td>~15cm</td>
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<td><strong>45.37</strong></td>
</tr>
<tr>
<td>~ 5cm</td>
<td>6.33</td>
<td><strong>10.67</strong></td>
<td>8.33</td>
</tr>
<tr>
<td>~10cm</td>
<td>16.00</td>
<td><strong>25.33</strong></td>
<td>21.67</td>
</tr>
<tr>
<td>~15cm</td>
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First, the total average in Table 3 reveals that the proposed method c realized the smallest errors compared with the measured cross sections throughout the overall part, Section A, and Section B. The average of the total results for Section A reveals that about 95% is included within 15cm, which is the allowable error for MMS, indicating that a 3D model with high precision has been generated. This is a reason the vegetation noise in the upper part of the crown surface is properly removed.

Second, Section A with the distance mark of 7.6km in Table 3 reveals that the 3D model generated by Method c is able to reproduce the crown surface more precisely than the ones created by the other two methods. Figure 10 shows the result of superposing the cross section at the distance mark of 7.6km with cross section drawings created from the 3D models by each method. Figure 11 reveals that the cross sections of 3D models created by Methods a and b do not agree with the measured cross sections in the part of crown surface, indicating that the 3D models are generated at higher position than the measured cross section. On the other hand, the 3D model created by Method c is able to have represented the present shape, showing the similar shape of the crown surface as that of the measured cross section. When analyzing the point cloud data at the distance mark 7.6km, there were wall-shaped noises at the upper part of crown surface including the top of slope. On the other hand, the 3D model generated using the proposed method was able to remove the wall-shaped noise on the crown surface with high precision.
Third, Section B in Table 3 reveals that approximately 30% of points fall into the range within 15 cm of difference in elevation by all the methods. It is considered that this is due to the characteristics of measurement with MMS that it allows obtaining a great amount of point cloud data in front of the measurement vehicle or neighborhood areas but the number of obtainable point cloud data decrease at the places where laser is hard to reach such as the slope face or toe of slope. Consequently, it is considered that the precision dropped in Section B compared with that on the crown surface because it was necessary to generate a 3D model depending on a small number of point cloud data.

![Graph of cross sections](image)

**Figure 10:** Results of superimposing a cross section of 3D model and a measured cross section at the distance mark of 7.6 km

![3D models](image)

**Figure 11:** 3D model generated from point cloud data

### 5 CONCLUSION

This research proposed a method for automated generation of a 3D model from a large amount of point cloud data in consideration of boundaries of planes of the river levee. The experimental results show that the two problems left in the existing method are solved: the problem of freshness due to the update cycle of DM data and the problem of wrong extraction of breaklines due to wall-shaped noise between the crown surface and slope face of the river levee. In other words, technologies are successfully developed for automated generation of a 3D model reproducing the present topographic features with high precision by referring only to an enormous amount of point cloud data with vague boundary planes. Specifically, technologies for handling the following point cloud data were developed:

- Technology to estimate the crown surface of a river levee using the density of point cloud data from the point cloud data measured with MMS.
- Technology to remove wall-shaped noise contained in point cloud data from the point cloud data measured with MMS using geometric characteristics of the river levee.
In this research, all the point cloud existing on the crown surface was assessed as noise in order to estimate the boundary lines of vague planes represented by point cloud data. In the future, demonstration experiments will be conducted to verify to what degree of differences occur between the 3D model generated using such a noise removal method and actual present topographic features, and the applicability to practices and effects to be enjoyed will be made clear.

This research generated 3D models for a river levee, and since the proposed method of this research has high versatility, its applicability to other civil engineering structures (roads, tunnels, or dams) will be examined in the future. Moreover, though the applicability was verified with focus on construction stages (information-oriented construction), some of the challenges to solve in future can be development into a method for assisting creation of register maps for maintenance as well as a management approach using spatial-temporal model added with time base.

Finally, this paper is part of the outcome of the activities of "Workshop on establishing a data circulation environment for river projects" set up in Kinki Regional Development Bureau, MLIT for the purpose of promoting new technology development with public and academic sectors as its core. We plan to make further studies to realize environment for smooth data circulation.

Acknowledgements

We would like to thank the members at MLIT Kinki Regional Development Bureau MILT for their Invaluable advice given on this paper, Nippon Koei Co.,Ltd. and Mitsubishi Electric Corporation for their cooperation in measurement of the point cloud data used in this research.

References

DESIGN AND DEVELOPMENT OF 3D-CAD ENGINE

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Abstract: Civil infrastructure drawing data are normally generated by computer-aided design (CAD) software in the design phase, and are also frequently needed during the construction and maintenance phases. An environment would be provided in which 3D construction information can efficiently and smoothly be used throughout the project lifecycle. Then, a 3D-CAD engine should be developed and operated to create and modify 3D structure information, but Japan’s CAD vendors have not had a product of the 3D-CAD software. Therefore, the purpose of this research is to spread 3D-CAD rapidly and at low cost throughout the construction industry in Japan. To achieve this purpose, we designed and developed a 3D-CAD engine. Our research and development made progress step by step with the research, the outline design, the primary design, and the detailed design. To verify the designed algorithm, we developed a prototype. After this we developed a 3D-CAD engine, and also simple 3D-CAD software equipped with this engine.

1 INTRODUCTION

It is important for the construction industry in Japan to build an environment where 3D-CAD data are used for BIM, CALS/EC, and IT-based construction to improve productivity. The current use of 3D-CAD data in the industry is infrequent because a quality affordable 3D-CAD engine does not exist. 3D-CAD software use the kernel for modeling, which is expensive for Japanese construction CAD software companies to use their CAD software. Such a 3D-CAD engine must be designed and developed in order to enable low-cost use and quick implementation, leading to its deployment in various stages of the life cycle of construction projects.

The purpose of this project is to spread 3D-CAD rapidly and at low cost throughout the construction industry in Japan. To achieve this purpose, we designed and developed a 3D-CAD engine. Our research and development made progress step by step with the research (use cases, seeds, standards), the outline design (3D representation models, functional requirements), the primary design (3D data exchange specifications, user interface, user operation), and the detailed design (data model, algorithm, API functions). To verify the designed algorithm, we developed a prototype. After this we developed a 3D-CAD engine, and also simple 3D-CAD software equipped with this engine.

Using the 3D-CAD engine that we developed, we created 3D geometric shapes by parametric modeling. We also designed data structure in conformity with ISO10303 (STEP). In addition, settings of diverse
attributes such as the time terms were realized. These are the contents of our research as follows: Outline of Kaiser Project in Kansai University, Design principle of 3D-CAD engine, Data structure in the 3D-CAD engine and its relationship with ISO, and Future expansion.

2 OUTLINE OF KAISER PROJECT IN KANSAI UNIVERSITY

The master plan of the project is shown in Figure 1. The project started from the fiscal 2008. As the product of research aid by Ministry of Land, Infrastructure, Transport and Tourism (MLIT), we prepared the investigation report and the primary design document. As the product of Kaiser Project in Kansai University, we prepared the outline design specification, the detailed design document, and the prototype. Finally, we developed the 3D-CAD engine and the simple 3D-CAD as the final product.

An overview of the 3D-CAD engine is shown in Figure 2. At the center is a 3D model. The model is composed of a sketch, modeling operational histories, and 3D geometric shapes. Connecting them with each other allows a 3D model to be generated. A 3D model also maintains diverse attributes. At the bottom are application program interfaces, which provide various features for creating, editing, and operating a 3D model, as well as for processes including volume and surface area calculation. Moreover, using API for data conversion into drawing data, the data can be converted into the drawing data on the right. The data can also be converted into the exchange data on the left by converting in conformity with the 3D data exchange specification.

The organization of research of this project is shown in Figure 3. The project management office plays a central part. Participating members of the project include research institutes, IT vendors, trading companies, and CAD and GIS vendors. The total amount of the fund is 100 million yen, offered by companies such as Mitsubishi Electric, as well as MLIT.

As to the operation of the project, we established the project management office, which is abbreviated to PMO. PMO plays a key role in the project operation as shown in Figure 4. Activities of PMO include the confirmation of budget execution, the order and inspection, the quality corrections in the project, the risk detection and direction of preventive measures, and the operation of progress meetings. Meetings were
held 43 times over 4 years and a half in this project. Each time about 15 members attended the meeting, including CAD vendors, IT vendors, construction consultants, and university researchers.

![Figure 2: Overview of 3D-CAD Engine](image)

![Figure 3: Organization of Research](image)

![Figure 4: Operation of Project](image)

3 DESIGN PRINCIPLE OF 3D-CAD ENGIN

3.1 Preconditions of Design Principle

As the preconditions of the design principle, we developed only 3D-CAD engine in this project. We also developed simple 3D-CAD software for verifying the 3D-CAD engine. Using the 3D-CAD engine that we developed, IT vendors and CAD vendors in Japan can develop domain CAD software, such as for roads, bridges, rivers etc.
3.2 Modeling Techniques

There are two kinds of 3D-CAD modeling: the direct modeling and the parametric modeling. The direct modeling directly creates and edits 3D geometric shapes to make drawings. It is easy to handle with its intuitive operation, but inefficient for making modifications. In contrast, the parametric modeling is a technique for defining the geometric shape of a model by setting variable parameters such as coordinate and size values to the model and giving values to the parameters. The parametric modeling is characterized by its easiness to edit because it allows the user to represent the design intent of a structure. The 3D-CAD engine developed in this project adopted parametric modeling. The CAD kernel is used for parametric modeling in commercial CAD software, which is expensive for Japanese CAD companies to use.

3.3 Basics of 3D Modeling

There are two basics of 3D modeling: the plane view drawing using sketches, and the 3D modeling based on plane view drawing. Regarding sketches, plane views are created to use as the foundation of CAD. In a plane view drawing in 3D-CAD, unlike 2D-CAD, it is not necessary to draw a plane view precisely since the length and angles of elements are determined by constraints later. After making plane view drawings, we go to the process of 3D modeling. As an example of 3D modeling, Fig.5 and 6 show some examples of creating a plane view drawing with sketches and 3D modeling with sweep.

3.3.1 Sketch

First of all, a sketch surface is made as shown in Figure 5. On the initial state of the sketch surface, a rectangle is created. Geometric constraints are applied to the rectangle to create a square. In this example, a square is created by constraining all lines to have the same length, and constraining all angles between the lines to be 90 degree.

![Sketch surface](image1)
![Making rectangle](image2)
![Specify target of geometric constraints](image3)
![Making square](image4)

Figure 5: Sketch Surface

3.3.2 Sweep

A sweep action as shown in Figure 6 is applied to the square created with a sketch. To make a sweep action, a sweep line is created. A sweep line is created as a 3D geometric element. After this, a combination of a sweep plane and a sweep line is specified, and a sweep action is executed. Then a sweep model is generated based on the sweep surface and sweep line.
3.3.3 Extrusion

As to the extrusion as shown in Figure 7, someone can create an extrusion model by extruding the sketch by the specified length.

3.3.4 Chamfer

Figure 8 shows an example of the chamfer. After specifying the chamfer distance, the chamfer process is performed.
3.3.5 Fillet

Figure 9 shows an example of the fillet. This generates a round surface based on the specified radius.

![Whole view and Enlarged view of Fillet](image)

Figure 9: Fillet

3.3.6 Boolean

Figure 10 shows an example of using the boolean. A pipeline is connected to a pipeline to a manhole.

![Boolean for Connecting Pipeline to Manhole](image)

Figure 10: Boolean for Connecting Pipeline to Manhole

3.3.7 Example of Creating Alignment

Figure 11 shows an example of creating an alignment by using the sweep. An alignment model of road or railroad can be created by generating a cross-section using Sketch, and making a sweep action.

![Example of Creating Road Alignments](image)

Figure 11: Example of Creating Road Alignments
4 DATA STRUCTURE IN 3D-CAD ENGINE AND ITS RELATIONSHIP WITH ISO

We explain the data structure in the 3D-CAD engine and its relationship with ISO.

4.1 Data Structure of 3D Model

Figure 12 is the data structure of a 3D model to be generated by the 3D-CAD engine. 3D models designed in Kaiser Project conform to ISO 10303, which is also called STEP. This figure shows elements of a 3D model and their corresponding parts in ISO 10303 that they conform to. Sketch conforms to Part 108, the modeling operational histories to Part 55 and Part 111, the 3D geometric shapes to AP 203 (ISO 10303-203: 1994) and Part 42, and the attributes to Part 41.

![Diagram of 3D CAD Engine with ISO](image)

Figure 12: Data Structure of 3D-CAD Engine with ISO

4.1.1 Part 108

For the sketch, we adopted part 108 (ISO 10303-108. 2005.), which is about the parameterization and constraints for explicit geometric product models. Part 108 specifies the resource constructs for representing model parameters and constraints, together with the mechanisms necessary for associating them with geometric or other elements of models.

4.1.2 Part 55 and 111

For the modeling operational histories, we adopted Part 55 (ISO 10303-55. 2005.), which is about the procedural and hybrid representation, and Part 111 (ISO 10303-111. 2007.), which is about the elements for the procedural modeling of solid shapes. Part 55 specifies the representation of constructive operations used to build models, in other words, elements to record operational sequence. Part 111 specifies feature-based modeling commands, prescribing input parameters, output parameters, command specifications and so on.

4.1.3 AP203, Part 41 and 42

For the 3D geometric shapes, we adopted AP 203, which specifies the configuration controlled design. And Part 42 is referred to for geometric elements in AP 203. The conformance class, or CC, is CC4, which is the surface models with topology. For the attributes, we adopted Part 41, which specifies the fundamentals of product description and support.

4.1.4 Part 109

For the assembly, we adopted Part 109 (ISO 10303-109. 2004.), which is about the kinematic and geometric constraints for assembly models. Part 109 specifies the schemas for representing assembly feature relationship and for representing assembly constraints.
4.2 Assembly Process

Figure 13 shows the examples of the assembly process. For instance, a viaduct can be created easily by the assembly modeling, using data of the viaduct pier and the viaduct superstructure. Addition of the time attribute to 3D model, which is actually one of the features of the developed engine, enables the construction simulation to be performed.

![Viaduct assembly process](image)

Figure 13: Assembly Process

4.3 Roads on Terrains with Point Cloud Data

Other functions of the engine include a function of reading the point cloud data. As Figure 14 shows, this function makes it possible to read the point cloud data to generate a terrain, to create a road there, and to connect it with the viaduct created previously.

![Roads on terrain with point cloud data](image)

Figure 14: Creating Roads on Terrains with Point Cloud Data

5 FUTURE EXPANSION

5.1 Future Vision

We mention how to expand the project in the future.

5.1.1 Kensetsu System Co. Ltd.

One of the participating companies of the project, Kensetsu System Company draws its future vision like Figure 15. This company is planning to introduce the 3D-CAD engine into Dekispart and SITECH 3D, both of which are the software products of Kensetsu System.
5.1.2 Forum 8 Co. Ltd.

Also one of the participating companies of the project as shown in Figure 16, Forum 8 Company is planning to realize efficient construction of 3D spaces by introducing 3D-CAD engine into different applications such as UC-win/Road, Engineer's Studio, and CAD for 3D bar arrangement.

5.2 Life Cycle Business using 3D information

The spread of 3D information by using the developed 3D-CAD engine is expected to contribute to the exchange, linking, sharing, and reuse of 3D information as shown in Figure 17. For example, using GIS data for Road database, engineers can make 3D evaluation with digital topographic maps. Using this, they can work out a design, and use the design data to perform structural modification or estimation. Then they can create execution data through the work progress control system and information-oriented construction, which they can add to GIS data. Finally they can deliver the GIS data to the road database. It is possible to realize such a cycle.

6 CONCLUSIONS

The project, which we have been working on for 5 years, started for the purpose of spreading 3D-CAD rapidly and at low cost throughout the construction industry in our country Japan. To achieve this purpose, we designed and developed a 3D-CAD engine. We also developed simple 3D-CAD software that implements an engine, for the purpose of verifying the 3D-CAD engine and its free provision to educational institutions. We expect that the 3D-CAD engine which we developed will be implemented in domain CAD software.
Under the policy of spreading the 3D-CAD engine, we are promoting its implementation in the domain CAD software of the participating companies in the project, as well as providing it free of charge to high schools, technical colleges, and universities all over the country. We are also considering its use in CIM, that is, construction information modeling. We believe that the life cycle realized by 3D models can contribute to productivity improvement for overall construction projects.

Figure 17: Exchange, Linking, Sharing, and Reuse of 3D Information

Acknowledgements

The name of the project is named after the athletic association of Kansai University, which is called “Kaisers”. Since this is a big project of university-industry collaboration, we named it Kaiser Project.

References

AN INTEGRATED MODEL FOR AUDITING CONSTRUCTION PROJECTS – A CASE STUDY OF OIL AND GAS PROJECTS

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Abstract: Nowadays, organizations implement projects for many purposes. Using the project as a strategic success factor for project-oriented companies is increasing continuously. However, most of the time, the results are not the same as they had been planned. Some projects fail to achieve their objectives; others are canceled, where some others have to re-plan their strategy. Project-oriented companies know that maintaining an ideal and logical balance between the project's time, cost, and quality constraints can vastly guaranty project success. One of the most applicable tools to assess and monitor project performance and thus find the associated issues is Project Audit, which is a comprehensive and organized assessment of effectiveness and efficiency of project performance, management, and compliance. This paper presents an integrated model for project audit that incorporates a detailed design module, which shows the model's structure, questionnaire module, and a scoring module. The model is developed as an integrated project audit application where the user is easily able to select, plan, implement, and report a project audit. The model's output consists of two parts: 1) a comprehensive report that shows project situation in five main project processes and nine project functions (i.e., planning cost or closing procurement); 2) useful analytical reports and graphs of the project performance, which compares project's planned and actual time and cost, calculates variances, and forecast the final cost and time based on the current performance. The model is validated by using an actual Oil and Gas project to test its workability and capabilities.

1 INTRODUCTION

Projects are considered as critical strategic success factors for organizations, especially for those who are project oriented. The importance of the project success is continuously increasing. Results of projects are used for many purposes but these projects do not always achieve the planned results. Some projects are not successfully implemented because they are either over budget, behind schedule, or fail to achieve the required quality, whereas others have to be cancelled, and in many cases organizations should re-plan the project strategy. It is rare to find a successful project in which the results are better than what was planned. Usually, spending higher cost and using more resources in a project can be due to lack of efficiency while planning the project deliverable. Poor Project's quality is a result of failing in clearly defining quality requirements and specifications. Project-oriented organizations know that maintaining an ideal logical balance among project constraints such as time, cost, and quality can vastly improve the chances of project success. In construction projects, because of the huge amounts of work, time, and money that are spent, it is very important to know the status of the project and to determine if it meets the predetermined objectives and to ensure its successful implementation. To save time, reduce costs, and improve quality of projects, it is necessary to improve the performance and efficiency during their whole
life cycle. This is attained only when organizations switch from applying traditional project management methods to modern, scientific, and up-to-date project management methodologies. There are different tools and techniques (i.e., project control methods, risk management methodologies, cost management applications, value engineering techniques) that can be applied during the implementation of construction projects. Heavy infrastructure projects (i.e., oil and gas, roads, and dams) require huge amount of investments around the world, organizations should not only use valid standards, rules, and regulations for this type of projects but they must also always assess the outcome of them. Project Audit is one of the most useful tools by which project-oriented organizations can assess their project success, find project’s issues, and monitor its performance. Project audit will result in a positive outcome, whether a project manager and his/her team passes or fails the project. An audit is defined as a systematic, integrated, and independent assessment to determine the level of achieving project requirements and progress. A project audit is an assessment of the effectiveness and efficiency of project performance, management, and compliance. A construction project audit is a detailed evaluation of all its functions in order to discover the project’s concerns, issues, and challenges so that sets of corrective actions can be provided. A project audit can be formal or informal. Also, it may be quick or comprehensive. It can be done anytime during the project life cycle including the conception stage, the implementation stage, or the closing stage. Finding the reasons for uncomfortable symptoms is the primary purpose of a project audit.

The main achievement of a project audit is to identify the lessons learned that would result in a positive impact on the performance of new projects by avoiding repeating the same errors and mistakes. A project audit may be done by asking the project team simple, rather than complicated and technical questions related to: a) project performance, b) project management approach, c) project current status, d) project plan status, e) project requirements, and f) project team and organization. Therefore, in project-oriented organizations, the project audit is highly beneficial for the following reasons: 1) Providing an idea about the current status of the project to know whether it is on-track or off-track; 2) Defining the project success factors (i.e., being on-time, being on-budget, having acceptable quality, satisfying stakeholder expectations); 3) Defining the necessary corrective action plan that is needed to address current problems and enhance the likelihood of success in future projects; 4) Providing a list of guidance for risk management based on all the issues and concerns that are mentioned in the project audit report under project risks; 5) Identifying the lessons learned from previous projects that can be applied by the organization in future projects; 6) Providing list of recommendations to prevent potential problems and challenges; and 7) Showing the project’s performance trend, especially for projects that their construction span over a long period of time, such as oil and gas projects that take more than 5 years, by doing periodic project audits. The main objective of this paper is to describe the methodology used to develop an integrated project audit model, which interrelates several modules, that can be used as a tool during the project implementation. This developed model is based on actual problems (i.e., delay, over budget, quality/safety, resources, and project management) that organizations and project team face during the project life cycle. The said model can be applied for any construction project regardless of its location (National/International) and report the status of project processes, functions, and performance. The methodology is implemented through number of steps, starting by a condense literature review, passing through analysis and development and ending by validation.

2 LITERATURE REVIEW

The focus of the literature review is on reviewing and evaluating the models that are commonly used while doing project audit and accordingly identify the advantages and disadvantages of each of these models. A project is "a temporary endeavor undertaken to create a unique product, service, or result" (PMBOK, 2012). According to Spinner (1997), a project has several distinguishing characteristics such as: 1) well-defined objectives; 2) specified product or result; 3) no repetitive endeavour; and 4) limited sources to consume. Construction projects not only meet the definition of projects but also contain a high degree of risk related to time and cost. However, according to the Michigan Office of Project Management, there are three specific characteristics for every project: temporary, unique, and progressive elaboration. They are temporary because every project has a finish time. They are unique because the product or service of every project is different from those of others although they may have a similar platform. Progressive elaboration integrates the two prior characteristics and means that the
project will be developed step by step and in detail (Woodward, 1997). Although an oil and gas refinery project may have similar engineering specifications and may need the same types of equipment during its construction, it has specific uncertainties about its time, cost, and quality constraints.

Generally, there are five main groups of processes for every project that are also used for construction projects: 1) Initiating; 2) Planning; 3) Executing; 4) Monitoring and Controlling; and 5) Closing Process Groups. According to Lester (2014), most construction projects pass through different life cycle based on their type, complexity, and size. However, any construction project passes through four main periods during its life cycle: 1) beginning the project, 2) arranging and setting up, 3) carrying out the project work, and 4) finishing the project (Chou, 2012). On the other hand, project functions include set of tasks, concepts, and definitions. These functions are mostly defined based on number of factors: 1) project type (i.e. construction, IT, research and development); 2) size (i.e. small, medium, or large), and 3) complexity (i.e. simple or complex). However, project functions are relatively similar in every project. While, Woodward (1997) classified cost, time, scope, and quality as project functions, Spinner (1997) added to these functions the integration, risk, procurement, human resources, and communication. Construction Extension of Project Management Body of Knowledge (2007) added safety, environment, finance, and claim to the nine functions defined by Spinner (1997). Figure 1 shows the changes in the project functions during the last two decades.

![Figure 1: Comparing project management functions over two decades](image)

According to the National Institute for Further Education of Netherlands (2010), the project audit is described as: “the process of verification of the extent to which the project realisation complied with the rules and principles of project management for that specific project”. The project audit has many goals, one of which is to inspect and evaluate the current situation of the project. It also helps the project team to find whether the project is complying with all the defined criteria or not. Moreover, the project audit identifies the points of strength and weakness in the project and provides an idea on whether that project is moving toward success or not. Generally, project issues, challenges, and concerns, which usually happen during the construction phase of a project, are not covered by the conducted project audit. It is worthwhile for the project team and other stakeholders to spend time considering what has gone well in the project and which parts need to be improved so that the project will be completed successfully. According to Ruskin and Estes (1984) project failure is mostly due to problems arising during the planning and executing processes that are not corrected because of many reasons such as either the project team does not notice these problems or there is no time to fix them at that stage. McDonald (2002) believes that the main reasons for a project audit are: 1) to force the project team to develop a reliable project plan that will likely result in a successful project; 2) to increase the possibility of identifying the risks associated with the project; 3) to determine the corrective actions that should be taken to have the project within
budget, time, and quality. Project performance can be assessed by measuring critical success factors (CSFs). Although lots of researchers have tried to identify the CSFs for projects but these have not been clearly defined specifically in the project management body of knowledge. Mian et al., (2004) think that CSFs may be different from one project to another, however, there are some common CSFs (i.e. cost, time, quality) while other researchers focus on new types such as productivity, contract disputes, and procurement strategy where Young and Poon (2013) identify success factors specifically related to the construction process. Bates and Coles (2012) list the steps that should be taken to implement a project audit as follow: 1) Development of project success factors; 2) Development of a questionnaire; 3) In-depth investigation; 4) Final report. To start, collaboration between all the project’s stakeholders is needed in order to define the appropriate success criteria because these are extracted from stakeholders’ expectations. Next, a questionnaire is developed by the auditors and may either be sent directly to the project team or may be answered through personnel interviews. Then, one or more project site-visits is/are planned to collect detail information about the project beside reviewing all project historical data and documents such as the Project Plan, Milestone Report, Team Structure, Business Requirements, Meeting Minutes, Issue Logs, Change Logs. Finally, all collected information from the previous steps are compiled, analysed, and reported. To design an integrated and comprehensive model, the following eleven (11) different project audit and improvement models have been reviewed and analysed: 1) Portfolio, Programme & Project Management Maturity Model (P3M3); 2) Prince2 Maturity Model (P2MM); 3) Capability Maturity Model Integrated (CMMI); 4) Kerzner Project Management Maturity Model (KPM3); 5) Project Management Process Improvement (PMPI); 6) ISO 10006:2003 Standard for Project Management (ISO 10006); 7) Roland Gareis Model (Ronald); 8) German Association Model for Project Management (GPM); 9) Lynn Craford Maturity Model (Lynn Craford); 10) Project Excellence Model (PEM); and 11) Organizational Project Maturity Model (OPM3). The results of this review and analysis help in identifying the advantages and disadvantages of these models.

Tables 1 and 2 show the advantages and disadvantages of the reviewed models respectively, where the “+” annotation means that the model includes an advantage or disadvantage and the empty cell means that the model includes none.

Table 1: Advantages of the reviewed models

<table>
<thead>
<tr>
<th>Advantages</th>
<th>P3M3</th>
<th>P2MM</th>
<th>CMMI</th>
<th>KPM3</th>
<th>PMPI</th>
<th>ISO</th>
<th>Roland</th>
<th>GPM</th>
<th>PHT</th>
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<th>OPM3</th>
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Table 2: Disadvantages of the reviewed models

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>P3M3</th>
<th>P2MM</th>
<th>CMMI</th>
<th>KPM3</th>
<th>PMPI</th>
<th>ISO</th>
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<th>GPM</th>
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To rank the models, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which is a multi-criteria decision analysis method, is used. TOPSIS has many features such as: 1) an understandable logic; 2) considers both the best and worst alternatives simultaneously; 3) a straightforward calculation process; and 4) considers several criteria to rank alternatives. Also, in this method, all the alternatives are compared based on defined criteria. The result of TOPSIS shows that the Project Excellence Model (PEM) has the highest rank and therefore its advantages can be included in the proposed model while the Portfolio, Programme & Project Management Maturity Model (P3M3) has the lowest score and thus its disadvantages should be excluded from the proposed model. Figure 2 shows the results of ranking the models by TOPSIS.

### Advantages should be included in the proposed model

<table>
<thead>
<tr>
<th>Rank</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>9th</th>
<th>10th</th>
<th>11th</th>
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</thead>
<tbody>
<tr>
<td>Model</td>
<td>PEM</td>
<td>OPM3</td>
<td>Lynn Crawford</td>
<td>KPM3</td>
<td>GPM</td>
<td>Roland</td>
<td>PMPI</td>
<td>P2MM</td>
<td>ISO 10006</td>
<td>CMMI</td>
<td>P3M3</td>
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<tr>
<td>Score</td>
<td>0.88</td>
<td>0.60</td>
<td>0.75</td>
<td>0.74</td>
<td>0.56</td>
<td>0.46</td>
<td>0.40</td>
<td>0.35</td>
<td>0.31</td>
<td>0.13</td>
<td>0.12</td>
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</table>

### Disadvantages should be excluded from the proposed model

- ISO
- Roland
- GPM
- PEM
- OPM3

Figure 2: Final score of the models

## 3 DEVELOPMENT OF THE MODEL

The results of TOPSIS are considered in developing an integrated and comprehensive model for project audit. Figure 3 illustrates the model’s architecture. Generally, the project audit can be conducted by considering the following three critical aspects: 1) project processes; 2) project functions; and 3) project performance. Series of questions and their associated documents are assigned to both the processes and functions needed to audit the project and measure its status. The project performance is computed by applying the Earned Value Method (EVM).

The project processes include four main parts: 1) project planning; 2) project executing; 3) project monitoring and controlling; and 4) project closing. Planning includes all the processes required to establish the project plan, to cover the project scope and to achieve the project objectives. Executing consists of all the processes required to complete the project work as planned and to satisfy the project specifications. Monitoring and controlling includes all the processes responsible to track, review, and
regulate the project work and progress. Closing consists of all the processes related to finalizing the project activities and closing it.

Project functions include nine parts: 1) Project Cost; 2) Project Time; 3) Project Quality/Safety; 4) Project Scope; 5) Project Human Resources; 6) Project Communication; 7) Project Risk; 8) Project Procurement; and 9) Project Integration. Cost is related to estimating, budgeting, managing, and controlling project costs so that the project can be completed within the determined budget. Time includes project activities duration, scheduling the project and completing it on time. Quality/Safety consists of activities, which need to be performed in order to determine policies, objectives, and responsibilities to quality of the project specifications with defined safety. Scope is required for ensuring that the project works will be completed and any other type of works that are out of the project scope will be reported. Human Resource part is necessary to organize, manage, and lead the project team. Communication consists of collecting project information, generating appropriate reports, and distributing reports. Risk is related to identification, analysis, response, and control of project uncertainties. Procurement includes activities, which are needed to purchase or acquire products, services, or results needed from outside the project team. Integration combines and integrates project management activities. As for the project performance, it is computed through the application of the Earned Value Method (EVM). This part provides useful analysis related to the project indices. EVM relies on three key data points; 1) Budgeted Cost of Work Performed (BCWP); 2) Budgeted Cost of Work Scheduled (BCWS); 3) Actual Cost of Work Performed (ACWP). First, two important indices, Schedule Performance Index (SPI) and Cost Performance Index (CPI), are computed by the model. SPI shows how efficiently the project used its time. CPI indicates how efficiently the project used its budget to date. SPI is computed by dividing the BCWP by the BCWS. SPI is a number that can be either lower than 1 (under schedule) or bigger than 1 (ahead of schedule). CPI is computed by dividing the BCWP by the ACWP. CPI is a number that can be either less than 1 (over budget) or greater than 1 (under budget). Two other important values that EVM calculates are: 1) Schedule Variance (SV) and 2) Cost Variance (CV). SV indicates that a project is ahead of or behind schedule and it is calculated by subtracting the BCWP from BCWS. A positive value is a favorable condition and a negative value is an unfavorable condition. CV indicates that a project is over or under budget and it is calculated by subtracting the BCWP from ACWP. A positive value is a favorable condition and a negative value is an unfavorable condition. There are some other useful values that can be computed with the earned value method; 1) Time Estimate at Completion (TEAC); 2) Estimate to Completion (ETC); 3) Estimate at Completion (EAC); and 4) Variance at Completion (VAC). While the EVM results are numerical numbers that their interpretation is clearly explained there is a need for a scoring system to compute the quantitative values of the project processes and functions. The proposed model uses equation 1 and equation 2 to compute the scores for both the process and function. The total obtained score divided by max score that can be achieved for the process or function. Table 3 provides a guideline of the scoring used by the model.

\[
\%\text{process} = \frac{\sum \text{scores related to the process}}{\text{Max score that can be achieved for the process}} \times 100
\]
Six modules are considered for developing the model: 1) table relationship module; 2) project information module; 3) audit questions module; 4) plan a project audit module; 5) record audit results module; and 6) reports module, as shown in Figure 4.

### Table 3: Score interpretation guideline

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>%0 and %20</td>
<td>Very bad</td>
</tr>
<tr>
<td>%20 and %40</td>
<td>Bad</td>
</tr>
<tr>
<td>%40 and %60</td>
<td>Medium</td>
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<tr>
<td>%60 and %80</td>
<td>Good</td>
</tr>
<tr>
<td>%80 and %100</td>
<td>Very good</td>
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</tbody>
</table>

The development has been implemented using Visual Basic for application Programming language for Microsoft Access 2010, and Microsoft Excel 2010. Table relationship module shows the tables, which are needed to store the project data. These data consist of the project main information (i.e. name, code, start and finish date) and project progress data (i.e. time and cost). Also, some tables are needed to store the questions and the results of the calculations. Project information module store the information needs to be provided to implement the audit effectively. The information is divided into seven groups: 1) construction process; 2) construction function; 3) construction stage; 4) contract type; 5) scoring levels; 6) project plan; and 7) project information. Audit questions module consists of several questions to audit project processes and functions. Each question is related to a project process and a project function. Furthermore, to satisfy each question, two or more documents need to be prepared. Plan a project audit module is needed to plan and schedule audit. In other words, some information (i.e. audit date, project name, project stage, and auditors) need to be selected from the form that has been designed for this purpose. Two approaches are considered to audit a project: 1) comprehensive; 2) quick. Comprehensive audit includes all processes and functions to audit a project. Quick audit is used when project managers need to prepare a report for a specific function or process and they do not have enough time or resources to implement a comprehensive audit. Record audit results module is divided into two categories: 1) question results, which include the results of all the questions related to project processes and functions; 2) performance results, which consists of the project progress information that should be entered in the model (i.e. actual progress and actual cost). Reports module is able to generate several types of reports and to generate a variety of new user-defined reports. In other words, some reports are generated from the main information (i.e. project information, processes, and functions) and others are the result of the analysis and computations that the model implement. Two groups of reports have been designed in this model: 1) main reports, which generate from the main information menu (i.e. project information, processes, functions); 2) analytical reports that present results of the project audit.
4 TESTING AND VALIDATION

The capability and workability of the developed model, showed in figure 3, is tested by auditing a real construction project. Information from a real Oil and Gas project is used to implement an audit for that project. It is commonly known that an Oil and Gas project is classified as a heavy infrastructure project because it consists of different construction projects including un-industrial and industrial buildings, pipelines, roads, warehouses, refinery, tanks, vessels and etc. The project has a starting date of October 2011 and the planned finishing date is October 2015. Using the developed model to audit this project shows that owners, project manager, project team are provided with a very useful tool that helps them to assess all aspects of a project (process, function, progress performance) during the project lifecycle. The process is implemented in four steps: 1) Entering related information; 2) Planning (schedule) a project audit; 3) Recording project audit results; 4) Analytical reports. First, the project information must be entered into the model. As shown in figure 5, the user should click on the “Related Information” button to open another tab that provides the main menu from which the user can select and input related information.

![Figure 5: Related information menu components](image)

The project audit should be planned and scheduled as mentioned earlier. Because the audit of the case project covers processes, functions, and performance, comprehensive audit is selected from the menu. There are two options in the “Plan Audit” form, comprehensive audit and quick audit. There are several fields that should be entered. Audit ID is a six character field in which the first four characters are for the year and the two other characters present the number of the audit in that year. As shown in figure 6, for that actual project the ID is 201402. The date that the audit will be implemented and the project name should also be entered in this case it is 01/06/2014. To record project audit results, there are two types of data that should be entered in the model to be analyzed: 1) entering the answer of the audit questions; 2) updating the project progress. Usually, there is a project management office in project oriented organizations that supports project managers during the project lifecycle and it is responsible for performing project audit. Therefore, the project audit results are entered to the developed model by this office. Once all the audit data is entered, the model will analyse all these data and generate two different types of reports as mentioned earlier, main reports and analytical reports. The main report provides all reports of related information menu. The analytical reports of the model have been divided in two categories; audit questions and progress performance. The final score of the project audit is 50.63 or
medium. Project performance reports also can be generated by the model. These reports represent all the analytical indices of the project based on the project plan that was input into the model during the first step. Also, the model can generate a comprehensive report of the project performance indices that contains useful data and an interpretation of these results.

![Figure 6: Project audit results - processes and functions score](image)

Two related data should be entered in the model: 1) audit ID; and 2) audit date to generate the report. For the real case project Audit ID is 201402 and 23/05/2014 is entered. Figure 7 shows project performance indices and factors.

![Figure 7: Project performance indices and factors](image)

For example, in May 2014, the project schedule variance (SV) is a negative number and the Schedule Performance Index (SPI) is a number less than 1. These indices support the finding that the project is behind schedule. Also, indices related to cost performance, project cost variance (CV) and Cost Performance Index (CPI) are negative and less than 1 respectively. This means that the project is over budget. The value of ETC (t), which represents the estimated time to completion, is 55 months. Comparing 55 months to the project planned duration, of 48 months; it means that with the current performance the project will take seven months more than had been planned. Cost forecast value also show that the project needs $105,831,190 from the project audit date, 2013/06/01, to be completed. This
means the project final cost will be $299,113,636 instead of the $214,000,000 as planned, which means an extra cost of $85,113,636 from what is estimated. The system provides a guideline for interpretation of earned value indices if the user clicks on the blue question mark sign on the top-right of the form.

5 CONCLUSION

In this paper, the steps followed in developing an integrated model for construction project audit during the project life cycle were described. The model was developed based on the advantages and excluding the disadvantages of other project audit and improvement models. The developed model has several advantages. It assesses all aspects of a project (process, function, progress performance) and reports critical project performance factors at the same time. Also, users have the ability to customise the audit to do a comprehensive audit or quick audit, which is applicable to all project stages and compatible with the project life cycle. With this model all project data can be stored and pulled up at anytime even after the project implementation. Reviewing the project audit results during the project implementation helps the project manager to find project problems, issues, and concerns and to try to address them on time. Users can plan, schedule, and implement a project audit with this model and analyse the results within a minimal time frame. It provides valuable analytical information of the project, which presents the current status of the project.

References

MULTI-AGENT SYSTEM FOR IMPROVED SAFETY AND PRODUCTIVITY OF EARTHWORK EQUIPMENT USING REAL-TIME LOCATION SYSTEMS

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Abstract: The growing complexity and scope of construction projects is making productivity and safety of earthwork of a great concern for project and site managers. In earthwork operations, where heavy machines are being used, various safety and risk issues put the timely completion of a project at stake. Additionally, the construction working environment is heavily susceptible to unforeseen changes and circumstances that could impact the project, both cost and schedule wise. As a response to the looming safety threats or unforeseen changes of working conditions, re-planning is almost always required. In order for re-planning to yield the optimum results, real-time information gathering and processing is a must. GPS and other Real-time Location Systems (RTLSs) have been used for the purpose of real-time data gathering and decision-making in recent years. Similarly, Location-based Guidance Systems (LGSs), e.g., Automated Machine Control/Guidance (AMC/G), are introduced and have been employed mainly for the purpose of high-precision earthwork operations. However, the current application of LGS is limited to the machine-level productivity optimization, which is not sufficient to address the project-level monitoring and decision-making needs. In the context of complex earthwork operations where several teams are concurrently working towards different ends, the globally optimized operations should coordinate the actions of multiple teams of equipment to eliminate the productivity lost by organizational, logistics and operational management. Therefore, the objective of this paper is to develop a Multi-agent System (MAS) structure to orchestrate the machine-level information (i.e. states and poses) induced based on RTLSs to a coherent project-level system committed to support operations towards the enhanced productivity and safety of the overall project. In the proposed MAS, several layers of agents are processing and managing the huge amount of collected sensory data into useful information that can be used in decision making at different operational levels. The proposed MAS has a semi-distributed structure to strike a balance between the optimality of the outputs and the required computational efforts. A case study is developed to demonstrate the applicability of the proposed MAS. Also, a two-layer safety mechanism is proposed based on which near real-time collision-free path planning and real-time collision avoidance can be performed. In the light of the results of the case study, it is found that the the proposed MAS structure is able to effectively address the team-level coordination of different pieces of equipment and improve the safety of construction site using the proposed two-layer safety mechanism.

1 INTRODUCTION

The construction industry is concerned with Improving the productivity and safety of construction projects (Beavers et al. 2006). In earthwork operations, where heavy machines are being used, various safety and
risk issues put the timely completion of a project at stake. Additionally, the construction working environment is heavily susceptible to unforeseen changes and circumstances that could impact the project, both cost and schedule wise. As a response to the looming safety threats or unforeseen changes of working conditions, re-planning is almost always required. In order for re-planning to yield the optimum results, real-time information gathering and processing is a must. The Global Positioning System (GPS) and other Real-time Location Systems (RTLSs) have been used for the purpose of real-time data gathering and decision-making in recent years (Perkinson et al. 2010). Similarly, Location-based Guidance Systems (LGSs), e.g., Automated Machine Control/Guidance (AMC/G), are introduced and have been employed mainly for the purpose of high-precision earthwork operations. LGS integrates geopositioning technologies with 3D design models and Digital Terrain Models (DTMs) to either (1) support the machine operator through the provision of continuous guidance on a digital screen mounted in the cabin of the machine, or (2) control the position and movements of the equipment (or part of it). While GPS and total stations are the main tracking technologies used in AMC/G, other types of emerging Real-time Location Systems (RTLS), e.g., Ultra-Wideband (UWB), can be integrated with similar monitoring mechanisms to provide monitoring and guidance capabilities for earthwork equipment.

The current application of LGS is limited to the machine-level productivity optimization in large projects, which is not sufficient to address the project-level monitoring and decision-making needs. There are several challenges that have to be overcome in order to maximize the benefits of using this technology in the 3D surveying-design-contract-construction-inspection workflow (Dunston and Monty 2009, Torres and Ruiz 2011, Vonderohe 2009). The problem of providing near real-time guidance or control support for the operators of earthwork equipment based on the consideration of the entire fleet can become complex, in line with the fleet size and equipment interactions. For such complex problems, the conventional approach of central problem solving becomes far-fetched, attributable to the fact it is difficult or impractical to globally grasp and analyze the multi-dimensionality and dynamisms of such problems. Distributed intelligent systems are designed to address such complex problems in terms of several collaborating intelligent agents, who try to solve the overall problem by synthesizing limited views of individual agents (Ferber 1999). Such systems are referred to as Multi-Agent Systems (MASs), which consist of several intelligent agents capable of interaction.

Furthermore, despite the growing availability of LGS, its application for safety is limited to real-time proximity-based object detection and warnings. In the existing systems, the increasingly affordable advanced sensing and location systems are used to mitigate the collision risks by warning the operators against the potential dangerous proximities in real time (Burns 2002, Carbonari et al. 2011, Zhang and Hammad 2012, Guenther and Salow 2012, Wu et al. 2013, Zolynski et al. 2014, Vahdatikhaki and Hammad 2015a). Cheng (2013) proposed to use the pose and speed data for the generation of the workspaces. This method does not consider the equipment state as a means to economize the use of space around the equipment and does not cover the equipment with rotary movements, e.g., excavators. Therefore, there is a need for a solution that is able to reliably predict the operation of the equipment for a long-enough time window to enable different pieces of equipment to adjust their planned paths to avoid collisions in near-real time.

Therefore, the objective of this paper is to develop a MAS structure to orchestrate the machine-level information (i.e. states and poses) induced based on RTLSs to a coherent project-level system committed to support operations towards the enhanced productivity and safety of the overall project. The paper also aims to develop a two-layer safety mechanism: the first layer of which enables the equipment to plan a collision-free path considering the predicted movement of all other equipment, and the second layer is acting as a last line of defense in view of possible discrepancies between the predicted paths and actual paths. The structure of the paper is as follows. First, the proposed method is introduced, followed by the explanation of the implementation and a case study. Finally, the conclusions and future work are presented.

### 2 Proposed Method

Figure 1 shows an overview of the scope for the proposed MAS framework. The main assumptions are that every piece of equipment on the construction site has a sufficient number of RTLS Data Collectors.
(DCs) attached at specific locations to track its movement, and that every equipment operator is supported by an agent that can communicate with other agents in a MAS framework. The proposed MAS supports the project at three different levels: (1) Planning, (2) execution and monitoring, and (3) re-planning. At the planning level, the MAS is able to streamline the operation and task assignments to different equipment as well as to perform equipment path planning (Zhang and Hammad 2012), which is operationalized in terms of strategic and tactical planning. At the execution and monitoring level, MAS is committed to (i) provide visual guidance to equipment operators, (ii) collect and process RTLS data, (iii) apply appropriate error correction techniques to identify the pose of the equipment (Vahdatikhaki et al. 2015), (iv) identify the state of the equipment (Vahdatikhaki and Hammad 2014), (v) apply the Near Real-time Simulation (NRTS) (Vahdatikhaki and Hammad 2014), (vi) generate equipment workspaces, i.e., Dynamic Equipment Workspaces (DEWs) (Vahdatikhaki and Hammad 2015a) and Look-Ahead Equipment Workspaces (LAEWs) (Vahdatikhaki and Hammad 2015b), and (vii) report the necessary information to pertinent agents. The aforementioned two types of workspaces differ in that while DEWs are generated based on the equipment pose and speed in real time to form a safety buffer around the equipment that can help prevent collisions, LAEWs are built based on the predicted future motion of equipment and operator visibility in near-real time to help find a collision-free path for the equipment, as explained in Section 2.2. Finally, at the re-planning level, the proposed MAS framework addresses the need for task-reassignment, path re-planning, and design change requests, which may become necessary in view of the potential unforeseen safety risks identified at the monitoring level. As can be seen in Figure 1, while the proposed MAS framework offers advantages at both the operational and managerial levels, only the operational aspects of framework are addressed in this paper.

![Figure 1: Overview of the Scope for the Proposed MAS Framework](image)

The authors have previously presented the overview of the proposed MAS (Hammad et al., 2013). This paper extends this research by providing a more in-depth discussion of the agents’ functionality in the MAS and how the LAEWs are being used by different agents to avoid collisions.

A multi-layer agent architecture is proposed in which agents supporting the operators of single machines constitute the lowermost layer of the agent hierarchy. These agents process and manage the huge amount of sensory data, provided by an UWB system or other types of location systems, into useful information that can be used in decision making at different operational and managerial levels. Figure 2
shows the proposed MAS architecture where several teams working in the proximity of each other are supported by different types of agents, with different tasks and project views. Three functional agent types can be distinguished according to the distribution of the responsibilities, namely, operator, coordinator and information agents. In a nutshell, Operator Agents (OAs) support the equipment operators and have the essential knowledge about their current task, state and pose. In a construction site, often a group of equipment is teamed up to serve one particular operation, for instance several trucks and an excavator work together to move the earth. The team coordinators are supported by Team Coordinator Agents (TCAs), whose main objective is to track the progress of operations based on the data gathered from their subordinate OAs and to ensure safe and smooth delivery of the operations’ objectives. Depending on the level of coordination each TCA offers, several layers of TCAs and a General Coordinator Agent (GCA) can be defined. Further, these different types of agents are fed by information agents who provide the required site, design or project-related data to the agents, and frequently get updated based on the changes happening in the site as the construction progresses.

![Multi-Agent System Architecture](image)

Figure 2: Multi-Agent System Architecture (Adapted from Hammad et al. 2013)

Information Agents are in charge of handling the information required for MAS and encompasses the Site State Agent (SSA), Project Document Agent, (PDA), and Design Document Agent (DDA). The SSA provides and updates the Digital Terrain Model (DTM), which is often obtained from Light Detection and Ranging (LIDAR) scans by surveyors. Additionally, the SSA uses a variety of local sensors coupled with the information from weather agencies to constitute a database of weather as expected at the planning time, at the current time and as forecasted. The main functionalities of the SSA are to provide information to TCAs and OAs, when needed, and to update their data whenever a change befalls. The DDA, on the other hand, encapsulates the designer-provided 3D models and updates them should any changes be made in the course of the project. The 3D design model is used by all the coordinator and operator agents as a reference for decision making and task execution. Finally, the PDA hosts all the basic project documents based on which an earthwork project is typically managed, including safety regulations, available resources, project schedule, construction methods, and available sub-contractors.

2.1 Agents Responsibilities and Functionalities

2.1.1 Operator Agents

The OA requires information about its surroundings, task and environment. These combined types of information are referred to as external information because they are provided by external sources. Surroundings information contains the poses, states and DEWs of other pieces of equipment. This information can be directly used by the OA to identify safety threats and take immediate actions, if required. Task information allows the OA to perform its (semi-)autonomous operations and contains safety warnings, LAEWs, a strategic plan, and NRTS-generated schedule provided by the TCA and 3D design model made available by the DDA. High-level flowchart of the functionalities of an OA is shown in Figure 3(a). Given the unequal priorities of various functionalities of the OA, and in order to embed these priorities in the MAS structure, a modified subsumption architecture is chosen for agents. Subsumption
architecture is based on breaking the activities of an agent in vertical modules where every module has limited responsibilities and the results of the higher modules always supersede those of the lower modules, if there is a conflict between various modules (Ferber 1999). In a nutshell, OAs constantly monitor the operations and perform the routine calculations for the equipment condition monitoring, pose and state-identifications, cycle time, generation of tactical plans, generation of risk maps, detecting underground utilities, and generating DEWs.

Figure 3: High-Level Flowchart of (a) the OA Functionalities, and (b) the TCA Functionalities

2.1.2 Coordination Agents

Coordination encompasses agents representing team coordinators who are responsible for making critical decisions, e.g., new work schedules or command for the suspension of the operation, using data from all other agents, and further communicating their decisions with the appropriate OAs for the execution. Essentially, this component consists of one GCA and several TCAs. However, depending on the characteristics of the project, the phase of the project and simultaneous operations, several layers of teams and sub-teams can be formed. Each team is coordinated and supported by a TCA.

The role of a TCA is to assign tasks to the subordinate OAs or sub-TCAs and to collect information from them. Figure 3(b) shows the high-level flowchart of the TCA functionalities. The main functionality of a TCA is to assign and monitor the tasks of the OAs. At the top of the flowchart, the TCA determines whether a new operation is assigned or an operation is ongoing. In the first case, the operation is broken into OA-executable tasks and assigned to the relevant available OAs. Next, in view of the reports from subordinate OAs, the progress monitoring, NRTS, and LAEWs (if any risk is identified), either the tasks are rescheduled if the problem can be resolved locally, or the GCA (or higher level TCA) is informed for directions. Local resolvability means that the problem can be solved by the information present to a single TCA, without the need to engage into negotiations with other TCAs. The negotiation between agents in a decentralized MAS structure is outside the scope of the present paper.

The GCA is responsible for monitoring and controlling the operations to ensure the smooth execution of the project. The GCA also generates the operations' schedule and the resource distribution based on the available resources, project schedule, the chosen construction methods and available sub-contractors. The functionalities of the GCA are realized through the accumulation of information about the project and the progress of different operations. The project information is the combination of all essential documents/information based on which an earthwork project is executed. At a high-level abstraction, safety regulations, available resources, project schedule, construction methods, and available sub-
contractors, all of which are coming from the PDA, are the main ingredients of the project information. Safety regulations are used to derive basic safety rules that need to be observed throughout the project. Available resources and available sub-contractors are used for the resource configurations and distribution. The project schedule is used for the generation of operation schedules that can be assigned to different TCAs. The Construction methods provide the GCA with the initial information needed to retrieve the right operation procedures.

2.2 Safety Management in MAS

As stated in Section 2, the safety of earthwork operation in the proposed MAS structure is supported through a two-layer mechanism which includes near real time collision-free path (re-) planning using LAEWs and real-time collision avoidance using DEWs. These two layers are running independently in parallel with different update rates. Given the nature and functionality of DEWs, they are updated in real time with the same rate offered by the tracking technology \((dt)\). LAEWs, on the other hand, require intensive computations and communications between various agents, and thus they are updated with a rate less than DEWs. The LAEWs are generated over every \(\Delta t\) and whenever a deviation from the predicted path of various equipment is observed. While the details of the two types of workspace are presented in the previous work of the author (Vahdatikhaki and Hammad 2015a, Vahdatikhaki and Hammad 2015b), a brief explanation of each workspace is presented in the following sections.

2.2.1 Look-Ahead Equipment Workspace (LA EW)

The flowchart of the proposed method for the generation of the LAEW of one piece of equipment (equipment \(q\)) is shown in Figure 4(a). As shown in this figure, the input of this method comprises the sensory data, the equipment specifications and its accurate 3D model, the current pose and state data generated by the OA of the equipment \(q\) (OA\(_q\)), and future state data coming from the NRTS that is performed by the TCA. A rule-based system is used to identify the states of different equipment with a high accuracy by leveraging a set of equipment proximity and motion rules that determine the states of the equipment (Vahdatikhaki and Hammad 2014). Also, a robust optimization-based method that uses geometric and operational characteristics of the equipment is used to improve the quality of the pose estimation (Vahdatikhaki et al. 2015). Additionally, the updated 3D model of the site, and the project’s detailed plan (including the location of different scheduled tasks, their time frame, and the site layout) are available through the Information Agent. Finally, a set of heuristic rules that define the operation of a skilled operator is also required to be available to each OA. The generation of LAEW is based on the discretization of the entire site space into cells, and then calculating the risk associated with each cell given the future expected states of different pieces of equipment, which is performed by each OA. As shown in Figure 4(b), the pose data are used to identify the current state, which is then passed on to the TCA to perform the NRTS in order to generate the operational pattern of each OA. These data are then communicated with the OA\(_q\) who will first integrate the equipment pose with its 3D model and the updated 3D model of site to situate the equipment in the virtual environment. Then, the OA will use the project plan, and the rules that govern the operation of the machine by a skilled operator to generate the risk map of the equipment. Finally, the OAs transfer their individual risk maps to the TCAs who will first combine these risk maps and then use the tolerable risk level of each OA to generate the LAEW. It should be highlighted that LAEW\(_p\) for equipment \(p\) is generated based on the combination of the risk maps from all pieces of equipment surrounding equipment \(p\), excluding equipment \(p\) itself. LAEW\(_p\) can be used by the OA\(_p\) to perform path re-planning, if required. Similarly, the path-replanning performed by the OA\(_q\) at the end of the flowchart shown in Figure 4(a) is realized using LAEW\(_q\).

2.2.2 Dynamic Equipment Workspace (DEW)

DEWs aim to use the pose, state, and speed characteristics of the equipment to generate a space around the equipment that would allow the prevention of immediate collisions with other pieces of equipment or obstacles on site, considering the equipment stoppage time \((t_s)\). \(t_s\) can be used to determine how much of the space in the moving direction of equipment is unsafe after the operator becomes aware of a potential collision considering the operator reaction time and braking time. In addition to the DEWs of the equipment, semi-dynamic obstacles (such as trenches, temporary or permanent structures, etc.), also
need to be represented by their own corresponding safety zones to enable effective collision avoidance at
the global level.

![Diagram](image)

Figure 4: (a) Flowchart for the Generation of LAEW, and (b) Schematic Representation of LAEW
Generation Process

For the DEWs to be effectively used for the purpose of collision detection and avoidance, every OA needs
to be able to generate its own DEW and have near-real-time information about the DEWs of other OAs.
Figure 5(a) shows the flowchart for the generation of the proposed DEWs. With the 3D model of the
equipment and its pose and state information available, the method proceeds to determine the linear and
angular speeds of the equipment. For instance, an excavator can travel on its tracks with the linear speed
of \( \dot{v} \), move its bucket with the linear speed of \( \dot{v}_{bp} \), or swing with the angular speed of \( \dot{\omega}_{bp} \). Upon
the determination of the speed vectors, the DEW can be generated based on the type of the equipment and
the equipment state. For example, two distinct types of states can be identified for an excavator, namely
stationary states (swinging, loading, dumping, and waiting) and traversal states (relocating,
maneuvering). Figure 5(b) shows different DEWs of an excavator for different states. Next, to avoid
redundant computation, an OA can perform pairwise comparisons of DEWs only with the OAs that are in
its vicinity. To determine the equipment in vicinity, the multi-layer workspace concept (Chae 2008, Wang
and Razavi 2015) can be applied. In this method, the pairwise distances between every two pieces of
equipment are calculated and if the two pieces of equipment have a distance less than a threshold, then
the collision detection between their DEWs is performed. In order to further reduce the computation
efforts and avoid redundant calculations, the priorities of the different equipment can be used to delegate
the calculation to the OA of the equipment with the lower priority. If a collision is detected between
the two, the equipment with the lower priority will stop and send a warning to the OA of the other equipment.
If both pieces of equipment have the same priority, then the OAs of both should perform the collision
detection and if a collision is detected they should both stop.

3 IMPLEMENTATION AND CASE STUDY

In order to demonstrate the feasibility of the proposed MAS approach in improving safety using LAEWs
and DEWs, a prototype system is implemented using Unity3D game engine (2015) and two simulated
scenarios are examined. The scenarios used for the case study consider an excavation operation for a
specific day of the project where two excavators are scheduled to dig a ditch and load two trucks, which will haul the soil to the dumping area, dump it, and return to the excavators for the next load.

![Flowchart of the Generation of DEW, and Examples of Excavator DEWs in Different States](image)

Figure 5: (a) Flowchart of the Generation of DEW, and (b) Examples of Excavator DEWs in Different States (Adapted from Vahdatikhaki and Hammad 2015a)

In the first scenario, the feasibility of applying LAEWs for collision-free path planning is investigated. The scenario covers a portion of the earthmoving cycle where Excavator A, which is assumed to have a higher priority than Excavator B, is expected to swing to Truck A, and Excavator B is expected to swing away from Truck B, as shown in Figure 6(b). The algorithm for the operation logic of excavators is shown in Figure 6(a) (Hammad et al 2014). The articulate digging and dumping movements of the excavator parts at a Digging Station (DS) are planned initially using parametric scripting. If the results of the LAEW-based safety check revealed a potential collision, the path re-planning is done using Rapidly-exploring Random Tree (RRT) (La Valle 2006). Figure 6(b) shows the initially planned paths for Excavators A and B. Since Excavator A has a higher priority, its initial planned path is approved. However, while the initial path of Excavator B would require it to swing counter-clockwise to the truck, given that this path had a collision with the LAEW, a new clockwise path is generated using RRT, as shown in Figure 6(c).

In the second scenario, the effectiveness of DEWs is investigated in another simulated scenario. In this scenario, as shown in Figure 7(a), while Truck A is hauling the material to the dumping point, Truck B is returning from the dumping point to the DS. It is assumed that although their planned paths have been collision-free, Truck A fell behind its planned path, which could lead to a potential collision. In this case, as explained in Section 2.2, DEWs can be used as the last line of defense to avoid the collision by requiring one of the equipment to stop. The algorithm shown in Figure 5(a) is implemented in Unity for the real-time generation and collision detection of DEWs. As shown in Figure 7(b), upon the detection of collision between the two DEWs, Truck B, which has a lower priority, is stopped, and Truck A is allowed to continue its path to the dumping point, as shown in Figure 7(c).
Figure 6: (a) Algorithm Representing the Operation Logic of Excavator, (b) Current Poses and Initial Paths of Excavator, (c) LAEW of Excavator B and Final Path of Equipment B

Figure 7: (a) The Layout of the Second Scenario, (b) Collision Detection between DEWs, and (c) Collision Avoidance Decision made by OAs

4 CONCLUSIONS AND FUTURE WORK

In this paper, a MAS structure is introduced for improving the safety and productivity of automated guidance and control of earthwork equipment. In the proposed MAS structure, every piece of equipment is supported by an operator agent to oversee the task and provide guidance whenever needed. A multi-layer agent hierarchy assigns monitors and coordinates the task executions, and a set of three types of agents feed the system with the relevant information. The functionalities, jurisdictions and the input-output scheme of every type of agents were discussed. A two-layer safety mechanism was introduced, where the first layer enables the equipment to plan a collision-free path considering the predicted movement of all other equipment and the second layer acts as a last-line-of-defense in view of possible discrepancies between the predicted paths and actual paths.

In view of the results of the case study, it is shown that the MAS is capable of effectively handling the harmonization of various pieces of equipment on the site beyond what is available by the conventional
LGSs. The combination of LAEWs and DEWs are found to be an efficient approach to deal with collision-free path planning and real-time collision avoidance. The authors are planning to investigate the negotiation between different levels of agents as part of their future work.

References


SENSOR-BASED FACTORIAL EXPERIMENTAL STUDY ON LOW BACK DISORDER RISK FACTORS AMONG ROOFERS

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Abstract: Roofers have long suffered from low back disorders (LBDs), which is a primary non-fatal injury in construction. Until present, most of the research on roofing safety is mainly focused on fatal injury risks such as falls from height, leaving much to be desired in the risk assessment of non-fatal, cumulative musculoskeletal disorders among roofers. Ergonomics studies have identified several physical risk factors associated with LBDs in workplaces and applied selective ones to develop predictive models for general LBD risk assessments. However, these models cannot be used for roofing assessments in that they are designed for general tasks without considering different roofer working postures and the effect of working on uneven rooftops. To understand the relationship between the risk factors (i.e., slope angle, posture, facing direction, and working pace) and LBD incidence in roofing shingle installation, a factorial in-lab experiment is conducted with the aid of the Vicon camera system and Electromyography (EMG) sensors. The bending angles and muscle strengths in the low back, which are measured by the two sensor systems, are analyzed as facts that indicate the LBD risk. The proposed experiment finds out the risk factors with significant effect on the LBD injury and interaction between the studied factors. The findings may be used to study the detailed ergonomic safety guidelines for roofing contractors, which will be useful for eliminating LBD risk factors on the roofing sites.

1 INTRODUCTION

As a major construction workforce, roofers have long suffered from low back disorders (LBDs), which is a primary non-fatal injury in construction. For roofing workers, it was found that 30% (i.e., 3,300 of 10,815) cases of injuries and illnesses occurred in the trunk (Fredericks et al. 2005). In roofing, shingles are widely used as roof covering materials, and shingle installation is a most time-consuming activity where most injured cases take place (Wiki 2015; CPWR 2015). Without enough knowledge of the nature and disease formation of LBDs, roofers tend to adapt themselves to the harsh workplace environments (e.g., steep rooftops) and fast work pace. In addition, the roofers’ working postures can vary due to their personal preference. It has not been revealed what factors are prone to cause LBDs and needs to be rectified. Till present, there are only general guidelines available, which are designed for general industrial tasks (e.g., manual material handling) (Wang et al. 2015), ignoring the differences in environment settings, working procedures, job rotations, and alternative postures. The research in roofing safety mainly focuses on fatal injuries, while existing efforts in non-fatal studies are focused on sample studies and disease diagnosis. In order to better understand the relationship between the LBD incidence among
roofers and the potential risk factors, in this study, the main risk factors in the roofing shingle installation are identified. Then, a factorial experiment is designed to study their effects and their interaction on LBDs. Advanced motion capture system Vicon and skeletal muscle signal recording system Electromyography (EMG) are utilized to conduct the LBD risk measurements. Through this experiment, it is expected to reveal the effects of the risk factors on the LBDs and to report the risk level at certain conditions, which may be helpful to the study of detailed ergonomics guidelines for roofing workers.

2 RESEARCH BACKGROUND

2.1 State of Practice

In the United States, there is a total of approximately 132,700 workers employed as roofers whose main jobs include repair and install the roofs using shingles, asphalt, metal, and solar panels, etc. (BLS 2015a). Roofing work can be categorized into commercial roofing on low-pitch roofs (below 10°) and residential roofing on a relatively steep roof (10°~45°) (National Contractors Inc. 2015). Roofing work can be hot and physically demanding. It involves heavy lifting, as well as climbing and bending. According to the survey (BLS 2015b; Fredericks et al. 2005), roofers spent over 60% of their working time on roofs. Shingle installation is a major repetitive task for roofers. The time roofing workers spent on crawling, squatting, stooping and kneeling is among top 7 of all industrial activities (O*NET 2013). The cumulative effects of stooping, kneeling or squatting may not only lead to low back pains, but also can increase forces in the knee (CPWR 2015).

Roofers have a higher incidence rate of injuries and illnesses than the national average. Among all construction sectors, roofing workers have the second largest WMSD (work-related musculoskeletal disorder) incidence rate (i.e., 50.7 per 10,000 full worker year) (BLS 2013). Roofing workers suffer from not only fatal injuries, but also non-fatal injuries. In terms of fatal injuries, workers may slip or fall from scaffolds, ladders, or roofs. Through proper safety protection, most accidents can be prevented (EU-OSHA 2015). In contrast, roofing installation contractors frequently conduct labor-demanding operations, including stooping, kneeling, lifting, twisting, bending, and drilling. Although such operations would not cause acute pain after a short period of work, high repetition could accumulate the burden on the musculoskeletal system in the back and pose roofers to a threat of LBDs (Wang et al. 2015).

Till present, there are very limited guidelines promoted to protect roofers from non-fatal injuries like LBDs. The documented guidelines simply list the causes of hazards, such as severe stooped postures, keeling, lifting and carrying (CPWR 2015). Comparing to fatal injuries, the non-fatal issues are not receiving enough attention. In industry, the sacrifice of safety for productivity is common (Lynch Ryan 2015). An agricultural study revealed that reduced productivity outweighs the benefits brought by knee support intervention which is designed for LBD injury prevention (Jin et al. 2009). However, non-fatal injuries can have a significantly negative impact on productivity by resulting in long days away from work. Besides, workers who had a history of WMSD injuries are reported to have a higher possibility of recurring and can decrease the productivity, in that the risky posture can cause pain in body parts and consequently affect productivity (Serranheiro and Smith 2014).

2.2 State of Research

Plenty of roofing research has been conducted with a focus on fatal injuries (e.g., fall, slips). The implemented studies covered risk assessment, communication, and prevention (Hisao 2014). In contrast, the up-to-date studies in non-fatal injuries are still at the stage of performing sample studies and injury formation analysis. Hunting et al. (2004) have conducted a survey study of the nature and cause of injuries among 2916 injured construction workers by detailed occupation. It revealed that half of injuries among the roofers are in the back and most non-fatal cases are caused by overexertion and strenuous movement. Fredericks et al. (2005) has analyzed the U.S. Bureau of Labor Statistics (BLS) data in roofing and revealed the trends and causes of both fatal and non-fatal injury incidences among roofers. It was reported that roofers spend 61% of their time on roofs and typically spend 3-4 hours daily on manual lifting/carrying. In addition, they have conducted a self-report survey of injuries and risk factors, including
personal information, working environment, and lifting/carry strength to identify the most frequent roofing injury combination.

In epidemiological and ergonomic studies, a lot of efforts have been put in studies of injury nature and risk assessment methods for WMDSs and LBDs (Wang et al. 2015). However, these methods are mostly developed for general industrial tasks, for example, lifting, bending, and carrying (Pan et al. 1999). Up to date, observation tools and predictive models have been developed by summing up the detected risk factors multiplied by assigned weights to evaluate the LBD risk in the workplaces, such as NIOSH lifting equation (Waters et al. 1994) and 4D WATBAK (Neumann et al. 1999). However, for roofing construction activities, no specific studies have been conducted to identify and measure the risk factors on roofing sites.

3 RESEARCH PROBLEM STATEMENT

All the presented data brings forward the problem of LBDs among roofers, which requires actions taken to study and alleviate LBDs among this population. The existing observation tools are able to detect the LBD risk in the workplaces, but provide no clue on how to redesign the work procedures and the environment settings in order to reduce the LBD incidences (CPWR 2015). Epidemiological studies have identified certain physical risk factors for LBDs in workplaces and predictive models are developed based on those selected factors. However, the models cannot be used for roofing activities due to dissimilarity in the survey sample that determines the coefficients and the raised risk factors need modification before applying to roofing tasks. These models do not take into account a diversity of roofer working postures (e.g., stooping, kneeling) and effects of working on slanted rooftops. In addition, in roofing, the effect of gender can be ignored as the majority (over 90%) of workers on construction sites are male (BLS 2015a). Through abundant literature review and site observation, the main risk factors in roofing tasks are detected and summarized as follows for the examination of the experiment.

3.1 Postures: Stooping and Kneeling (or Crawling)

Through on-line search and site observation, two main postures in shingle installation were found: stooping and kneeling. Roofers can use different working postures due to personal preference. Stooping posture, which requires the roofers to bend forward while holding their legs upright, is illustrated in Figure 1. In contrast, kneeling typically requires the workers to kneel on the roof and make the trunk parallel to the roof (Figure 2). However, the existing risk assessment methods do not examine the relationship of an injury to stooping or/and kneeling. Reducing the incidence of work-related LBDs among roofers requires a new focus on identifying and describing stooping and squatting postures as specific LBD risk factors in the workplace (Fathallah et al. 2004).

![Figure 1: Stoop posture on the roof](image1)

![Figure 2: Kneel posture on the roof](image2)

3.2 Environmental Conditions: Roof Slope

For the work environmental setting, the risk of working on a slant roof surface to the LBDs is not well investigated. There are studies on fatal fall risks exploring the effects of the roof slope. One of these is to study the influence of the surface slopes (18°, 26°, 34°) and frequencies on postural balance in shingle installation with stooped postures (Choi et al. 2008). For each surface slope, the Maximum Acceptable
Roof Shingling Frequency (MARSF) was reported. It is found that as the slope slant increases, the MARSF decreases from 206 shingles per hour to 168 shingles per hour. The influence of the slope slant was revealed by this experiment, but it did not indicate that it is the same decreasing trend for the LBD risk as the slope rises.

3.3 Task-Related Factors: Facing Direction on the Roofs

The experimental setup was designed to mimic a shingle installation task in a laboratory setting. Based on our video database search and on-site observation, it is noted that different roofing materials require different installation methods on certain pitches (NINDS 2015). For three- or four-tab residential shingles, roofers are used to installing them parallel to the ridge, which requires the roofers stand facing uphill. For solar panels, the roofers usually stand perpendicularly to the ridge while installing them in order to avoid stepping on these panels. This means that the roofers will work on the roof facing side (hip). In the most recent ergonomics study, it is found that manual handling sudden loading on uneven surface can have a significant difference with on the ground on the LBD risk (Zhou et al. 2015), which provoke the needs for studies on jobs conducted on uneven surfaces such as roofs.

The identified three risk factors, each of which can have at least two factor levels, indicate that there can be different combinations of the slope slants with the roofer working behavior. In order to study the risk on a certain combination, a factorial experiment is designed to analyze the influence of each factor, expected to study the effects of and among different factors to the LBD risk.

3.4 Limitations of Existing Research

It is mentioned that the promoted guidelines and practices still lack practicality. Most guidelines are in rough description and still require expert observation to reveal on-site LBD risk factors and improper work design (CCOHS 2013; Wang et al. 2015). The workers’ insurance compensation put much more emphasis on medical care than preventive efforts, and the injury statistics data is driven by an event or an acute injury rather than cumulative trauma (Fathallah et al. 2004).

Upon the review of the state of practice and research, the main risk factors in roofing industry have been summarized. However, the authors have identified that there are still several areas that need exploring in order to understand and eliminate the LBD risk among roofers. That is: 1) the development of risk measurement for LBDs among roofers, 2) the knowledge of the effects of different risk factors and their combinations on LBD risks (i.e., slope, posture, facing direction, frequency), and 3) comparison of two different postures (i.e., stooping and kneeling) on the effect of developing LBD risks.

Given above limitations, in this study, a sensor-based ergonomics experiment is designed to reveal the relationship between roofing activities and risk factors through lab empirical studies.

4 EXPERIMENT AND IMPLEMENTATION

The purpose of this study is to understand the relationship between the risk factors (i.e., roof slope, posture, facing direction, working frequency) and LBDs in roofing shingle installation. A factorial experiment is designed with advanced EMG to estimate the forces and loadings on the trunk, and motion capture system Vicon to capture the bending angle of the trunk.

Four factors are selected as the independent variables for factorial analysis from the view of individual factors, environmental settings, and task-related factors: 1) Slope: 0°, 15°, 30°; 2) Posture: stooped and kneeling; 3) Facing direction: uphill and side; 4) Frequency: slow (12 seconds/shingle), fast (6 seconds/shingle). Based on the site observation data and studies on maximum acceptable working frequency on roof slopes (Choi et al. 2008), a duration of 12 seconds is set for one shingle installation at slow frequency level; a duration of 6 seconds is set for fast frequency. Given that shingles are usually prepared beforehand, the process of carrying shingles and walking on the roof is ignored. In this simulation, we particularly focus on the nailing process. The participants are required to hold a same nail
gun while simulating shingle installation process on the platform. A total of 16 combinations of the four risk factors are tested and 2 repetitions for each condition are conducted.

In our experiment, there are two independent variables which are generated from data captured by Vicon and EMG.: 1) Maximum lumbar trunk flexion angle which measures the angular difference between the T12 and S1 motion sensors in the sagittal plane (Hu et al. 2014); 2) Average normalized EMG signals which measure the activeness of the muscles on the back (with detailed discussion in 4.4 Data processing). The two independent variables (response variables) are utilized to help establish measurements of the LBD risk and could also verify each other. In addition, the two variables are synchronized using Vicon Nexus software (Vicon, Oxford, 2002). Analysis of variance (ANOVA) is a popular statistics technique which is used to investigate the relationship between the independent variable(s) and the response variable (Miller 1997). In our study, ANOVA is conducted to study the effects of each factor and interaction among risk factors. For all statistical analysis in this study, the criteria p-value is set at 0.05.

4.1 Participants
There were 4 participants in this study. The age, stature and whole body mass (with standard deviation) of this study population were 25.2 year (1.3), 176.4 cm (3.4), and 70.6 kg (8.4). All subjects had no history of low back injury. The research involving human experiments was approved by the Institutional Review Board of West Virginia University (Hu et al. 2014).

4.2 Apparatus
The experimental setup was designed to simulate a shingle installation task in a laboratory setting. The shingle installation simulation was conducted on a 1.4m by 1.7m wood platform (Figure 3). The platform was connected to a hydraulic lift table. By elevating the lift table, the wooden roof could be lifted to a slope angle ranging from 0 to over 60°. In this experiment, a Vicon camera system was utilized to capture the human motion data; and EMG sensors were utilized to capture the signal of the main muscles on the back. Video streams were also recorded for off-time observation.

The Vicon system is a 3D motion capture system that involves multiple cameras surrounding the capture volume where human motion can be tracked (Richards 1999). Vicon data was recorded at a frequency of 100Hz. To capture the posture of the lumbar spine, five Vicon markers are attached to each participant. Three sensors were placed on the spine to calculate the trunk flexion angle: one at the C7 area (near the neck), one at the T12 area (around the chest) and the other at L5 area (lumbar). The three sensors provided measures of angle in the sagittal plane and were then used to estimate the lumbar flexion angle (Dolan et al. 1994). Another two sensors were placed on the shoulders to help recognize the postures and facing directions. They could be used to calculate the trunk twisting angle in the future.

EMG was mainly applied in human kinematics experiments by attaching a group of muscle sensors on the skin (Marras and Granata 1997), as shown in Figure 4. It features in synchronous recording of muscle tension and computerized analysis of myoelectric signals, and is widely used to evaluate muscle actions and the loading in body parts (Reaz et al. 2006). The EMG data was collected at a rate of 1000 Hz. In this experiment, 4 pairs of surface electrodes were placed on the abdomen and low back of the subjects that were used to collect the electromyographic (EMG) muscle activity of the sampled muscles. The sampled muscles included two pairs on the abdomen (Ab1, Ab2), and two pairs on the back (erector spinae (ES), multifidus (MF)). These muscles were chosen as they were reported to have a direct impact on spinal loading (ES, MF). In ANOVA analysis, signals of those muscles were hypothesized to be affected by shingle installation posture (Fathallah 2004; Zhou et al. 2015).
4.3 Procedure

The first phase of the experiment consisted of a series of static trials that focused on collecting the maximum voluntary capacity and static low back posture. The second phase of the experiment consisted of two repeated trials on each condition which is a combination of the selected factors, such as, stooping on a 15° slope at a fast working pace while facing uphill. At this phase, both Vicon markers and EMG surface sensors were placed on the subject’s trunk and low back. This way, kinematics data and muscle signals were recorded simultaneously and synchronized for post-processing. The stooped trials were simulated first, and then kneeling postures.

4.4 Data Processing

The trunk kinematic data collected from the Vicon during the trials were used to compute the trunk flexion angle. The three markers placed on the trunk were reconstructed in the 3D space using Vicon Nexus. The derived 3D coordinates were used to track the trunk motion and compute the bending angle.

The EMG data collected during shingle installation cycle was rectified, filtered using butter filter, and averaged over the whole nailing period. These data were then normalized to the percentage of the Maximum Voluntary Capacity (MVC) of the muscle. During the experiment, the subjects were required to follow the same time schedule (trunk flexion, nailing, and trunk extension) during a working cycle. Nailing process was extracted by defining the starting and ending time of the nailing process. As denoted in Figure 5, two peaks were captured during a single shingle installation cycle. The first peak of EMG signal reflects the trunk flexion process, and the second peak reflects the trunk extension process. The flat curve between the peaks represents the nailing process.

![Figure 5: EMG signal process and nailing process extraction](image-url)
5 RESULTS

Prior to conducting the formal analyses, the assumptions of the ANOVA technique (normality of residuals, and independence of observations) were evaluated using the graphical approach advocated by Montgomery (2001). Interval plot each factor vs each response variable was drawn to show the sample’s tendency and variability. In addition, F-test was conducted to investigate the effects of each factor on the response variables (Flexion from Vicon, ES (erector spinae) and MU (multifidus) from EMG data) and presented in Table 1. “+++” denotes a significant effect and “/” denotes no significant effect. For example, frequency difference has no significant effects on the flexion angle captured by Vicon. It is because either for slow cycle or faster cycle, the participants followed the exact same posture and procedures, which would result in no noticeable difference.

Table 1: F-test for measuring the effects of the factors (p-value: 0.05)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Flexion (Vicon)</th>
<th>ES (EMG)</th>
<th>MU (EMG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>+++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Frequency</td>
<td>/</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Direction</td>
<td>++</td>
<td>+</td>
<td>/</td>
</tr>
</tbody>
</table>

The subsequent univariate ANOVA showed that the response of the erector spinae and the multifidus followed a consistent trend on most conditions. Besides, the Vicon and EMG data supports each other in effects of slope angles, but contradicts each other on certain conditions. As mentioned, both Vicon and EMG data serve as the risk measurements of the loading on the back. As stooping and crawling are two totally different postures, correspondingly, the back muscles and the rest of the body parts can differently be involved in the procedure. At this stage, the comparison of stooping and crawling is not discussed. In the following section, the results of stooping and kneeling postures are presented. For each posture, we respectively conduct ANOVA analysis to study the effect of each factor on the LBD injury development.

5.1 Stooping Posture

5.1.1 Influence of slant

The effects of slope angles on maximum flexion angle can be revealed in Figure 6. The flexion angle calculated from Vicon data shows the trend that the flexion angle is decreasing as the slope angle increases, which indicates a decreased LBD risk. Survey score from the subjects also indicates a same trend.

Figure 6: Effects of slope angles on flexion angle (stooped)

This result is verified by EMG data as a same trend is detected both in ES and MU muscles, shown in Figure 7.

Figure 7: Effects of slope angles on EMG (stooped)
5.1.2 Influence of facing direction

From the flexion angle, we can detect that the flexion angle of working facing side tends to be higher than that of facing uphill, as shown in Figure 8. Besides, as to facing side, a more severe twisting of the trunk is reported by the subjects in the survey. For each degree of slope, except the flat ground, a higher risk for facing side than facing uphill is indicated. But as mentioned, the EMG data contradicts the trend on some conditions, which still needs further studies.

![Figure 8: Effects of facing directions on flexion angle by slope angle (stooped)](image)

5.1.3 Influence of speed

The Vicon data shows there to be no evident differences between slow and fast working paces in flexion angles. On the contrary, the response of EMG shows the trend that the muscle signal in both MU and ES muscles become stronger as the working rate accelerates, which indicates an increased LBD risk (Figures 9 and 10).

![Figure 9: Effects of frequencies on MU EMG signal (stooped)](image)

![Figure 10: Effects of frequencies on ES EMG signal (stooped)](image)

5.2 Kneeling Posture

For kneeling postures, the facing direction was assumed to be uphill as only uphill was detected in video observation. The effects of the slant and frequencies are discussed respectively as follows.

5.2.1 Influence of slant

The response of Vicon shows the trend that the flexion angle decreases as the slope rises, which indicate a decrease LBD risk, as shown in Figure 11. For both fast and slow frequencies, Figure 12 shows that there is a consistent trend. That is, as the slope rise, the flexion angle decreases, indicating a decreased LBD risk. As we increased the slant to 40 degrees, the trend is consistent. EMG signals verify this finding as well.
5.2.2 Influence of frequency

Similar to stooped postures, the response of EMG shows a trend that the muscle signal becomes stronger as the working rate accelerates, which indicate an increased LBD risk for kneeling postures.

6 DISCUSSIONS AND CONCLUSIONS

This paper proposed a method to examine the effects of the common risk factors in roofing jobs. A factorial experiment was designed to reveal the effects of a combination of the identified factors. From the result analysis, the effects of each factor were revealed. From this study, faster working pace resulted in a higher LBD injury risk. As the slope angle increases from 0° to 15°, and then 30°, a decrease in LBD risk was detected. The facing side working condition posed extra pressure on the lower back due to a twisting angle. These findings might be helpful to develop specific guidelines and prevention training for tackling the LBD risk among roofers. The existing study did show a significant effect of the selected factors on the changes of the response variables, which indicated an influence on LBD risk. Some of the findings contradicted people’s common sense. For example, people tend to believe that it is risky on steep roofs and poses more injury risk to the trunk. But through the laboratory study, a relief in pressure on the back was observed for a larger slope. It is worth noting that similar guidelines exist; That is, to avoid working on the floor/inclination degree, when possible, raise the work height by using a workbench (CPWR 2015).

However, there is still room that could be further improved both in the experiment design and post analysis. 1) The twisting angle of the trunk is not captured in this experiment, which is expected to differentiate side and uphill posture better. 2) Only the trunk muscle is studied and used for the risk analysis. However, the ankle and knee are also prone to WMSD risks due to heavy use in two roofing postures. 3) As in a dynamic experiment, the duration of a single trial is short, which could add difficulty to reflecting the difference of factor levels by EMG. (4) Currently, the sample size is relatively low. In the future, an expanded experiment involving more subjects with a diverse distribution in age, stature, body fat percentage, etc. would be carried out.

References


EXAMINING AND SIMULATING HUMAN MOBILITY UNDER THE INFLUENCE OF HURRICANE-IMPOSED MOBILITY CONSTRAINTS

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Abstract: Hurricanes can significantly influence urban populations. The understanding of human movements in urban areas plays a key role in improving our disaster response, evacuation, and relief plans. However, there is a lack of research on human mobility perturbation under the influence of hurricanes. Furthermore, limited simulation studies have had access to empirical human travel data in urban areas during natural disasters. In this paper we examine human mobility during the approaching and strike of hurricanes. Inspired by animal movements in a fragmented habitat, we examined human movements in New York City and its adjacent areas during the striking of Hurricane Sandy. We found that while the urban travels within New York City did not experience strong perturbation, the movements crossing the boundaries of the city decreased dramatically during Hurricane Sandy. Based on the patterns observed, we also proposed a framework for a data-driven agent-based GIS model to simulate human movements during hurricanes. The model simulates human mobility patterns in three different scenarios: (1) the imposition of evacuation zones; (2) the occurrence of flooding; (3) and the abrupt failure of certain infrastructures. The research effort aims to inform policy-makers and support decision-making under different emergency situations that can arise during hurricanes.

1 INTRODUCTION

Natural disasters severely disrupt human society and cause significant damage to buildings and infrastructure. UNISDR (2013) reported that from 2002 to 2012, natural disasters caused 1.2 million deaths, influenced 2.9 billion people, and resulted in a total of 1.7 trillion dollars of economic loss. It is predicted that the numbers will increase due to on-going climate change. Humans are facing an ever pressing challenge to remain resilient during natural disasters.

Governments, especially those in large urban areas and population centers, have developed different coping mechanisms to fight natural disasters. Disaster response and evacuation plans are particularly prevalent. These plans evaluate possible risks brought by different disasters and attempt to control and minimize the consequences. However, the effectiveness of these top-down plans is often questioned due
to their lack of sufficient understanding and consideration of human behaviors (Chakraborty, Tobin, and Montz 2005, Drabek 2000, Wolshot and Marchive III 2007). Take New Yorkers’ actions during Hurricane Sandy as an example. While 71 percent of the New Yorkers living in evacuation areas were aware of the mandatory order to evacuate, more than 50 percent of them stayed nonetheless (Schuerman 2013). Regretfully, many of the fatalities occurred in the evacuation areas (CDC 2013). Even the people who evacuated were not entirely safe. Data from FEMA (US Federal Emergency Management Agency) show that the flooding areas in NYC during Hurricane Sandy were 15 percent larger than the evacuation areas, putting people who stayed in some of the assumed safe areas in severe threat (Rosenzweig and Solecki 2014). It is critical that we better understand human mobility during natural disasters to increase the percentage of the population that heeds the evacuation orders and to adjust that mobility dynamically when predicted evacuation areas change in unpredictable ways during a natural disaster. In short, we need to do a more effective job at getting impacted urban populations to safety.

Existing research has already pointed out that human mobility plays a key role in disaster evacuations (Pan et al. 2007, Schneider et al. 2011). On one hand, human mobility determines the effectiveness of evacuations. As Pan et al. (2007) pointed out, overcrowding and car crashing during emergency situations can cause incidents and thus injuries and loss of lives. Take the snow storm that pummeled Atlanta in December 2013 as an example. Alarmed by the approach of the severe snow storm, City of Atlanta officials issued a blizzard warning and advised people to leave school and work early. Without foreseeing such consequences of such a warning, many people crammed onto the roads and highways at the same time causing a city-scale traffic jam. People were still stuck on the roads or forced to abandon their vehicles to seek shelter when the snow storm arrived (Beasley 2014). Without a deeper understanding of human movements during natural disasters, the same situation is bound to occur again.

Human mobility also has an impact on the effectiveness of information communications during emergencies. When a region’s communications infrastructure is damaged by a natural disaster, human mobility effectively determines the bandwidth of emergency information networks and thus the speed and width of information diffusion. Natural disasters could possibly damage and/or destroy communication infrastructures and in that case, human movements would determine the width of temporary communication networks built on portable devices (Chaintreau et al. 2007, Feeley, Hutchinson, and Ray 2004, Kleinberg 2007). Furthermore, deep understanding and accurate prediction of human mobility can potentially save lives. In the case of Hurricane Sandy, if it had been possible to identify vulnerable individuals and provide them with detailed instructions, their lives might have been spared. The critical roles of human mobility related to all three of these aspects call for in-depth investigations to build our understanding of how best to work with real-world human behaviors in disaster situations (Wang and Taylor 2014). All these three aspects, namely effective evacuation, reliable communication, and accurate locating, are indispensable to disaster management in emergency situations.

Despite the critical importance of human mobility, studies of human mobility perturbation under the influence of natural disasters are limited. Current studies and models explicitly or implicitly assume that human movements happen in a continuous space without considering constraints and/or gaps. Such an assumption may not hold true during the occurrence of natural disasters. Many situations can cause gaps in space, such as road blocks, traffic jams, evacuation zones, and so on. These gaps can force people to change their routine movement trajectories.

This paper focuses on space constraints imposed by natural disasters, examining their influences on human mobility. While no research has studied this phenomenon in urban and built environments to the best of our knowledge, the problem has gained attention in natural environments. Inspired by these existing studies, this study focuses on discovering whether space constraints in urban environments have effects on urban dwellers similar to the effects of habitat gaps to animals. If so, we explore if it is possible to predict human movements better during the occurrences of natural disasters. The objectives of this research is to (1) understand human mobility perturbation under the influence of hurricanes, (2) explore how geographical constraints during natural disasters can influence human mobility by examining a case study in New York City, and (3) propose an agent-based model to integrate empirical data and simulate human mobility in emergencies and extreme events.
2 BACKGROUND

Researchers have attempted to describe animal movement patterns for over one hundred years. Pearson (1905) first proposed a mathematical model to capture human and animal movements. This model stated that an individual moves consistently where each movement has a set distance, but a randomly different angle from its previous movements. Such a model is called a random walk model. Later on, Lévy modified the model and made the distances of steps follow a heavy-tailed probability distribution such as a power-law (Mandelbrot 1983). This model was called a Lévy flight. Research has shown that the movements of many types of animals follow Lévy flight patterns (Bartumeus 2007, Benhamou 2007, Viswanathan et al. 1996).

Lévy flights observed in animal movements have inspired studies in human mobility. Brockmann et al. (Brockmann, Hufnagel, and Geisel 2006) was an early researcher that studied human mobility using a large quantity of empirical data. Using the travel distances of 464,670 one-hundred-dollar bills, the study confirmed that human mobility follows the Lévy flight model. The truncated power-law distribution governs human mobility, and the exponent value was found to be around 1.59. Such findings have been supported by multiple subsequent studies with exponent values ranging from 1.59 to 1.88 (Brockmann, Hufnagel, and Geisel 2006, Cheng et al. 2011, González, Hidalgo, and Barabási 2008, Havetka et al. 2013).

Undoubtedly an important discovery, Lévy flight patterns may not always be the best model to describe animal movements. An assumption of Lévy flights, though it may not be explicitly pointed out by researchers, is that animal movements happen in a continuous space without any constraints. In reality, animals’ habitats and foraging spaces always have boundaries. It is also evident that human activities have imposed more constraints and limitations to animal spaces. All of these constraints can make the Lévy flight pattern an inappropriate model to describe animal movements.

One example where human activity influences animal movement is habitat fragmentation. Habitat fragmentation is the process where a large habitat is transformed into several smaller patches. These patches become isolated from each other, and the total area of these patches is always smaller than that of the original habitat (Wilcove, McLellan, and Dobson 1986). Habitat fragmentation was observed to be associated with different types of long-term effects such as population reduction and extinction, edge effects, and reduced gene flows (Wolff, Schauer, and Edge 1997). Research has shown that habitat fragmentation can dramatically change animal movements as a short-term effect (Diffendorfer, Gaines, and Holt 1995). Laurence et al. (2004) studied how roads and human clearing influenced birds’ movements. They found while there were no physical constraints that prevented birds from flying near or crossing the roads built inside of forests, birds avoided doing so due to edge and gap avoidances. In fact, comparing two areas of the same size, one in a forest and one crossed by a road, the number of movements reduced by 50% in the latter case.

While mainly observed in animals, similar fragmentation can happen in human societies as well. As mentioned before, such fragmentations are particularly common during the occurrence of natural disasters. Different situations, such as road blocks, traffic jams, evacuation zones, disaster damaged areas, etc., can fragment urban spaces. In these emergency situations, urban dwellers may find it difficult to cross these gaps and be forced to reduce their activities to a smaller area, and/or be denied to the primary locations they visit in ordinary days. All of these can cause constraints to human movements.

Inspired by habitat fragmentation and its influence on animal movements, this study examines whether this phenomenon in built environments has a similar influence on human movements. Using a case study of Hurricane Sandy, the research attempts to discover whether evacuation zones separated New York City from its adjacent areas. Though not as effective as expected, the mandatory evacuation areas forced many New Yorkers to leave the area and prohibited people from going back or passing by it. Technically, it separated New York City from the adjacent land. We examined if such separations influenced movements crossing the gaps. Such understanding will not only reveal a critical pattern of human mobility perturbation under the influence of natural disasters, but also potentially improve our ability to predict human movements in similar situations.
3 METHODOLOGY

We collected human movement data from New York City and its adjacent areas during Hurricane Sandy. The data was then analyzed to identify any perturbation caused by habitat fragmentation.

3.1 Data Collection

Human mobility data were collected from Twitter. We used Twitter’s open API and created a continuous connection between a computer in our research lab and a streaming endpoint at a Twitter server. The connection continuously downloaded tweets in real-time. Each public tweet was collected if the tweet had both geolocation information, also known as being geo-tagged, and if the coordinates were within 74°15'W to 73°40'W longitude and 40°30'N to 40°57'N latitude, the range of coordinates that contains the studied area. The data collection started around 4pm on October 29th and lasted for 12 days. Every tweet included: the text information, the tweet’s ID, the name and ID of the user who posted the tweet, the time stamp for when it was posted, and its coordinate location. More details about the data collection process can be found in Wang and Taylor (2015).

3.2 Data Analysis

We analyzed NYC data and determined both the total displacements and the crossing displacements during and after Hurricane Sandy. A displacement is the distance between two consecutive locations of the same user. A crossing displacement occurs when the starting point of a displacement is within NYC with its corresponding end point located outside of NYC, or vice versa. The distance was calculated using the Haversine formula shown in Equation 1 (Robusto 1957):

\[
d = 2r \times \sin^{-1}\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos \phi_1 \cos \phi_2 \sin^2\left(\frac{\phi_2 - \phi_1}{2}\right)}\right)
\]

[1]

Where \( r \) is the earth’s radius, which approximately equals to 6,367,000 meters, \( \phi \) is the latitude, and \( \varphi \) is the longitude.

![Geographical data from New York City](image_url)

Figure 1: Geographical data from New York City
We used ArcGIS and its associated Python package arcpy to conduct our analysis. The grey area in Figure 1 shows the shapefile of NYC. Each black point was a geographical coordinate retrieved from a geo-tagged tweet. The red shaded areas are the mandatory evacuation zones. The accuracy of each location is 3 to 8 meters depending on the geo-tagging devices. To minimize the possible errors caused by both the shapefile and devices, we created a buffer of 200 meters around the original shapefile (thick blue outlined areas in Figure 1). A crossing displacement needs to have one point inside the original shapefile, and the other point outside of the buffered shapefile.

4 RESULTS

Table 1 shows the total displacements and crossing displacements for each day data was collected. We found no significant changes in the total displacements during the strike of Hurricane Sandy. In fact, the total displacements increased by 19% during the first 24-hours after the landfall of Hurricane Sandy. However, the crossing displacements were dramatically reduced, and the reduction was up to 50%.

The crossing displacements gradually recovered to its steady state level. The phenomenon reflected the infrastructural situations in New York City. Hurricane Sandy caused flooding in several tunnels and a widespread power outage. Most public transportation systems did not resume partial or full scheduled service until 36 to 72 hours after Hurricane Sandy struck (Kaufman et al. 2012), and over 1 million people in the city were still without power until 2pm Nov. 2 (McGeeham 2012).

Table 1: Total displacements and crossing displacements

<table>
<thead>
<tr>
<th>Day</th>
<th>Total Displacements</th>
<th>Crossing Displacements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51185</td>
<td>310</td>
</tr>
<tr>
<td>2</td>
<td>38438</td>
<td>321</td>
</tr>
<tr>
<td>3</td>
<td>42746</td>
<td>373</td>
</tr>
<tr>
<td>4</td>
<td>40457</td>
<td>353</td>
</tr>
<tr>
<td>5</td>
<td>51894</td>
<td>466</td>
</tr>
<tr>
<td>6</td>
<td>46863</td>
<td>421</td>
</tr>
<tr>
<td>7</td>
<td>41764</td>
<td>495</td>
</tr>
<tr>
<td>8</td>
<td>43184</td>
<td>615</td>
</tr>
<tr>
<td>9</td>
<td>43367</td>
<td>576</td>
</tr>
<tr>
<td>10</td>
<td>45220</td>
<td>521</td>
</tr>
<tr>
<td>11</td>
<td>37879</td>
<td>474</td>
</tr>
<tr>
<td>12</td>
<td>41168</td>
<td>612</td>
</tr>
</tbody>
</table>

The geographical analysis highlighted the impact of habitat fragmentation on human mobility. Figure 2 shows that crossing displacements usually radiate from the lower Manhattan area to other places. During this emergency, areas surrounding the lower Manhattan area became evacuation zones and separated Manhattan from New Jersey. Comparing the three panels in Figure 2, the separation significantly reduced human mobility from crossing New York City to its adjacent areas.

5 FUTURE STUDY

Research has shown that agent-based simulations play a key role in the study of human mobility during an emergency situation (González, Hidalgo, and Barabási 2008). The analytical results and large scale data of human movements enable the possibility to build an agent-based model to simulate human mobility during the occurrences of hurricanes and typhoons. Therefore, we propose an agent-based GIS model structured by three levels: an individual level, an aggregate level and an environment level (Figure 124-5).
3). On the individual level, an agent represents a person in NYC. The analytical results from the human movement data will be used to create algorithms that govern each agent’s attributes, decision-making, behaviors, and interactions with other agents. Each agent will have its own individual center of movement, radius of gyration, trajectory, primary visiting locations, traveling routes, etc. An agent will also have their own preference to deal with the risk presented by environmental changes, i.e. a hurricane approaching and striking. On the aggregate level, we will simulate the aggregate properties and patterns from all of the agents. Following a pattern-oriented modeling approach (Grimm et al. 2005), distributions found from human displacements, shifting of movement centers, radius of gyration, and social degree will be used to govern the aggregate properties in the model. Lastly, on the environment level, GIS data of NYC’s urban setting and road system will serve as the context for agents’ movements and behaviors.

Figure 2: Geographical distribution of crossing displacements
Computational experiments will be conducted to test three scenarios using the agent-based GIS model. These three scenarios are: (1) the imposition of evacuation orders, (2) the occurrences of flooding, and (3) the abrupt failure of infrastructure that cause certain road blockage. In each scenario, we will test how human movements perturb and how human mobility patterns differ in various scenarios. The results will support the decision-making of policymakers for different emergency situations.

6 CONCLUSION

Natural disasters can significantly influence human activities and impose constraints on human mobility. One such influence is caused by habitat fragmentation. When natural disasters occur, they often force people to stay away from certain land areas due to present or potential damages. Even small gaps in the human habitat can cause significant perturbation in routine urban travels. While habitat fragmentation has not been examined in human movements, it has gained much attention in animal movements (Laurance, Stouffer, and Laurance 2004). Research has examined how habitat fragmentation can influence movement patterns from different animals (Diffendorfer, Gaines, and Holt 1995).

Inspired by these studies, this study examined whether such a phenomenon could be observed in human mobility. Using Hurricane Sandy as a case study, we retrieved human mobility data and analyzed the crossing displacements around the New York City area. We found that evacuation zones caused habitat fragmentation and substantially influenced human movements across these gaps. Crossing displacements reduced to approximately half the amount observed in normal states. The influence of habitat fragmentation gradually diminished when the city recovered from the hurricane.

The study confirmed that habitat fragmentation can significantly influence human mobility. To predict human mobility during natural disasters, the urban constraint is a key factor that needs to be considered. Therefore, we proposed the framework of an agent-based GIS model. The model incorporates urban fragmentation and can simulate human mobility in different scenarios. The model will help us explore the impact of habitat fragmentation in urban areas to improve our understanding of human mobility patterns under the influence of hurricanes.

Acknowledgements

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GOVERNMENTAL DUST CONTROL IN CONSTRUCTION INDUSTRY: A STUDY OF POLICIES

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Abstract: Construction dust emission has become an outstanding issue in the construction industry. As a key content of green construction, governments around the world have the responsibility of mitigating the adverse effects of dust emission on the environment. However, little has been known of how governments can sharpen their efforts in this area. Using literature survey and content analysis, this study aims to identify the main roles of governments in construction dust control. Considerable policies were collected for analysis. It is found that governments have three characters in the dust control, namely opinion leaders, policy makers and technical supporters. As policy makers, governmental measures for dust emission control span widely, which include technology, economy, management and organizational governance. The results shed some lights on the measurement of governmental policies in the dust control.

1 INTRODUCTION

The construction industry plays a vital role in a socio-economic entity. However, it has become the targets of environmentalists and sociologists. One of the main reasons is that the construction industry has become a key consumer of energy and a major pollutant of the physical environment (Wallis 2012, Wang 2014). Basically, construction activities including land excavation, concrete construction, demolition activities, roadwork and building decoration generate a great deal of environmental pollution such as dust, noise, garbage and solid waste (Shen et al. 2010). Of all these pollutants, dust emission poses considerable threats on human health and local environments and it has attracted closer attention in recent years (Bergdahl et al. 2004).

Dust emission on construction sites enforces frontline workers and local people more vulnerable to suffer from clinical health problems or other potentially longer-term health problems (Steenland et al. 2001). Silica dust, wood dust, demolition dust and other construction dust involving gypsum, limestone, marble and dolomite are the four main types of construction dust on construction sites (Partanen et al. 1995). There is widespread concern about the over exposure of construction workers to respirable crystalline silica, which is a major constituent of dust emission (Flanagan et al. 2010). Previous studies suggested that approximately 60% workers employed in the construction industry were possibly exposed to silica in 2009 in Netherlands (Lumens and Spee 2001), and the exposure levels of silica exceed occupational exposure limits (OELs) in works such as drilling, blasting, screening, grinding, crushing and earth-moving which involve silica-containing material or equipment that creates particles (Nij et al. 2003).
Construction dust has also been found as a main reason for severe diseases including silicosis, bronchitis, obstruction of trachea, occupational asthma as well as the decline in pulmonary function (Chisholm 1999). As revealed in a cohort mortality study of industrial sand workers, there is a causal relationship between lung cancer and crystalline silica exposure (Nget al. 1987, Steenland et al. 2001). Other hazard substances of construction dust like wood dust and demolition dust also presenting a risk of disease such as occupational asthma and Chronic Obstructive Pulmonary Disease (COPD). COPD is predominantly caused by smoking; however exposure to harmful dusts can also bring on the onset of COPD even if the person does not smoke (Bergdahl et al. 2004).

Particulate matter, also known as PM, is a complex mixture of extremely small particles and liquid droplets including acids, organic chemicals, metals, and soil or dust particles (Zhao et al. 2006). As for the environmental impact, growing size of construction activities have enhanced the level of PM10 and PM2.5 (particulate matter with aerodynamic diameters less than 10 um and 2.5 um) in cities. Researchers have found that high death rates of asthma, heart disease, and other ailments are attributed to all PM components (Lumens and Spee 2001, Zhang 2006). Major cities in the world such as London, New Delhi and Mexico and many cities in China have suffered from high levels of particulate pollution over the past two decades. In fact, a series of environmental impacts caused by construction activities have been worse off. Early in 1989, in appreciating account energy efficiency and emission reduction, the Chartered Institute of Building report (CIB 1989) identified four areas for improving environmental management on construction sites - (i) Efficient use of energy and natural resources; (ii) Carefully selecting environmentally friendly building materials and the control of toxic chemicals and dangerous wastes; (iii) Pollution control, clean technologies, recycling and waste management, and (iv) Environmental education via intensive training. In line with these principles, fugitive dust, as a major source of pollutants emission on construction site, is due to bear responsibilities for all negative influences.

Detailed planning and effective construction management are necessary to reduce the adverse impact of dust emission on the surrounding environment, the current mayor of London pointed out (Johnson 2014). As a key member of social regulator, governmental authorities ought to review and assess the situation of dust emission in the territory. This is the same case in many developing countries. In China, governmental efforts to control dust emission are gradually unfolded (Tanget al. 2013, Ye et al. 2013). Nowadays, governments worldwide are attempting to make due response to this challenge. However, what is the role of governments in this domain? How can they do effectively? Such questions have not yet been addressed clearly. Therefore, this study aims to investigate governmental policies on construction dust control with the intention of answering these two questions.

2 RESEARCH METHODS

The main method adopted in the study is literature review and content analysis. The research starts with identifying the roles of governments in the practices of construction dust control. Progress in promulgating dust control policies has been made worldwide including Asia, North America, and Europe. Relevant polices and regulatory documents of these regions were collected for analysis and comparison. As one of the largest developing countries, China is still in an important period of strategic opportunities for construction and will build at such an unprecedented speed and scale. Finally, the case of China was adopted analyze governmental measures introduced in surveyed policies.

3 ROLE OF GOVERNMENT IN CONSTRUCTION DUST CONTROL

Government plays a key role in practicing construction dust control. As the main point of green construction, fugitive dust controlling need for governmental intervention especially in the early stage. The limitation of people’s rational recognition and self-consciousness combined with the failed formation of evaluation criterion and behavioral patterns backed up by common goals further at this stage underline the necessity of making effective activities though correct induction of government. The effectiveness of construction dust control depends on a systematic program that involves a number of main bodies including governmental authorities at various levels and relevant parties like the owner, construction and supervision organization. As the owners of public works, governmental authorities bear responsibilities of
reducing dust emissions of their own projects; On the other hand, they play a role as social regulators in monitoring dust emissions in the local construction industry. While stakeholders in construction are largely profit-oriented, the actions taken by governments should be driven by a desire to improve social and environmental benefits. Institution-related drivers for government to improve both social and environmental benefits include affecting the behavior of individuals and firms, providing institutional guarantee and supporting and promoting technological innovation (Fraser 2013, Sharratt and Auvermann 2014).

3.1 Opinion Leaders
Prior to the formation of public willingness to pay for environmental protection, inducing and promoting practices for construction dust by affecting the behavior of individuals and firms is necessary. Individuals maximize temporary advantages, which is short-signed, while companies respond to costs and profits, which are their primary drivers (Witzke and Urfei 2001, Franzen and Vogl 2013). However, in construction, whether each stakeholder acknowledges and accepts the idea of environmentally friendly “Dust-free” and then makes it a lasting habit is more essential. Therefore, the great importance of government’s propaganda and guidance becomes to emerge; they pose a direct impact on public recognition and awareness and then form an industrial development pattern featuring the interaction between governments and enterprises (Wang and Ye 2010). American was the ultimate practitioner of this role, popularizing preventive and treatment knowledge of construction dust with the united efforts of Occupational Safety and Health Administration (OSHA) and Non-government organization (NGOs).

3.2 Policy Makers
The most fundamental function of government is to provide institution guarantee for various social undertakings, achieved by means of rules and regulations. As mentioned above, practices of construction dust monitoring place responsibility on all stakeholders; it is harder to correctly identify responsibilities of each stakeholders and that explains why regulatory gaps and overlapping responsibilities are most likely to occur. The governmental function of instituting policy support and improving supervisory mechanisms is necessary in this sense. In many countries, law of environmental protection, as the foundation law, stated the requirements of taking necessary measures to monitor dust emission. However, the most specific regulations were mostly promulgated by local governments of city or county level. Providing tools and practical guidance according to the general policies issued by central governments, local governments actually play a dual role.

3.3 Technical Supporters
Dust control needs technical support. Practices for suppressing dust emission in construction are quite miscellaneous but can be classified into several distinct categories, including suppression by water infusion or wet cutting methods, dilution by ventilation system, mitigation by water sprays and scrubbers, and isolation by personal respiratory (Nijet al. 2003). In the process of renovation which is difficult for dry sweeping, studies suggested the use of a central vacuum system as a control measure for construction renovation sites (Lehtinen et al. 1996). Commonly used infrastructures like vacuum cleaner, local exhaust system (LEV) and windbreaks hedge are developed by firms, whilst they must bear all risk and pressure during the process of technological innovation. It is government who provide a strong backstop for stimulating and supporting innovations through actions including providing basic infrastructures and platforms for communication, collaboration, and knowledge sharing (Patanakul and Pinto 2014).
<table>
<thead>
<tr>
<th>Country</th>
<th>State/County/ City</th>
<th>Year</th>
<th>Policy/Regulatory documents</th>
<th>Authorities</th>
<th>Requirements</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.K</td>
<td></td>
<td>2002</td>
<td>Control of Substances Hazardous to Health Regulations</td>
<td>Health and Safety Executive</td>
<td>Specify the maximum level of Respirable Crystalline Silica (RCS) that workers can suffer (Working Exposure Level).</td>
<td><a href="http://www.hse.gov.uk/coshh/">http://www.hse.gov.uk/coshh/</a></td>
</tr>
<tr>
<td>U.S</td>
<td></td>
<td>2013</td>
<td>OSHA's Proposed Crystalline Silica Rule: Construction</td>
<td>Occupational Safety and Health Administration</td>
<td>Measure the amount of silica that workers are exposed to; Provide respirators and medical exam to workers</td>
<td><a href="https://www.osha.gov/silica/factsheets/OSHA_FS3681_Silica_Construction.v2.html">https://www.osha.gov/silica/factsheets/OSHA_FS3681_Silica_Construction.v2.html</a></td>
</tr>
<tr>
<td>Ireland</td>
<td></td>
<td>2013</td>
<td>Safety, Health and Welfare at Work (Construction) Regulations 2013</td>
<td>Health and Safety Authority</td>
<td>Contractor shall ensure that appropriate steps are taken to suppress (water sprays or other means) any dust generated during the process of demolition.</td>
<td><a href="http://www.hsa.ie/eng/Legislation/New_Legislation/SI_291_2013.pdf">http://www.hsa.ie/eng/Legislation/New_Legislation/SI_291_2013.pdf</a></td>
</tr>
<tr>
<td>U.K</td>
<td>London</td>
<td>2014</td>
<td>The Control Of Dust And Emissions During Construction And Demolition SPG</td>
<td>the Greater London Authority and London Councils</td>
<td>The developers shall provide an Air Quality and Dust Risk Assessment including the confirmation of both dust emission control</td>
<td><a href="https://www.london.gov.uk/sites/default/files/Dust%20and%20Emissions%20SPG%208%20July%202014_0.pdf">https://www.london.gov.uk/sites/default/files/Dust%20and%20Emissions%20SPG%208%20July%202014_0.pdf</a></td>
</tr>
</tbody>
</table>
Table 1 (Continued): List of policies/ Regulatory documents on construction dust control

<table>
<thead>
<tr>
<th>Country</th>
<th>State/ County/ City</th>
<th>Year</th>
<th>Policy/Regulatory documents</th>
<th>Authorities</th>
<th>Requirements</th>
<th>Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.K</td>
<td>Buckinghamshire County/ Aylesbury Vale</td>
<td>2010</td>
<td>Construction Site Dust Management Guidance</td>
<td>Environment al Health Division: Aylesbury Vale District Council</td>
<td>If mobile concrete crushing or screening plant is present on site, the Land and Air Quality Team shall be notified in order to undertake a site visit and liaise with operator of plant.</td>
<td><a href="http://www.aylesburyvaledc.gov.uk/GetAss">http://www.aylesburyvaledc.gov.uk/GetAss</a> et.aspx?id=fA AxDIAAMwAz ADcAfAB8AF QAcgB1AGUA fAB8ADAAfAA 1</td>
</tr>
<tr>
<td>U.S</td>
<td>Wisconsin</td>
<td>N/A</td>
<td>Dust Control on Construction Sites Conservation Practice Standard</td>
<td>Wisconsin Department of Natural Resources</td>
<td>Asphalt and petroleum based products cannot be used for dust control; Dry applied polymers must be initially watered for activation to be effective.</td>
<td><a href="http://dnr.wi.gov/topic/stormw">http://dnr.wi.gov/topic/stormw</a> ater/document s/DustControl _1068.pdf</td>
</tr>
</tbody>
</table>

4 POLICIES TO MONITOR CONSTRUCTION DUST EMISSION

4.1 A Review on Relevant Policies

As policy makers, governments are responsible for provide institutional guarantee for suppressing on-site dust t. The policy and supervising framework that support the construction dust management served well in many regions of the world. It has gradually sustained massive decrease of construction dust contamination especially silica-oriented cases and, in doing so, has accelerate the global process of sustainable construction in parallel. America, whose policy system of dust monitoring is more developed comparatively, is exampled. Since relevant policies, rules are mostly formulated by local authorities of states, counties, districts and boroughs in the U.S, they varies evidently and present diversification as well. Taking Yakima Washington for example, the policy "Construction Dust Control Policy of the Yakima Regional Clean Air Agency", which was promulgated in August 9, 2012, aims to reduce fugitive dust emissions with an emphasis on prevention rather than mitigation (Pruitt 2012). And Clark county focus on license application and emission targets instead of specific control measures, which makes on-site managers feel easy to further strength their supervision and inspection on dust discharge through quantitative evaluation. In addition, other governmental agencies like OSHA and Health and Safety Executive(HSE)in U.K also take their efforts. This paper provides a review on these policies promulgated by various authorities. The policy data gained from the relevant sources are mainly about laws and regulations, administrative rules and governmental plan. And these sources are approached by visiting the official websites, as see the Table 1 for more information.

4.2 Governmental Measures for Construction Dust Control in China

Nationwide the legal demand for improvements in emission control of construction dust in China have been tightened severely in the past decades (Pilarczyket al. 2013). In practice, however, the legalization started lately and it did not gained inadequate attention at that time. Until the year 2000, the Chinese
government promulgated the third version of “Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution”. In this law, a dust-free view is addressed, and then firstly added contents related to construction dust monitoring (mentioned in paragraph 2 of article 43). Pattern of “Central coordination, local implementation” on monitoring construction dust is thus laid in China. Subsequently, in 2004, the ministry of construction issued a series of standards on construction site including some compulsory rules that shall be strictly enforced like enclosure construction and road hardening. After that, local governments have commenced to promote dust controlling practices, more practical standards and specifications were elaborated.

Capital cities function as centers of politics, economy, military and culture in different regions. By investigating related policies of 32 capital cities in mainland China, it showed that 26 cities including Beijing, Hangzhou and Shanghai have launched special scheme of prevention of dust pollution on construction site. More specific information about these regulations is described in Table 2.

<table>
<thead>
<tr>
<th>City</th>
<th>Promulgation date</th>
<th>Reference number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peking</td>
<td>1999/9/14</td>
<td>Order of the people's government of Beijing (No.37)</td>
</tr>
<tr>
<td>Tianjin</td>
<td>2004/2/16</td>
<td>Jian Zhu [2004] No.149</td>
</tr>
<tr>
<td>Shijiazhuang</td>
<td>2004/12/30</td>
<td>Order of the people's government of Shijiazhuang (No.140)</td>
</tr>
<tr>
<td>Changsha</td>
<td>2005/10/11</td>
<td>Chang Jian Fa [2005] No.2</td>
</tr>
<tr>
<td>Chengdu</td>
<td>2006/7/7</td>
<td>Cheng Fang Fa [2006] No.56</td>
</tr>
<tr>
<td>Shaoxing</td>
<td>2011/2/19</td>
<td>Shao Shi Jian Guan [2011] No.19</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>2011/7/22</td>
<td>Shui Jian Zhi [2011] No.773</td>
</tr>
<tr>
<td>Zhengzhou</td>
<td>2012/2/8</td>
<td>Zheng Zheng [2012] No.6</td>
</tr>
<tr>
<td>Nanking</td>
<td>2012/4/18</td>
<td>Ning Jian Zhi Zi [2012] No.381</td>
</tr>
<tr>
<td>Fuzhou</td>
<td>2012/6/27</td>
<td>Rong Jian An [2012] No.25</td>
</tr>
<tr>
<td>Nanchang</td>
<td>2012/12/24</td>
<td>Hong Fu Ting Fa [2012] No.139</td>
</tr>
<tr>
<td>Xi’an</td>
<td>2013/1/9</td>
<td>Shi Jian Fa [2013] No.10</td>
</tr>
<tr>
<td>Jinan</td>
<td>2013/11/18</td>
<td>Ji Da Qi [2013] No.5</td>
</tr>
<tr>
<td>Hefei*</td>
<td>2013/12/20</td>
<td>He Jian [2013] No. 156</td>
</tr>
<tr>
<td>Taiyuan</td>
<td>2014/2/20</td>
<td>N/A</td>
</tr>
<tr>
<td>Lanzhou</td>
<td>2014/2/22</td>
<td>Lan Cheng Chen ZhiZi [2014] No.1</td>
</tr>
<tr>
<td>Haikou</td>
<td>2014/3/4</td>
<td>N/A</td>
</tr>
<tr>
<td>Huhehot</td>
<td>2014/4/2</td>
<td>Hu Zheng Fa [2013] No. 34</td>
</tr>
<tr>
<td>Xiamen</td>
<td>2014/5/29</td>
<td>Min Jian Jian [2014] No.21</td>
</tr>
<tr>
<td>Shenyang</td>
<td>2014/2/26</td>
<td>Shen Jian Fa [2014] No.34</td>
</tr>
</tbody>
</table>

Using the method of content analysis, measures included in those policies (including 26 policies issued by governments of city level and standards mentioned before) above were extracted. The primary mission of content analysis is to make inferences by objectively and systematically identifying specified characteristics of messages (Holsti 1969). In current study, two steps under this method were followed, namely (i) identifying “construction dust” per regulatory document; (ii) identifying related dust control methods involved per regulatory document. By eliminating contents which are general, superficial and
untargeted, and then consolidating provisions that are similar, 30 measures were recognized as described in Table 3.

Table 3: Construction dust measures in 26 cities

<table>
<thead>
<tr>
<th>Categories</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology (TE)</td>
<td>TE1: Enclosure construction; TE2: Vehicle washing; TE3: Sedimentation tank; TE4: Ground surface hardening / greening / covering; TE5: Rational material stacking or storage; TE6: Prohibition of waste incineration; TE7: Prohibition of high altitude throwing; TE8: Prohibition of field concrete and mortar; TE9: Restricting construction during high winds; TE10: Wet work; TE11: Dust collecting system; TE12: Windbreaks hedge; TE13: Sprinkles</td>
</tr>
<tr>
<td>Economy (EC)</td>
<td>EC1: Administrative sanction; EC2: Budgeted overhead expenses; EC3: Levying charges for disposing dust pollutants; EC4: Special funds control</td>
</tr>
<tr>
<td>Supervision (SU)</td>
<td>SU1: Mass media supervision; SU2: Video monitor; SU3: Complaints from the mass; SU4: The third-party supervision</td>
</tr>
<tr>
<td>Organization (OR)</td>
<td>OR1: Dust proof bureau/Steering group; OR2: Establish joint conference system; OR3: Education and training</td>
</tr>
<tr>
<td>Assessment (AS)</td>
<td>AS1: Civilized construction unit competition; AS2: Taking dust control into political achievement system; AS3: Taking dust control into credit system of building market; AS4: Taking dust control into EIA (environmental impact assessment); AS5: Being linked to qualification and irregularities of construction companies; AS6: Being linked to irregularities of clients</td>
</tr>
</tbody>
</table>

Since these measures seem quite different from each other, they can be divided into five important aspects:

- TECHNOLOGY—Measures directly taken by construction enterprises on site (13 measures);
- ECONOMY—Instruments to steer stakeholders’ behaviours by using economic factors influential to the cost-effective (4 measures);
- SUPERVISION—Methods by which various subjects monitor stakeholders to standardize their behaviours during the process of following the legal requirements (4 measures);
- ORGANIZATION—Measures that are conducted to analyze organizational factors in the process of dust management in order to establish the internal accountability system and improve management and operation mechanism (3 measures);
- ASSESSMENT—Measures acting as an instrument to restrict and regulate the activity of individuals, enterprises even governments by making their performance being linked to related evaluation system (6 measures);

5 CONCLUDING REMARKS

The successful control of construction dust has been highly concerned in the domain of green construction. Server air pollution combined with more potential health hazards caused by construction fugitive dust has triggered the governmental alarm. Governments, as owner of public works, should endeavour to reduce dust emissions of their own projects; and have more responsibilities as leaders and supporters of sustainable strategy. In this study, three main role of government played in practices of construction dust management were recognized and analyzed. As policy makers, it is found that governments around the globe should make due response to provide institutional guarantee. By taking China as example, it is found that specific governmental measures suitable to control dust emission varies from one sector to another, including technology, economy, organization, supervision to assessment, which provides guidelines for other countries to formulate policies. However, which
measures governments are more interested in and what measures are major and effective have not explored explicitly. The research findings can pave some ways for future studies on effectiveness of governmental policies on construction dust control.

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VERTICAL DELIVERY CHALLENGES FOR HIGH-RISE BUILDING CONSTRUCTION

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Abstract: As buildings continue to be designed much taller than before, the increasing height of buildings produces problems of vertical delivery in efficiency, safety and cost. To address these challenges, researchers and engineers are applying new technologies and management strategies to improve vertical transportation of resources. This paper discusses state-of-the-art solutions to problems and successful examples of implementation in three selected areas: temporary hoists, concrete pumps, and tower cranes.

1 INTRODUCTION

The vertical delivery of materials and labour on construction sites is mainly achieved using temporary hoists, tower cranes and concrete pumping systems. However, the increasing number of high-rise building projects worldwide has introduced new challenges in vertical delivery (Chang et al. 2011). As the height of buildings grows, the efficiency of vertical transportation drops exponentially, thus affecting the safety, cost and overall schedule of projects. In particular, those sites in spatially-constrained urban areas are limited in the number of equipment that can be installed on site. This paper introduces the development of technology and management methods to enhance the safety and efficiency of on-site vertical delivery.

First, construction temporary hoists are the main method of transporting labour. Unlike materials that can be lifted during the night, workers only can be transported at the time of executing their assigned tasks (Moonseo 2013). Therefore, a significant amount of unproductive time is spent being transported to their designated floors, particularly in high-rise buildings. To counter this issue, current research introduces several methods to support decision making regarding hoist planning and operation. A case study and simulation experiments will show how operational strategies can improve the productivity of a construction hoist and reduce worker delays, which can significantly improve the productivity of labour.

Second, concrete is a common building material that is used throughout a project. Traditional methods of delivering concrete by crane and bucket are constrained by the limited number of cranes and weather conditions. The use of concrete pumps and an innovative method to reduce costs and guarantee constant flow will be highlighted.

Finally, tower cranes are used to lift and/or move heavy materials and large pieces of building components, and can be a big challenge in terms of safety. Special challenges for the use of tower cranes in tall buildings will be discussed.
2 CONSTRUCTION TEMPORARY HOIST

A construction temporary hoist, also known as a temporary elevator, construction elevator, or construction lift, is commonly used in building construction projects to lift materials and labour. For most building projects, hoists are leased or rented by the general contractor. Unlike a permanent elevator, temporary hoists are operated manually by an on-board operator, allowing direction changes or stops at any time according to the operator (Hwang 2009).

Hoists are commonly have single or double cages (1 or 2 cages per tower respectively) with a capacity varying from 25 to 35 people per cage (Chang-Yeon 2009). Capacity is reduced when materials and tools are carried with workers. The growing height of a building, limited number of hoists, and reduced capacity can make workers' movement between floors inefficient, resulting in a significant amount of time wasted waiting for hoists each day. For example, during the peak of construction at the Korea Convention and Exhibition Center in Seoul, South Korea, it took approximately 130 minutes to lift 1200 construction workers to their designated working floors (Moonseo 2013).

Hoist operations are also affected by weather and local regulations, which may restrict hours of operation. Therefore, optimized planning and operation of construction hoists is needed to reduce worker waiting time and improve overall schedule performance. Furthermore, since workers typically begin work simultaneously every morning, the biggest challenge of hoist operation optimization is to solve peak-hour congestion.

2.1 Construction Temporary Hoist Operation Optimization

Vertical transportation of construction workers and materials can be viewed as a cyclic operation, making it suitable for analysis and optimization using discrete event simulation (Ioannou and Martinez 1996; AbouRizk 2010). For the past decade, simulation techniques have proved effective in the development of improved lifting plans (Ahn 2004). The introduction of genetic algorithms to these models (Shin et al. 2010), lead to optimal lifting plans that minimized worker waiting times.

Strategies used in the elevator industry, such as zoning (Newell 1998), can be applied to minimize worker transit time in high-rise construction (Moonseo 2013). Zoning is used to divide buildings into groups of continuous vertical floors. These groups form zones that can be reached only by specifically assigned hoists. In this way, the number of stops each hoist has to make is reduced, and the total time to deliver a workforce is reduced. The challenge with this method is determining the optimal zoning configuration based on continuously changing conditions, including lift demand, floor demand, and number of floors. To solve these issues, a computer simulation incorporated with artificial intelligent and dynamic lifting demand was developed (Moonseo 2013). A case study in Korea shows that the application of zoning can significantly reduce the total lifting time by 40% (300 workers and the completed building height is 240 m).

Another, less restrictive way to reduce lifting times for sites with multiple hosts is to coordinate the hoists by optimizing the stops for each hoist when calls come for a pick up. The scenario of taking workers from the ground floor to their designated floors can be simplified to a travelling salesman problem (Cho 2013), which can be mathematically solved by a branch and bond algorithm. Combined with discrete event simulation, the hoist route becomes the objective of the optimization function. This method has been shown to improve the efficiency of hoist operations (Cho 2013).

Another alternative for dealing with peak hour congestion is to apply staggered arrivals to the workers' daily schedule. Staggered arrivals have been studied in transportation and elevator planning for office buildings (Kamleh 2014) to reduce the queue during morning peak hours. This concept achieves lower overall waiting times. While it is hard to manage arrival times of workers and visitors using elevators in operating office towers, construction sites may have more flexibility. Project managers can arrange staggered work hours to reduce the congestion at the start of the day.
2.2 Construction Temporary Hoist Alternatives

Because the elevator mechanical room is installed at the top of the building, the installation of the elevators happens after the building has been topped off and the roof has been completed and waterproofed. Due to recent developments in elevator technologies, elevators can be used at the early stages of construction by installing mechanical rooms that climb with the construction, eventually becoming the permanent elevator system. These jump lifts provide an alternative to exterior hoists for labour movement with several advantages: the elevators are up to 5 times faster than hoists and are unhindered during extreme weather. However, they are not typically designed to carry the weight of most construction materials, tools and equipment, and they are expensive. As far as the authors have been able to find, the first use of a jump lift in North America is currently underway at One Bloor in Toronto, Canada.

As hoists become the bottleneck of labour transportation during peak hours for high-rise building construction, a smarter and more efficient lifting plan is required to improve hoist productivity. Recent advances in elevator technologies are taking some of the pressure off hoists, allowing them to focus on material and heavier loads.

3 CONCRETE PUMPING SYSTEM

The majority of tall buildings under construction in Canada are concrete. The significant increase in the use of concrete in tall building construction is attributed to improvements in concrete technology including strength, admixtures, pumping, construction techniques and structural systems (Rizk 2010). To accommodate tight construction schedules, hydraulic concrete pumping has developed as a fast and economical method of transporting concrete due to its reduction in labour requirements and the ability to deliver continuous concrete pours (Mechtcherine et al. 2014). The traditional crane and bucket method of delivering concrete is limited by the availability of cranes, the effects of heavy winds, and its inability to deliver a continuous flow of concrete. Pumping methods aim to address these limitations.

3.1 Factors Affecting Concrete Pumping

Concrete pumping for construction purposes is directly related to two major factors, concrete composition and the mechanical characteristics of the pumping equipment. Concrete mix composition affects the properties of fresh concrete such as bleeding, segregation, viscosity, cohesion and compactness (Ngo et al. 2012). These properties have a significant impact on the pumpability of the concrete and the formation of a boundary layer (also referred to as lubrication layer), which forms at the interface between the concrete and the pipe (Choi et al. 2014). This lubrication layer is crucial to reducing the shear stress between the concrete flow and pipe wall to achieve the lower pressures necessary for pumping (Mechtcherine 2014).

Construction concrete is made of cement, water, aggregates, chemical additives and mineral admixtures. The concrete pump applies pressure through a pipe that is made from abrasion resistant material, and drives the concrete through the pipe. The cement paste deforms into the lubricating layer against the internal wall of the pipe. During pumping, this layer surrounds the “plug” along the center of the pipe that is made up of coarse aggregates and cement paste (Mechtcherine 2014). It is important for there to be enough mortar content in the fresh mix to form a lubrication layer throughout the length of the pipe, but that the mix composition remains homogeneous without segregation of the concrete constituents (see Figure 1).

The formation and effectiveness of the lubrication layer is highly dependent on the concrete mix. Another direct effect of the rheology of fresh concrete is the transmission of forces within the concrete plug. For the given equipment, adjusting the concrete mix can achieve lower necessary pumping pressures. Furthermore, using high pumping pressures can alter the properties of fresh concrete. For example, increased pumping pressures can lower air content, which increases the concrete’s plastic viscosity, leading to potential blockages. The challenge that engineers face is to find an optimal concrete mix to
reduce pumping pressure without negatively impacting other functions. There are various ways of optimizing the mix to achieve this (Ngo et al. cited 2012).

- Increasing the water to cement ratio (w/c) of the concrete makes the concrete flow more easily.
- If maintaining the w/c is necessary, increasing the paste volume while maintaining the w/c can achieve similar but less effective results.
- Similarly, a fine sand (0.5 mm) content of up to 10% has a very small effect on the plastic viscosity of the concrete yet improves the concrete’s slump. Beyond a 10% fine sand content however, the viscous constant begins increasing in a linear fashion.

A superplasticizer dosage of approximately 0.4%, which results in a slump of 21cm, produces a linear decrease in the viscous constant. Beyond this dosage, however, superplasticizers have no additional effect on the viscous constant.

![Figure 1 Schematic View of Plug Flow of Concrete during Pumping (Mechtcherine 2014)](image)

3.2 Emerging Solutions

To determine the required pumping pressures of concrete, standard tests such as the slump test or flow table test are used. The results from these tests are used as important inputs for estimation. The issue with this conventional way of determining pumping pressures is that monographs are often unable to account for extreme values of specific parameters, such as long pipe lengths or large spreads (Mechtcherine et al. 2014). More importantly, the concrete mix ratio which has a great influence on concrete attributes is ignored. While the traditional test is a good indicator of the yield stress of the concrete, it is a very poor descriptor of the plastic viscosity, which plays a major role in determining the pumping pressure required. Although concrete testing devices such as rheometers and viscometers can better estimate the palpability of concrete, their complexity and lack of mobility make them unpopular for on-site testing of concrete (Mechtcherine et al. 2014). To better describe the pumpability of concrete with a device that can be implemented in the field, the Sliding Pipe Rheometer (Sliper) was developed (Mechtcherine 2014). The crucial difference Sliper has compared to regular rheometers is its very close adaption to real pumping processes as well as its relatively simple and robust setup.

To further improve the pumping of concrete, testing in which electromagnetic currents are externally applied onto the pipe has been conducted (Choi 2014). This eases the formation of the lubrication layer, contributing to lower pumping pressures and increased flows. The electromagnetic field allows water to move more freely in the mix, and to form a thicker, more efficient lubricating layer. As a result of water's natural polarity, water molecules are typically attracted to each other and form clusters of approximately 100 water molecules at normal temperatures, reaching a thermodynamic equilibrium state between the association and dissociation of molecules in the cluster (Choi 2014). The application of the electromagnetic field allows the molecules to break off into single molecules or smaller clusters, which results in higher activity in the water and facilitates the formation of the lubricating layer. Using a special electronic called control device fluid liner, it was found that the optimal frequency range of the magnetic field was between 80 Hz and 1.1 kHz dependent on the composition of the mixture (Choi 2014). When these magnetic fields were applied, the pressure necessary to achieve pumping conditions was reduced by nearly 30% regardless of the concrete design mix. At equal pressures, pumping with an electromagnetic field resulted in a 15% increase in concrete flow through the pipe.

The reduction in pumping pressure makes it possible to use less powerful pumps, thereby reducing costs and improving the construction of tall buildings by facilitating concrete delivery. Although the magnetic
field was only applied to a 20 m length of pipe, pressure measurements along 1000 m of pipe
downstream showed an approximately linear relationship. This implies that the lubrication layer is
preserved through the piping during the pumping process (Choi 2014). This can be a major benefit for the
transport of concrete in tall building construction.

3.3 Summary

Concrete is a common building material in tall building construction. Advances in concrete mix design and
the implementation of new technologies, such as the application of an electromagnetic field, can help
reduce costs and improve overall process efficiency.

4 TOWER CRANES

Tower cranes are used on construction sites to lift materials or heavy building components. For those
sites located in urban areas, crane activities are confined, and any accident can lead to serious
consequence to workers and pedestrians. The use of tower cranes during tall building construction is
even more challenging because the increasing height adds problems of visibility, wind load and safety
issues for the operator.

4.1 Visibility Problems

Increased height often comes with visibility problems due to congested construction sites, the location of
the crane cab, and intensified weather conditions. Limited visibility forces the operator to rely on radio
communications when they are unable to see the load or the crew providing hand signals. In these cases,
communication, responses, and productivity become slower. Typical visibility problems include blind lifts,
sight distance, and poor weather.

- Blind lifts occur when crane operators experience partial obstruction of the loading or unloading
  working zone or the travel path (Shapira and Lyachin 2009). In these cases, the reliance on signals
  and radio communications to guide the lift becomes necessary, but it brings an increased risk of
  misunderstandings and accidents.
- Tower crane operators enjoy a bird’s eye view of the construction site, which contributes to good sight
  coverage of the site. However, as the height of the tower crane increases with the building, the
  operator’s perspective of the loading and working zone becomes nearly vertical, thereby losing some
  depth perception. Additionally, the operator’s ability to distinguish details decreases with the distance
  to the target. Long sight distances and vertical sight angles lead to difficulty in precise lifts or
  placements, which forces operators to depend on signals and increases the risk of accidents (Shapira
  et al. 2008).
- Poor visibility due to lighting or weather is an important contributor to crane problems. Operators
  sometimes have to work during dawn, dusk, night, or in direct or reflected sun glare (Shapira et al.
  2008). These circumstances reduce their ability to distinguish their target from the surrounding visual
  noise. This can cause eye fatigue and visual images to be blurred. Weather-related visibility problems
  may also result from heavily overcast skies, rain, snow, fog or dust. Visibility works both ways as
  operators may be challenged to see the loads that they are lifting, while others are challenged to see
  the tower crane. For example, in 2013, a helicopter hit a tower crane atop a 235m building that was
  under construction in central London, UK (BBC 2013).

Recent research has made progress in developing 3D and 4D simulation tools to optimize tower crane
and other equipment layout to reduce obstacles for operators during construction (Al-Hussein et al. 2006).
However, planning strategies have limitations in real-time management. New technologies have been
deployed on cranes to monitor their operations using wireless sensors and GPS (Kim et al. 2003). Proper
training of operators by increasing their situational awareness of construction site layouts has proven
effective in reducing accidents (Cheng and Teizer 2014).
4.2 Wind Loading Effect

Working at heights is also associated with higher wind speeds. Wind speeds may be represented using the power law, shown in Equation 1 (Sen et al. 2012), where $Z$ is the elevation, $V$ is the wind velocity ($V_2 > V_1$), and $n$ is the exponent that represents local climatology, topography, surface roughness, environmental conditions and weather stability.

$$\left(\frac{Z_1}{Z_2}\right)^n = \left(\frac{V_1}{V_2}\right)$$

Using average winter wind speeds for downtown Toronto shown in Table 1 (Environment Canada 2003) as the reference speeds for $Z_1=30m$ and $Z_2=80m$, an exponent of $n=0.34$ was calculated. This is a reasonably good fit with the general estimate of $n=0.4$ for a city area with tall buildings (Sen et al. 2012). With those two exponents, the average winter wind speed at 150m above ground level, or approximately 50 storeys, can be extrapolated using the power law as being between 8.0 and 8.8 m/s, almost double the speed at 30m. At wind speeds greater than average, there is a significant danger in underestimating the impact of doubling the apparent wind at ground level when lifting large loads up a tall building.

<table>
<thead>
<tr>
<th>Building height above ground level (m)</th>
<th>Average wind speed in winter (m/s)</th>
</tr>
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<tbody>
<tr>
<td>30</td>
<td>4.6</td>
</tr>
<tr>
<td>50</td>
<td>5.4</td>
</tr>
<tr>
<td>80</td>
<td>6.4</td>
</tr>
<tr>
<td>150</td>
<td>8.0-8.8</td>
</tr>
</tbody>
</table>

Operation guidelines (not regulations) for tower cranes often cite 13m/s (30 miles per hour) as a maximum wind speed for crane operations, with warnings that operations may cease at 9m/s if conditions warrant (Worksafe BC 2015). This may be in consideration of the changes in wind speed with height that may not be obvious on the ground. Although the tower crane is designed to withstand much higher wind speeds while out-of-service, in-service wind speeds are lower because of the effect the wind has not only on the crane itself, but also on the load that it is lifting. Therefore, high wind speeds can increase the frequency in which cranes are out-of-service. Since heavy components such as glass curtain walls or concrete beams are primarily transported by tower cranes, their serviceability directly affects the overall schedule.

The wind can exert a significant load on the crane structure itself (Watson 2004) depending on the direction of the wind relative to the jib and on the size, weight, and proportions of the item being lifted. Formwork, for example, may impose forces well in excess of its weight if the load is moved by the wind from its expected position directly below the jib block. If the wind is from the side, then the displacement causes side loading of the jib, something for which it may not be designed to withstand. If the wind load is from behind, the movement can increase the load radius beyond the end of the jib and significantly reduce its capacity (Watson 2004). Additionally, high winds can cause movement of the load and directly strike workers or pedestrians. A moving load can also cause equipment or materials to fall when struck by the load and result in injuries. In 2008 in downtown Toronto, the cable from a derrick crane on the top of a topped out but not yet complete 51 storey building was caught in winds from a winter storm and broke windows between the 30th and 40th floors of the tower, showering glass at ground level (Reinhart 2008). The increased length of the crane’s tower and jib highly increase the complexity of its structure, making structural analysis more difficult, and causing more problems while installing and dissembling. Any malfunction of an element could cause the failure of whole structure, leading to a catastrophe.

Another potential hazard is the behavior or wind load on a tower crane when erected alongside a building (Mara 2010). The presence of the tower crane alongside the building significantly changes the aerodynamics of the building because the tower crane alters the geometric cross section of the building.
Based on a wind tunnel study (Mara 2009; Mara 2010), two recommendations were made to minimize wind loading effects on tower cranes.

- First, the location of tower cranes shall be restricted to the middle portion of a building face to reduce torsion forces on the crane. When tower cranes are placed near the center of building face, the wind load on the crane will match that of the building. As the cranes approach the edge of the building, the mean and fluctuation values of torsion forces significantly increase.
- Second, the tower cranes should be located along the leeward face of the building to reduce the wind loading due to the shielding effect provided by the building.

4.3 Safety Management

The main causes of tower crane accidents are carelessness, negligence or misjudgment of participants, inadequate training, sub-contracting operators, and pressure from tight schedules (Tam et al. 2011). Carelessness is often cited in conjunction with other factors, such as working too close to a high-voltage line or being struck by a moving load (McCann 2009). Therefore, safety management and safety culture on site are crucial for the decrease of accident rates related to tower cranes. The following factors influence on-site safety performance.

- The length of work shift for tower crane operators usually extend beyond normal working hours because materials are often delivered before and after work hours. Hence, the crane operators are typically the first to arrive and the last to leave. Further, due to the time and effort required for operators to get into the crane cab, managers tend to minimize shift changes. The long, repetitive, and monotonous work may cause the crane operator to lose focus and alertness. With the increase of both physical and mental fatigue, the chances of accidents increase as well (Shapira and Lyachin 2009).
- Operator aids includes crane monitoring and the information received from signalers and crews. Communications between operators and signalers are usually achieved by radio or similar technologies, where the instructions from a signaler plays an important role. Hence, signaler shall be trained to properly instruct crane operations. Crane safety monitoring systems include digital-display load indicators, 2D/3D crane operation graphic displays, GPS based weather and wind warning systems, anti-collision and zoning systems for sites with overlapping cranes, and video cameras that enable the operator follow the review of loading (Peurifoy 2002; Shapira et al. 2008, 2009). These new technologies often compensate for human fallibility and prevents accidents (Neitzel et al. 2001).
- Human resource management helps to ensure that the operator has the characteristics required to ensure a safe working environment. Objective measures of operator skills include formal training and certifications, accumulated experience and safety record (Shapire 2008).

To sum up, the chances of tower crane-related accidents significantly increases when safety management is deficient. Tower crane safety can be achieved through site-level and company-level actions. Site-level actions include training, preventive actions, monitoring, on-going inspections and balanced rewards and punishments (Ng et al. 2005). Safety for company-level management are usually measured by the allocation of resources, planning and scheduling, and strictly enforced inspection policies and procedures. (Shapira 2008).

5 CONCLUSION

Vertical delivery has a significant effect on the overall performance of the schedule for tall building construction projects. To address this challenge, technologies and management strategies are being developed to improve the efficiency and safety performance, while at the same time reducing the cost of vertical transportation on construction sites.
REFERENCES


DECONSTRUCTION AND MAINTENANCE OF STEEL BRIDGE USING FATIGUE DATA AND BIM

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Abstract: Design for deconstruction is one of the emerging concepts for sustainability. For existing structures, the concept can be extended to optimize maintenance schedule for different components. Many existing steel bridges are at a stage in their lives where decisions need to be made to either continue in existing condition, to strengthen or to deconstruct them. This decision is highly dependent on the fatigue resistance of the steel connections which is a function of remaining structural strength, service load, expected future use and other environmental factors. Over the years a great deal of research work has been done in assessing the fatigue life of steel structures. This study utilizes these fatigue information to carry out a life cycle assessment of bridge elements and layer the system using BIM. As the BIM system will apply economic analysis for maintaining the bridge versus deconstructing and rebuilding of a new bridge, it will be instrumental to optimize the decision on any intervention in the bridge.

1 INTRODUCTION

A large number of steel bridges were constructed in the last 100 plus years and many of these bridges are still in operation. Many existing steel bridges are at a stage in their lives where decisions need to be made to either continue in existing condition, to strengthen them or to demolish them. The decision making process is dictated mainly by remaining serviceable life of the bridge. Fatigue is one of the key factors that need to be assessed in making decision about the bridges. The fatigue life, in turn, is a function of remaining structural strength, service loads, expected future use and other environmental factors. There exist many standards and approaches for bridge evaluation and one of the widely used approach is AASHTO (2011).

The construction and demolition industry accounts for 25-30 per cent and sometimes more than 50 per cent of the municipal solid waste in Canada (Yeheyis et al., 2012). Design for deconstruction is one of the emerging concepts for sustainability (Morgan and Stevenson, 2005; Shell et al. n.d.). As the structure, buildings, bridges and other infrastructure, constructed in the industrial boom of 20th century are coming to age, a comprehensive approach in assessing their remaining lifespan, function and re-usability is essential. Although the design for deconstruction has so far been limited to design of new buildings with view of optimizing deconstruction, the concept should be extended to sustainable use of existing infrastructure.

For existing structures, the concept of design for deconstruction should be extended to assess remaining life-span, optimize maintenance schedule for different components and increase function and life-span of the structures. Many existing steel bridges are at a stage in their lives where decisions need to be made...
to either continue in existing condition, to strengthen or to deconstruct them. This decision is highly
dependent on the fatigue resistance of the steel connections which is a function of remaining structural
strength, service load, expected future use and other environmental factors. Over the years a great deal
of research work has been done in assessing the fatigue life of steel structures. This study utilizes these
fatigue information to carry out a life cycle assessment of bridge elements and layer the system using
BIM.

A fatigue evaluation in bridges involves numbers of uncertainties and the practice, in general, has been to
assign a conservative fatigue life. The conservative consideration is reflected in the fact that “some
bridges with satisfactory service history are accordingly determined to have negative remaining fatigue
lives (NCHRP, 2012).” NCHRP (2012) mentions that “a number of factors may have contributed to this
conservatism: overestimated load distribution factors, unintended composite action ignored, the S-N
curve’s lower bound being used, etc.” However, not all cases of fatigue evaluation are believed to be
overly conservative. For example, truss or two-girder bridges carrying more than one lane of traffic may
have un-conservative fatigue life estimates because of the single lane loading prescribed in the MBE.
When multiple lanes are carried by the two trusses or girders, the fatigue life may be significantly
overestimated because possible simultaneous loads on other lanes are ignored (NCHRP, 2012).”

Maintenance and rehabilitation of the steel bridges require a comprehensive evaluation scheme for
decision making. Building information modelling (BIM) “is a digital representation of physical and
functional characteristics of a facility. A BIM is a shared knowledge resource for information about a
facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest
conception to demolition (NBIMS).” Overall scope of BIM, as outlined in NBIMS (2007), has three
categories: BIM as product for digital data representation, BIM as a collaborative process and BIM as a
facility lifecycle management tool. As BIM is gaining wider popularity in the construction industry,
extension of its application in evaluation, maintenance and rehabilitation of bridges will be instrumental to
support the decision making process. There already exist a number of such methods, schemes, tools and
approaches for this purpose; however, a comprehensive BIM approach is still not completely developed.

This paper presents a scheme of applying BIM in assessing fatigue life of steel bridges and applying that
information in BIM model to support decision making process. The system includes gathering field data,
applying the data for create drawings, develop finite element models from the drawings, assessing fatigue
life of the bridge and applying that information to make decision about status of the bridges.

2 INFORMATION MODELLING

The process used in the BIM is shown in the flow chart in Fig. 1. The first phase is the collection of data
from existing bridges, and then using this information an AutoCAD drawing is creating that is
representative of the bridge connection to be modeled. The AutoCAD drawing can be imported into a
finite element modeling software such as AutoDesk Simulation Mechanical. The model is loaded and the
necessary boundary conditions are applied and the stresses are obtained as the output from the finite
element analysis (FEA) software. The elastic stress concentration factor is then obtained by dividing the
maximum stress (in this case the maximum principal stress) by the nominal applied stress as used and
proposed by Wokem (2010) and Pilkey (1997), respectively. Using this information the fatigue life at any
instant of the bridge connection can be obtained and hence the remaining life of the bridge connection
knowing the load history of the bridge. Decision can be made based on the remaining fatigue life of the
connection whether to maintain or deconstruct the bridge. These decisions can be influenced by a lot of
factors such as how many connections are near to the end of their fatigue life within the same bridge, cost
of deconstruction, and importance of the bridge for traffic amongst others. The fatigue life of the
connections will give very useful information to guide this decision making process.
3 STEEL BRIDGE INFORMATION

For the purpose of this study, bridge samples constructed in early 20th century were considered. These bridges are constructed using riveted joints with or without staggered arrangement of the rivets (Fig 2 a, b).

Although presence of tack welds has significant effect in fatigue life of a riveted joint, the welds are not easily visible and their presence, strength and contribution cannot be easily ascertained. Furthermore, contribution of tack weld is to increase fatigue life resulting in conservative estimate of the remaining life. The effect of tack welds in this case is therefore not accounted for in this study. However, once the
presence of tack welding and its effect is ascertained, it is a simple process to include that in the BIM process discussed in this paper here.

4 NUMERICAL AND ANALYTICAL MODEL

The drawings of the bridge connection as shown in Fig. 2 a. and finite element model of the same the same connection are shown in Fig. 3. Drawing, in this study, has been accomplished using AutoCAD and the finite element modeling is done using Autodesk Simulation Mechanical.

![Figure 3: A typical rivet connection in a steel truss bridge is drawn in AutoCAD, exported to Autodesk Simulation Mechanical for FEA to obtain stress and strain information.](image)

4.1 Model geometry and the material properties

The typical angle connection of a bridge was modeled in AutoCAD. The equal leg angle connection had a dimension of 102 mm and a thickness for the angle was 12.7 mm. The gusset plate had a thickness of 12.7 mm. The analysis was elastic. The material properties used in the modeling was; Young's modulus of 200,000 MPa and a Poisson's ratio of 0.29. The rivets were modeled using the bolt command in the Autodesk Simulation Mechanical and a rivet diameter of 20 mm was used and a rivet head of 25 mm was specified for the simulation.

4.2 Finite element mesh

The angle and the gusset plate were modeled using a plate element. The rivet hole had a finer mesh size of 1 mm and the other parts of the connection detail were modeled with coarser mesh. The finer mesh was used around the rivet hole because the maximum stress is expected to occur in these holes rather than in any other part of the connection.
4.3 Load and boundary conditions

A stress of 200 MPa was applied to one end of the angle and the gusset plate. The gusset plate had the other end fixed. The leg of the angle that was not attached to the gusset plate was restrained from translating in the z-axis and the x-axis, and also there was no rotation about the y-axis in the leg. The angle leg attached to the gusset plate was not restrained at all.

4.4 Finite element analysis result

Fig. 4 shows the finite element analysis result for the bridge detail. A maximum principal stress of 706.51 MPa was obtained for an applied load of 200 MPa. The maximum principal stress occurred in the gusset plate and at the first hole closest to the point of application of the tensile stress in the detail. The results show that the first and the last holes had the highest stress concentration.

![FEA model showing location of maximum principal stress](image)

Figure 4: FEA model showing location of maximum principal stress

5 FATIGUE ANALYSIS

Autodesk Simulation Mechanical was used to obtain the maximum stresses and hence the stress concentration was obtained by dividing the maximum principal stress in the detail by a nominal applied stress, and fatigue strength of the typical connection type shown in the Fig. 3. The output from the finite element analysis and calculation of fatigue life as proposed in Bannantine et al. (1990) is shown below.

Calculations for the fatigue Life
Applied stress on the FEA = 200 MPa
Maximum Principal stress = 706.51 MPa (Obtained from FEA)
Maximum von Mises stress = 712.34 MPa (Obtained from FEA)
Ultimate strength of Steel = 400 MPa = Su
Kf = Max principal stress/gross section stress = 3.53
Assume notch sensitivity factor of q=1, therefore Kf = Kf = 3.53
For Steel (from Bannantine et al. 1990):
at 1000 cycles, S1000=0.9Su = 360 MPa
at 1000000 cycles S = 0.5 Su = 200MPa
Now accounting for the stress concentration from the FEA the new S-N curve becomes

<table>
<thead>
<tr>
<th>Fatigue Life, N (Cycles)</th>
<th>Stress, S (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>56.66</td>
</tr>
<tr>
<td>1,000</td>
<td>101.98</td>
</tr>
</tbody>
</table>

Using the new S-N (from Table above) and the following equations (Bannantine et al. 1990) the fatigue life can be obtained:

\[ N = 10^{-c/b} S^{1/b} \]  
\[ C = \log \frac{s_{1000}}{s} \]  
\[ b = -0.333 \log \frac{s_{1000}}{s} \]  

A hypothetical case is shown below as an example to demonstrate fatigue life of a bridge. A bridge has the connection type modeled; the loading in the bridge was converted to an equivalent fully reversed stress of 70 MPa. What will be the life of the bridge at this time given that it is subjected to 1000 equivalent constant stress cycles per year?

**Solution**

From the equations above

\[ C = 2.264, \text{ and } b = -0.085 \]

Hence \( N = 8.48 \times 10^4 \) cycles

Therefore the bridge fatigue life is 84.8 years. The S-N curve for the detail is shown in Fig. 5. If the same bridge is subjected to an equivalent fully reversed stress of 69.02 MPa, then either by using Eq.1 or the S-N curve in Fig. 5, the fatigue life of that detail is 100 years given the same stress cycles per year of 1000.
6 BIM MODEL

Building information modelling (BIM) "is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (NBIMS)." In this paper a combination of picture representation, drawing and FEM tools (AutoCAD and AutoDesk Simulation Mechanical from AUTODESK) and spreadsheet (MS-Excel) is used to represent the data, to analyze the stresses and to evaluate the life-cycle of a typical rivet connection of a steel bridge. The schematic diagram is shown above in Fig. 3 and a screen capture from spreadsheet is shown below in Fig. 6.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Picture</th>
<th>Drawing</th>
<th>Analytical model</th>
<th>Stress concentration factor</th>
<th>Equivalent stress</th>
<th>Stress cycle</th>
<th>Bridge fatigue life</th>
<th>Remaining life</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>![Joint 1 Picture](100x393 to 171x453)</td>
<td>![Joint 1 Drawing](251x468 to 324x528)</td>
<td>![Joint 1 Analytical model](258x387 to 317x460)</td>
<td>3.53</td>
<td>70 MPa</td>
<td>1000</td>
<td>84.8</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>![Joint 2 Picture](72x468 to 170x528)</td>
<td>![Joint 2 Drawing](98x468 to 170x528)</td>
<td>![Joint 2 Analytical model](98x468 to 170x528)</td>
<td>3.53</td>
<td>69 MPa</td>
<td>1000</td>
<td>100</td>
<td>20 yrs</td>
</tr>
</tbody>
</table>

Figure 6: A schematic model showing hypothetical case of two typical bridge connections and calculation of remaining life from fatigue analysis. In this example, considering a hypothetical case in which the bridge has served 80 yrs of life, joint 1 has 4.8 yrs remaining life and joint 2 has 20 yrs remaining life. Joint 1 is critical needs immediate attention.

7 DISCUSSION AND CONCLUSION

As the structure, buildings, bridges and other infrastructure, constructed in the industrial boom of 20th century are coming to age, a comprehensive approach in assessing their remaining lifespan, function and re-usability is essential. Although the design for deconstruction has so far been limited to design of new buildings with view of optimizing deconstruction, the concept should be extended to sustainable use of existing infrastructure. BIM, which is not only data representation and storage system but also a life cycle management tool, needs to be extended to assess remaining life of infrastructure which will help in decision making of the continuing use of the infrastructure. In this paper a model is presented to analyze remaining fatigue life of bridge using drawing tools, Finite element analysis tools and spreadsheet application in assessing critical joints for bridges. The model can be further extended to include other factors such as serviceability condition, existing condition of infrastructure and functionality of the structures before making a final decision on how to optimize life-cycle of the infrastructure in question. In a bridge the is invariably going to be several connection details, and hence a BIM system is essential to track the connection type, the stress concentration, the fatigue life, and hence information on maintenance or deconstruction can be made in time.
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VALUE-ORIENTED APPROACH TO HOME ENERGY ASSESSMENT PROCESS DESIGN

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Abstract: While significant investments have been made to advance energy auditing methods to reduce energy consumption in the residential sector, homeowners are still challenged to take action and realize energy savings on their utility bills. Key challenges facing homeowners in need of energy efficiency improvements were found to be: 1) lack of information, 2) lack of financing, and, 3) lack of skilled workforce (2009 CEQ report). Recent research examining home energy auditing has revealed significant process waste, including audits that do not lead to energy upgrades; distrust between auditors and homeowners; a tendency for audits to lead only to one time improvements as opposed to continuous improvement. In response, variable types of home energy audit practices and strategies are emerging, including standardization of training and rating programs, as well as alternative methods to lower the costs of audits through partial “assessments.” This research takes a value-oriented approach to study the energy audit process of residential homes, and seeks to elevate the effectiveness and efficiency of home energy assessments through process design. The objectives of this research are: 1) To characterize “on-site” value delivery during a 90 minute home energy assessment, 2) to present relationships between building trust and deliver value via a model, and 3) to explore how these trust-value relationships influence homeowners’ decision making to take action in a manner of home improvements. In addition to home energy audit sectors, elevation of value distribution and trust relationship in a productive process, not only enhance distributing characterized value during operation, but also increase identification of linkages between specific tasks and the accumulation of trust leading to action on behalf of participants in the design and construction industry.

1 INTRODUCTION

The purpose of a home energy assessment process is to identify and prioritize opportunities to improve energy efficiency in a manner that leads to action on behalf of the home occupant. Challenges facing the home energy assessment process include information barriers, available finances to invest in energy upgrades and trust relationship (Palmer, Walls, Gordon, & Gerarden, 2013). Past approaches in addressing these challenges have included homeowner outreach and education programs, weatherization training programs, and standardization of methods to characterize home energy assessment methods. Many of these approaches focused on the physical characteristics of homes, instead of occupants conditions. Opportunities exist to improve assessment processes, based on unique conditions in homes and homeowners, in a manner to generating value for both homeowners and energy efficiency service providers. Womack and Jones (J.P Womack & James, 2006) define value as: “a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer.” Unlike objective characters of products, the provision of services has a nature of intangibility. Customers often have little idea what to expect until they consume it, and typically perceive a service as a risk. Research into the exchange of value within service-focused industries has demonstrated that trust
helps raise consumer comfort in situations characterized by a high degree of risk, uncertainty, or lack of knowledge or information, during interactions between customers and service providers (Coulter & Coulter, 2002).

While significant research has been focused on standardizing the energy audit process, limited effort has been invested in subjective characters of service, such as trust cultivation during the audit process. Trust relationships are notable as a critical success factor in any service relationship (Coulter & Coulter, 2002). This research focuses on value distribution related to build trust relationship during home energy audit processes, as well as to indicate the relationships between invested effort in a manner of time spend in an audit process and the measurement of value- trust conversion involving in homeowners’ decision making system that leads to energy related home improvements. The specific objectives of this research are to: (1) Define and characterize the value dimensions and value adding processes of a home energy audit, (2) Construct a value conversion model with uniquely defined trust attributes that can be used to indicate value- trust conversions taking place during an in-house walkthrough inspection.

2 RESEARCH BACKGROUND

In the United States, the majority of residential housing is comprised of single family homes; and a large number of these homes were built prior to the development of energy codes. The U.S Energy Information Administration (EIA) states that the total energy consumption in the U.S, 2013 was 97.53 quads, or about 21.1% of the nation’s energy consumption came from the residential sector, followed by the transportation (27%), industrial (31.5%) and commercial (17.9%) sectors (EIA, 2013). In a study by the White House Council for Environmental Quality, key challenges facing homeowners in need of home energy efficiency improvements were found to be: 1) a lack of information, 2) a lack of financing, and, 3) a lack of skilled workforce to make home energy upgrades (2009 CEQ report). Since the time of this report, significant investments have been made to reduce energy consumption of the residential sector, including training of home energy auditors and weatherization workforce, as well as incentives and aid programs for home energy upgrades. While valuable opportunities, the role of the homeowner in making informed energy upgrade decisions is critical to the effectiveness of the outcomes.

The most well-known authorities in residential energy assessment are the Residential Energy Service Network (RESNET) and the Building Performance Institute (BPI). Both have developed assessment approaches and certification for professional auditors. However, the current energy audit approaches do not meet market demand, a survey of nearly 500 home energy auditors and contractors revealed that: 64% indicated that “homeowners lack an understanding about the information audits provided”; 50% stated that homeowners are “unaware that energy audits exist”; 74% stated that homeowners “cannot afford the upgrade that would be recommended”; 40% cited the high actual or perceived cost of audits; and close to 25% respondents believe the reason is due to a “lack of trust in the reliability and accuracy of an audit.” According to the research, almost 30% of survey participants stated that “half or more of their clients do not make any of the suggested improvements recommended in an audit.” (Palmer, Walls, Gordon, & Gerarden, 2013). Riley et al. (2012) state that notable inefficiencies of the home energy assessment process involving barrier categories, these include:

- **Process waste**: Wasted effort conducting audits that do not lead to upgrades, extensive diagnostics that do not provide value or are not understood by the customer
- **Information barriers**: Incoherent/confusing delivery of energy assessment information to homeowners, lack of understanding by homeowners on how to pursue improvements
- **Trust barriers**: Distrust due to poor communication, lack of understanding of customer behavior / choices by auditors, and infrequent or one-off approach to customer service

In an effort to reduce these barriers during a home energy audit, a value-oriented light-touch home energy assessment is introduced to enable flexibility, efficiency and effectiveness of in-house walkthrough. This approach emphasizes the execution of value adding processes that contribute to an efficient assessment process that maximizes the chance of action on the part of the homeowner.
3 THE OBJECTIVES OF THE NATIONAL ENERGY LEADERSHIP CORPS (NELC)

The National Energy Leadership Corps (NELC) is an education and research program aimed at the transformation of how homeowners think and act regarding energy decisions in their homes and other buildings, and provides the platform to examine the improvement of value delivery that is discussed in this research. The NELC program is designed based on expert input from home energy audit and weatherization programs, and research conducted on multiple approaches to engage homeowners in the delivery of low cost, meaningful, and scalable home energy assessments. The specific program objectives of the NELC are to:

1. Create a trusted network of 3rd party energy coaches who are capable of engaging homeowners in personalized home energy assessments;
2. Cultivate fundamental energy literacy for citizens through engagement of entry-level students and homeowners of all ages and demographics;
3. Enable scaled delivery of assessments at little to no cost to homeowners through the use of state-of-the-art practices and intelligent support tools; and,
4. Provide an on-ramp to credentials and careers in building energy efficiency and management.

These objectives are pursued through the development and deployment of curriculum, support tools and a supporting program infrastructure that enables instructors of multiple types of energy and sustainability-focused courses to integrate a student-led home energy assessment project into their curriculum. The program includes: (1). online learning modules that provide self-paced on-demand learning, (2) flipped classroom model to enable discussion and hands-on training in class, and (3) technical tools to facilitate data collection and report delivery, such as an I-pad application, energy efficiency measurement database, and web-based energy profile for homeowners to track utility usage and home improvements.

4 DECISION-MAKING AND VALUE DEFINITION

The implementation of energy upgrades reflects homeowners’ decision making processes. The study of value distribution in a home energy assessment can be pursued through decision theory and decision making processes involving a value-based approach. The decision theory methods contribute to increased accuracy in decision making by building a systematic structure into data gathering and analysis (Claudio et al. 2014). Two key elements to approaching a decision making process include: 1) Identify alternative options, 2) Determination of expected outcome on each option and the expression of values. With this approach, the decision makers are allowed to prioritizing from among a list of probable consequences (R. L. Keeney, 1971). A preferred decision is “the option whose expectation has the highest value” (Hazelrigg, 1998), which reduces the level of uncertainty by individuals in complex settings. Uncertainty can be stated as lack of understanding, incomplete information, lack of experience, or having no clear preference among several alternatives (Claudio et al., 2011b). “Value adding process” is a term referring to a set of activities which transfer an input into an output that is has increased value. Carol Sanford expands the term of value adding process as an ongoing value creation for stakeholders. The creation of value depends on continual improvement on how well the process serves stakeholders (Sanford, C., 2011), including users, co-creators, the environment, community, and investors.

The complex nature of homes as systems, coupled with the unique settings of individual households, an approach to value distribution seeks to align value adding processes with the unique types of value needed to support decisions made by homeowners to implement home energy improvements. This research seeks to categorize value dimensions in a manner that allows customization for specific circumstances. Examples of unique circumstances that may inform assessment process design include: market intelligence about homes or homeowners, specific services being promoted by energy service professionals, and opportunities to implement regionally available weatherization assistance programs.

4.1 Effort and the Concept of Home Energy Assessment Efficiency

When considering value in a home energy assessment, it is worthwhile to consider the effort invested in an assessment and the initial concept of assessment efficiency. As described in Lean principles, the goal of an assessment should be to maximize Value Adding Processes while also expending the minimal
Effort to be needed to enable these processes. “Effort” is introduced as an investment that can be measured in a variety of ways, including time and money. In the case of this research, effort is measured in time, specifically time spent during the home energy assessment. Total assessment effort expended includes all of the time spent by auditors on the physical home energy assessment, which is expected to be approximately 90 minutes in the NELC program. It is inevitable that only some of this time and effort contributes to the generation of value adding processes, and that some of this time is wasted, such as time spent waiting or looking for a misplaced tool, whereas, there is time spent on necessary but non-value adding, such as travel time between zones of a home. The study and categorization of effort in time invested into a home energy assessment systematically elevates the benefits of customize the assessment process for homeowners individually, and highlights value conversion in the inspection system. The elimination of waste effort spending on unnecessary tasks is also more feasible. For example, an assessor spends less time evaluating recently replaced equipment and spends more time on tasks that are related to homeowners’ expressed concerns, as well as the selection and representation of recommendations of home improvements based on homeowners’ market segmentation and worldview. Equation 1 is created to express the transformation from Effort in time to value adding effort, non-value effort and wasted effort.

Equation 1: Effort equation of value and non-value adding processes

\[ T_{\text{effort}} = V_{\text{effort}} + NV_{\text{effort}} + W_{\text{effort}} \]

Total effort \((T_{\text{effort}})\) = time spent on assessment (minutes)

Value adding effort \((V_{\text{effort}})\) = time spent or invested on the generation of value (minutes)

Non-value effort \((NV_{\text{effort}})\) = time spent on necessary but non-value adding activities (minutes)

Wasted effort \((W_{\text{effort}})\) = time spent on unnecessary and non-value adding activities (minutes)

Building on this foundation, the concept of assessment efficiency is introduced as useful metric that can be described as Equation 2 below.

Equation 2: Definition of Assessment Efficiency

\[ \text{Assessment Efficiency} = \frac{V_{\text{effort}}}{T_{\text{effort}}} \text{ in a manner of time (minutes)} \]

While assessment efficiency can be calculated through the use of time, the variability of value adding processes with respect to their contribution to action on the part of homeowners is significant and often unmeasurable. This research emphasizes the development of improved understanding of value dimensions and value adding processes as an approach to improving the design of home assessment processes and practices. Definitions of value in home energy assessment and trust attributes are introduced below to help better define how value adding effort leads to the outcome of decision making.

4.2 Value Definition of Home Energy Assessment

“Value refers to any aspect of a potential product that could influence the likelihood that customers would purchase that product” (Ralph L. Keeney, 2004). In the exchange of “value” within client customer relationships, the service sector, such as those services provided by an energy auditor, are defined heavily by the level of trust the client has in the recommendation of the service provider. Different industries have unique definitions of “value”. Womack (Womack, 1996) in their presentation of Lean theory define value as: “a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer.” Neap (Neap & Celik, 1999) also defined value as the “fair equivalent in service or commodities that an owner/buyer receives in exchange for money.”

To categorize value, this research adopts the value definition cited by John Kelly (Kelly, Male, & Graham, 2004), in the book of “Value Management of Construction Projects”, that value can be categorized into two dimensions - “objective value” and “subjective value”. **Objective value** refers to a measure of the
input resources used to create a physical component, object or service, such as units of cost, mechanical-related effort, information and resources. Examples of objective value creation in a home energy assessment include the gathering and exchange of information about the conditions of a home, and priorities of homeowners. **Subjective value** refers to the desire to obtain or retain an item, or how much the owners/buyers are prepared to pay for prestige, appearance, aesthetic, judicial, religious or moral reasons (Neap & Celik, 1999). In a home energy assessment, subjective value may take the form of the trust developed between the homeowners and the service provider, and is created through the means and methods delivering an audit. Subjective value strongly related to service providers’ personalities and delivery style, such as the approach to communicating with homeowners, how well they explain issues, and the demonstration of respect.

The concept of decision making and identifying the objectives of home energy assessments is a critical approach to defining value delivery. The initial objectives of a home energy audit are to: 1) inspect house conditions to assess opportunities to improve home safety, health and efficiency, and, 2) develop trust relationship with homeowners. Figure 1 illustrates the integrated concepts of invested value in an assessment, objectives of value of home energy audit, and value dimension as an initial framework of value model. Terms of Value of exchange ($V_{\text{exchange}}$) and Value of trust ($V_{\text{trust}}$) are introduced to define the objectives of the audit with its associated value dimensions. In layers of value categories in a home energy assessment including invested effort categories of Value adding effort ($V_{\text{effort}}$), Non-value effort ($NV_{\text{effort}}$), and Wasted effort ($W_{\text{effort}}$), the objectives of value, and dimensions of value.

![Diagram showing the initial framework of value model](image)

**Figure 1**: initial framework of value model: Layers of value types of home energy audit. Value adding processes ($V_{\text{effort}}$) yields instances of value transitions ($V_{\text{exchange}}$ or $V_{\text{trust}}$).

Value adding processes in home energy assessments take many forms, but can be classified based on objectives of value and dimensions of value, and the number of instances they take place during an assessment. Through observations of assessments over time, over sixty unique instances of value adding processes have been identified with corresponded categories of Vexchange, and Vtrust. In each case, the value adding processes are linked to a discreet task or transaction during a home energy assessment in which Vexchange, and/or Vtrust can be clearly identified. A deeper exploration of the types of value adding processes that take place during assessment and how they contribute to the generation of trust make up the remainder of this paper. Table 1 presents two examples of value adding processes that can be uniquely identified, corresponding descriptions of how value is generated, and the categorization of objectives of value ($V_{\text{exchange}}$ or $V_{\text{trust}}$) and dimensions of value (subjective or objective).
Table 1: examples of value adding effort and the corresponded value dimensions and objectives

<table>
<thead>
<tr>
<th>Example of value adding process identified in an audit</th>
<th>Descriptions of how value is generated</th>
<th>Objectives of Value</th>
<th>Dimension of value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify envelope penetrations that are in need of air sealing</td>
<td>Penetrations which result in a large (amount) percent of unwanted heat gain/loss are detected and can be addressed through air tightening measures</td>
<td>V exchange</td>
<td>Objective</td>
</tr>
<tr>
<td>Demonstrate active listening to homeowner by repeating and directly responding to information they have shared</td>
<td>Demonstration of listening and responsiveness to homeowners helps to build trust relationships</td>
<td>V trust</td>
<td>Subjective</td>
</tr>
</tbody>
</table>

4.3 Trust Attributes of home energy assessment

The home energy audit is performed as a type of service in the construction industry. Customers have an inherent need to trust in their service provider to deliver the desired service outcome. Trust is one of the key predictors of future commitments between customer and service providers (Coulter & Coulter, 2002). Trust generally is viewed as an essential ingredient for a successful relationship. Trust is defined as “a willingness to rely on an exchange partner in whom has confidence” (Garbarino & Johnson, 1999). Research has demonstrated that reduction of risk, uncertainty, and/or share with knowledge/information on the part of interaction facilitate to establish trust relationships between participants (Coulter & Coulter, 2002). Seven trust attributes have been introduced from service literature to represent trust characteristics: competence, customization, reliability, promptness, similarity, empathy, and politeness. The additional attribute of open and effective communication is also adopted as a trust attribute to directly address the need for information exchange between energy service providers and homeowners. The first four of these characteristics pertain to the auditors’ ability to deliver their service and are referred to as “offer-related” trust attributes. The latter four pertain to the auditors’ personal characteristics or manner of delivery, and are referred to as “person-related” trust attributes (Coulter & Coulter, 2002). Definitions and examples of offer-related and person-related trust attributes as interpreted for a home energy assessment are presented in Tables 2a and 2b respectively.

Table 2a: Definitions and examples of trust attributes in a home energy audit

<table>
<thead>
<tr>
<th>Offer-related Trust attributes</th>
<th>Definitions of trust attributes (adapted from Coulter &amp; Coulter, 2002)</th>
<th>Examples in a home energy audit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Competence</td>
<td>The degree to which customers perceive that the service representative possesses the required skills and knowledge to supply the basic service product</td>
<td>The auditors’ knowledge and experience of home energy audit</td>
</tr>
<tr>
<td>2. Ability to customize solutions</td>
<td>The service representatives’ ability (or willingness) to vary the product/service offering in terms of specific service attributes, in order to suit the individual customer’s needs.</td>
<td>Recommend a 5day+2day digital thermostat to a family who is often away on the weekend</td>
</tr>
<tr>
<td>3. Reliability</td>
<td>The delivery of that product/service in a dependable manner</td>
<td>Conduct the assessment and follow-up processes in a manner that meets expectations</td>
</tr>
<tr>
<td>4. Promptness</td>
<td>The delivery of that product/service in a timely manner</td>
<td>Arrive on time and complete tasks on schedule</td>
</tr>
</tbody>
</table>
Table 2b: Definitions and examples of trust attributes in a home energy audit

<table>
<thead>
<tr>
<th>Person-related Trust attributes</th>
<th>Definitions of trust attributes (adapted from Coulter &amp; Coulter, 2002)</th>
<th>Examples in a home energy audit</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Similarity</td>
<td>The degree to which a customer perceives himself/herself to be similar to the service representative, based on comparable tastes, preferences, appearance, lifestyle.</td>
<td>Share similar interests and values with homeowners, such as improving comfort or controlling of costs</td>
</tr>
<tr>
<td>6. Empathy</td>
<td>The degree to which the service representative possesses a &quot;warm considerate and caring&quot; attitude toward the situations and conditions the client is experiencing</td>
<td>Provide assessment in a manner that acknowledges unique challenges and is not judgmental about life styles</td>
</tr>
<tr>
<td>7. Politeness</td>
<td>The degree to which the service provider is perceived as being considerate, respectful, tactful, courteous.</td>
<td>Express gratitude, respect boundaries, and compliment homeowners’ role in process</td>
</tr>
<tr>
<td>8. Open &amp; effective communication†</td>
<td>The degree to which the service provider demonstrates active listening and conveys information to the client in an effective and sufficiently understandable manner</td>
<td>Use direct and clear language to explain issues to homeowners and take steps to verify understanding</td>
</tr>
</tbody>
</table>

†Based on the study of adoption barriers in home energy efficiency, "open and effective communication" is added in this research to detect the understanding and transparency of a conversation.

4.4 Trust -Value Conversion Model

Trust attributes described in Table 2a and 2b are used to evaluate individual tasks in an in-house walkthrough inspection in a manner of time. Discreet inspection tasks are classified based on the value dimensions: objective and subjective value. The value is aggregated based on the objectives of value that contribute either gathering information of home conditions (Vexchange) and the building of trust relationships with homeowners through caring homeowners’ concerns, priority and preference (Vtrust). The objective value categorized trust attributes(Competence, Customization, Reliability and Promptness) are used to demonstrate the value of inspecting house condition, and the subjective value categorized trust attributes( Similarity, Empathy, Politeness and Open and efficient communication) are mainly used to evaluate auditors’ personality and the quality of delivery assessment service.

Be more specifically, the objective value is evaluated as trust attributes are identified through house inspection and data collection, which mainly focuses on various home systems, such as: attic, appliance, cooling, heating, lighting, renewable energy, water heating, building envelop and house upgrade. Subjective value is used to characterize assessors’ methods delivering the assessment; such as communication skills, worldview techniques to learn homeowners’ priorities and concerns, and the assessors’ general behavior to interaction with homeowners during the assessment. Worldview refers to the study by the Shelton Group in which distinct market segments of home energy clients are categorized (in percentage of home energy clients) into four types: True believer (23.5%), Cautious Conservatives (22%), Concerned Parents (31%) and Working Class Realists (23.5%). Intrinsic and extrinsic motivations of each type of worldview are stated in table 3 (UtilityPulse program, Shelton group, 2013).

Table 3: Worldview†: Intrinsic and extrinsic motivations of each type of worldview (UtilityPulse program, Shelton group, 2013).

<table>
<thead>
<tr>
<th>Type of Worldview (% of home energy clients)</th>
<th>Characteristics and qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>True believer (23.5%)</td>
<td>Intrinsic – Protect environment live responsibility</td>
</tr>
<tr>
<td></td>
<td>Extrinsic – save money, rebates, payback/ ROI, social norms</td>
</tr>
<tr>
<td>Cautious Conservatives (22%)</td>
<td>Extrinsic – saving money, control, resale value</td>
</tr>
<tr>
<td>Concerned Parents (31%)</td>
<td>Intrinsic – health and welfare of their family</td>
</tr>
<tr>
<td></td>
<td>Extrinsic – lower bills, payback/ ROI</td>
</tr>
<tr>
<td>Working Class Realists (23.5%)</td>
<td>Extrinsic – lower bills, payback/ ROI</td>
</tr>
</tbody>
</table>
To integrate the processes of home energy assessments, there are various tasks required to complete in an in-house walkthrough assessment. Assessment tasks are categorized based on energy systems and locations in a home, and their corresponding trust conversions, which enables linkages to be made between invested effort and types of value contributions to actual home energy implementation.

In summary, categories of tasks used in this research represent groups of upgrades that are related and have common energy efficiency measures including: attic, appliance, cooling, heating, lighting, renewable energy, water heating, envelope, and living upgrades. Living upgrades refer to tasks that identify potential improvements to the health, safety and comfort of the home, and are included for two reasons. First, many of these conditions are related to energy efficiency measures and can provide added incentive to pursue energy upgrades. Secondly, the effort to identify health and safety issues in homes provides an opportunity to demonstrate credibility and empathy and as a result, help to build trust between homeowners and assessment provider. Additionally, three approaches of value distribution related to assessors are identified as communication skills, the ability to identify and respect variable worldviews, and professionalism. Figure 2 illustrates a comprehensive architecture of typical tasks of an assessment and the manners in which the assessment is performed are related to value dimensions and trust attributes. In this framework, the overall value generated through a home energy assessment (HEA) walkthrough is characterized by (1) the Objective value generated by information-gathering tasks and which lead to the generation of service-related trust attributes, and (2) Subjective value generated by the interactions between assessors and homeowners and which lead to the generation of people-related trust attributes.

![Diagram](image)

**Figure 2**: Trust-value conversion model - the categorized tasks of an assessment walkthrough with corresponded trust attributes and value dimension.

The evaluation of a home assessment with respect to the value distribution can be achieved through observing tasks performance and measuring the tasks performance according to the value dimensions and associated trust attributes. Table 4 provides an example of series of tasks of exterior walkthrough; tasks are categorized into related task system, trust attributes and value as a pilot study. The further
study will be spanned through calculating time spent in individual task and homeowners’ feedback of assessment service.

Table 4: a series of tasks of exterior walkthrough as pilot study are coded according to objectives of value and related trust attributes take place in an exterior walkthrough

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Tasks description</th>
<th>Category of task system</th>
<th>Trust Attribute</th>
<th>Value Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Take IR image of envelope</td>
<td>Envelope</td>
<td>Competence</td>
<td>V Exchange</td>
</tr>
<tr>
<td>2</td>
<td>Compliment house modifications</td>
<td>Professional trait</td>
<td>Politeness</td>
<td>V Trust</td>
</tr>
<tr>
<td>3</td>
<td>Inspect building envelope for air leaks</td>
<td>Envelope</td>
<td>Competence</td>
<td>V Exchange</td>
</tr>
<tr>
<td>4</td>
<td>Check age of appliance</td>
<td>Appliance</td>
<td>Competence</td>
<td>V Exchange</td>
</tr>
<tr>
<td>5</td>
<td>Explain IR image to homeowner</td>
<td>Communication skill</td>
<td>Open Communication</td>
<td>V Trust</td>
</tr>
<tr>
<td>6</td>
<td>Determine windows type</td>
<td>Envelope</td>
<td>Competence</td>
<td>V Exchange</td>
</tr>
<tr>
<td>7</td>
<td>Share experience with winter discomfort</td>
<td>Professional trait</td>
<td>Similarity</td>
<td>V Trust</td>
</tr>
<tr>
<td>8</td>
<td>Complete assessment in time requested</td>
<td>Professional trait</td>
<td>Reliability</td>
<td>V Trust</td>
</tr>
</tbody>
</table>

5 IMPLICATIONS

Energy retrofit projects for homes and buildings have significant potential to reduce energy waste, advance energy independence, and enable job-creating design and construction projects across sectors of the design and construction marketplace. Improved characterization of value exchange and the development of trust with clients will help lead to the design of more effective energy assessment delivery methods by helping to elevate the need to combine effective information gathering with the generation of business relationships between homeowners. These concepts also apply to energy assessment and auditing procedures for commercial buildings, where similar opportunities exist.

6 CONCLUSIONS AND THE NEXT STEPS

This research seeks to improve the home energy assessment process design through a value-oriented approach. The methodology presented here links value theory to the home energy assessment process via introducing the dimensions of objective and subjective value, and value objectives and trust attributes of home energy assessment. Currently, this research is focused on the design of a follow-up survey and feedback tool that will verify the value-trust model. By doing so, the expected contribution of this research are: (1) process of value distribution and the trust cultivation can be studied in more detail; (2) the design of assessment processes that target assessment efficiency; and (3) the facilitation of homeowners’ decision are aligned with homeowners’ interest and ability to act. Furthermore, this research proposes a feasible approach to analyze and measure continuous in-field activities in a quantitative manner, which leads to more possibilities to manage production/ service processes based on clients’ demands, as well as elevate customization with effectiveness and efficiency in the A/C/E industry.

Acknowledgements
The research team is appreciative of the support provided to the NELC by the ELECTRI International Foundation, The U.S. Department of Energy Building America program, the Consortium for Building Energy Innovation, and the BNY Melon Foundation, and the GE Foundation.

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AN EMPIRICAL STUDY ON THE SUSTAINABILITY OF PANELIZED RESIDENTIAL BUILDING CONSTRUCTION IN CANADA

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3 Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada;
4 ho8@ualberta.ca

Abstract: Panelized construction offers benefits to the construction industry including energy savings and reductions in carbon emissions and waste. This research addresses the sustainability of panelized residential construction during the framing phase, which consists of panel fabrication in the plant, transportation to the site, and on-site assembly. This study is conducted in collaboration with Landmark Building Solutions (LBS), a panel manufacturer in Edmonton, Canada. Two tasks with respect to assessing the sustainability of panelized construction are carried out in this research: (1) The positive impact of panelized construction on the construction schedule is evaluated by utilizing archived schedule data. In this task, the cycle time of framing for panelized construction is investigated; the results are compared with those of conventional stick-built construction, and the impact of framing cycle time on on-site winter heating is addressed. (2) The benefits of panelized construction are measured in terms of construction waste reduction by quantifying the recyclable and non-recyclable waste. The results are compared with those of the stick-built method, and the impact on embodied emissions in material waste is addressed. The primary data source is archives of the industry partner, including accounting records and construction records. A literature review and comparison are carried out to provide the necessary context for achieving the research objective. The preliminary results support the sustainability of panelized construction compared with the conventional stick-built method.

1 INTRODUCTION

Off-site construction has received wide attention due to benefits such as accelerated schedule, improved quality, decreased material waste, and sustainability in terms of energy savings and emission reductions. This research aims to evaluate the sustainability of panelized construction in terms of construction cycle time (operational carbon emissions from the construction process) and construction waste (embodied carbon emissions of materials). The carbon emissions are neutrally indexed in order to evaluate construction sustainability. Construction carbon emissions associated with construction, it should be noted, comprise operational emissions from the construction process and embodied emissions of materials. Operational emissions refer to the emissions from construction activities, while embodied emissions are indirect/upstream emissions associated with the building materials used, such as manufacturing of the equipment used in production or transportation of raw materials. In specific, these include emissions from the following: (1) extraction of raw materials; (2) raw material transportation to material processing plant; (3) building material manufacturing in plant; (4) building material transportation...
to the site; (5) construction on site; (6) operation and maintenance; and (7) demolishing, disposal, or recycling (Inui et al., 2011). The entire process is known as “Cradle-to-Grave”, and the corresponding emissions are referred to as “Cradle-to-Grave” emissions, among which those phases from raw material extraction to material leaving the manufacturing plant are specified as “Cradle-to-Gate”, including emissions from stages 1 to 3. “Cradle-to-Gate” is the domain most commonly used, and the one used in this study.

Li et al. (2014) quantified and compared the direct (construction operation) and indirect (embodied) emissions from panelized and stick-built construction, and concluded that the use of the panelized construction method reduces overall emissions by 42.76% compared to the stick-built method. They also found that on-site winter heating accounts for 34% and 50% of the measured emissions for the panelized and stick-built methods, respectively. The key aspect of panelized construction that leads to reduced emissions from on-site winter heating is the reduced cycle time of construction. Panelized construction is also proven to reduce wood waste from construction. Mah (2011) investigated the waste generated from the framing of residential buildings, and found that an average of 1,400 kg of waste is generated from the framing of a single-family home using the stick-built method, among which 89% is wood waste. Monahan and Powell (2011) investigated panelized timber frame construction, and found that there was a 34% reduction in embodied carbon when compared to traditional construction methods. In this research, to further investigate the benefits of panelized construction, the construction cycle time and generated waste associated with panelized construction are studied and compared with those associated with the stick-built method.

This research uses a case study to investigate differences in operational (direct) energy and emissions between the two methods with regard to winter heating. This case study is unique in that it reveals differences between the two methods specifically in a cold weather climate. Further investigation leads to a greater understanding of the differences in methods with respect to winter heating and waste, using environmental metrics such as embodied energy and embodied emissions as the indices. Embodied energy and emissions are summations of all the energy and emissions related to all materials, transportation, and construction up to the framing stage, i.e., the energy expended and emissions emitted from the upstream of the framing stage along the value chain.

2 RESEARCH OBJECTIVE

The aim of this research is to address the sustainability of panelized residential construction in the framing phase in terms of construction cycle time and construction waste. The research objective encompasses the following two tasks:

1. Evaluate the benefit of panelized construction in terms of construction schedule: In cold regions, on-site winter heating is a primary contributor to energy consumption and carbon emissions. Construction cycle time, in turn, is the determining factor for on-site winter heating duration. In order to assess the benefits of panelized construction, the average framing cycle time of panelized construction is evaluated based on archived construction records, the results are compared with those of stick-built construction, and the impact of framing cycle time on on-site winter heating is addressed using operational (direct) and embodied energy and emissions.

2. Measure the benefit of panelized construction on construction waste: Material waste is another important factor influencing the sustainability of construction. In this study, the waste generated with the state-of-the-art technology is categorized into recyclable and non-recyclable and then quantified. The results are compared with those of the stick-built method and the impact on material embodied energy and emissions is addressed.

To achieve the research objective, the required data is obtained from: (1) the industry partner’s operation records for 2013, including accounting and construction records, and (2) construction schedule records for January, 2011 to April, 2013. A literature review and comparison are also carried out.
3 CONSTRUCTION CYCLE TIME

Corresponding to the manner in which the current state-of-the-art technology is utilized, the milestones in the residential construction schedule are date to field, framing start, siding start, drywall boarding, finishing stage 1, and possession date. Based on the construction schedule records for January, 2011 to April, 2013, the cycle times of panelized and stick-built construction are given in Table 1, Figure 1, and Figure 2.

Table 1: Cycle time of panelized and stick-built construction

<table>
<thead>
<tr>
<th>Construction Method</th>
<th>Date To Field – Framing Start</th>
<th>Framing Start – Siding Start</th>
<th>Siding Start – Drywall Boarding Start</th>
<th>Drywall Boarding Start – Finishing Stage 1 Start</th>
<th>Finishing Stage 1 Start – Possession Date</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stick-built</td>
<td>35.8</td>
<td>51.2</td>
<td>19.0</td>
<td>59.0</td>
<td>42.8</td>
<td>207.8</td>
</tr>
<tr>
<td>Panelized</td>
<td>36.8</td>
<td>27.2</td>
<td>33.8</td>
<td>23.7</td>
<td>69.5</td>
<td>191.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Stick-built</th>
<th>Panelized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>84</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>61</td>
</tr>
</tbody>
</table>

The cycle time comparison between panelized and stick-built is graphically represented in Figure 3. Regarding construction schedule, the main difference between panelized and stick-built construction, which has to do with the construction technology used, is the span from framing start to siding start; other schedule differences are primarily determined by the business process and coordination of residential construction and are not specifically tied to either panelized or stick-built construction. Regarding the identified span during which there is a notable difference between the two construction methods, panelized construction is associated with a 47% reduction in duration from framing start to siding start compared with stick-built, as shown in Figure 3.
Construction cycle time has a major impact on on-site winter heating in cold regions. In cold regions, winter heating accounts for the largest portion of energy consumption and carbon emissions during the framing phase. On-site propane heaters operate 24 hours a day, 7 days a week, and are refilled by a 5-ton truck every 3 days on average in winter. The heating season in Alberta is about 6 months in duration, i.e., winter heating is occurring 50% of the time. However, the nature of panelized construction shifts many outdoor construction activities to a more efficiently heated indoor environment, which markedly reduces the use of on-site winter heaters. As well, panelized construction reduces on-site assembly cycle time, thereby reducing winter heating time.

The common practice within the residential construction sector is to install a 100,000 Btu propane heater in the basement once the foundation has been backfilled. The hourly propane consumption is calculated as Equation 1, and the diesel consumption of the truck carrying out the propane refill is assumed to be 20 L per instance.

\[ P_h = 100,000 \times \frac{CC}{HV} \approx 4.17 \text{ (L/hr)} \]

Where: \( P_h \) is hourly propane consumption (L/hr); \( CC \) is converting coefficient from BTU to MJ, 0.0010551; \( HV \) is heat value of propane, 25.3 MJ/L (Natural Resources Canada, 2010);

Based on the above calculation, the assumption regarding propane tank refilling, and the recorded cycle time, propane and diesel consumption per house is calculated for panelized and stick-built construction as shown in Table 2. Furthermore, to measure the impact of using the panelized construction method on winter heating, (as a result of improving the productivity of the process and reducing the idle time between framing and the downstream construction activities), the winter heating period for the purpose of comparison is defined as the span from framing start to siding start. The propane and diesel used for winter heating entails: (a) operational energy and emissions, which can be calculated using Equations (2) and (3), and (b) embodied energy and emissions, which can be calculated by means of Equations (4) and (5).
Where:

\[ E = F \times HV_F \]

\[ \text{CO}_2 = F \times EF_F \]

Where: \( E \) is operation energy (MJ); \( \text{CO}_2 \) is \( \text{CO}_2 \) emissions (kg); \( F \) is the amount of Fuel (L); \( HV_F \) is heat value of fuel: the \( HV \) of propane is 25.3 \( MJ/L \) (Natural Resources Canada, 2010), and the \( HV \) of diesel is 38.68 \( MJ/L \) (National Energy Board, 2015); \( EF \) is the operational emission factor of fuel: the \( EF \) of propane is 1.51 kg \( \text{CO}_2/L \) and the \( EF \) of diesel is 2.663 kg \( \text{CO}_2/L \) (Environment Canada, 2013).

\[ EE = F \times EF_F \]

\[ E\text{CO}_2 = F \times EEF_F \]

Where: \( EE \) is embodied energy (MJ); \( F \) is fuel consumption (L); \( EF \) is the embodied energy factor: the \( EF \) of propane is 26.44 \( MJ/L \), and the \( EF \) of diesel is 45.7 \( MJ/L \), \( E\text{CO}_2 \) is embodied \( \text{CO}_2 \) emissions (kg); \( EEF_F \) is the embodied emission factor of fuel: the \( EEF_F \) of propane is 0.22 kg \( \text{CO}_2/L \) and the \( EEF_F \) of diesel is 0.57 kg \( \text{CO}_2/L \) (Energetics, 2013).

The operational energy and emissions of winter heating calculated based on the above methodology are shown in Table 2, and the embodied energy and emissions are shown in Table 3.

<table>
<thead>
<tr>
<th>Winter Heating per House</th>
<th>Cycle Time (Days)</th>
<th>Total Propane Consumption (L)</th>
<th>Diesel Consumption for Refill (L)</th>
<th>( \text{CO}_2 ) Emissions (kg)</th>
<th>Energy Intensity (MJ/ft(^2))</th>
<th>Emission Intensity (kg/ft(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panelized Construction</td>
<td>27.2</td>
<td>2722.2</td>
<td>181.3</td>
<td>4,593</td>
<td>75,943</td>
<td>50%</td>
</tr>
<tr>
<td>Stick-Built Method</td>
<td>51.2</td>
<td>5124.1</td>
<td>341.3</td>
<td>8,646</td>
<td>142,952</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 3: Embodied energy and emissions of winter heating

<table>
<thead>
<tr>
<th>Winter Heating per House</th>
<th>Cycle Time (Days)</th>
<th>Total Propane Consumption (L)</th>
<th>Diesel Consumption for Refill (L)</th>
<th>( \text{CO}_2 ) Emissions (kg)</th>
<th>Energy Intensity (MJ/ft(^2))</th>
<th>Emission Intensity (kg/ft(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panelized Construction</td>
<td>27.2</td>
<td>2722.2</td>
<td>181.3</td>
<td>707</td>
<td>80263</td>
<td>50%</td>
</tr>
<tr>
<td>Stick-Built Method</td>
<td>51.2</td>
<td>5124.1</td>
<td>341.3</td>
<td>1331</td>
<td>151083</td>
<td>50%</td>
</tr>
</tbody>
</table>

4 CONSTRUCTION WASTE

Construction waste is another important metric of construction sustainability. Based on the assumption that the net materials used in a house are the same for both the panelized and stick-built methods, the waste difference determines the difference in embodied emissions of materials between panelized and stick-built methods. The wood waste of panelized construction consists of waste generated in the plant
and waste generated on site. The on-site waste accounts for only a small proportion (0.036 in this case) of the overall waste for panelized construction, so only the wood waste generated is considered in this research. To measure the sustainability of panelized construction, the waste generated is collected by reviewing accounting records, as shown in Table 4; Figure 4 shows the amounts of wastes shipped out from the manufacturing facility in 2013.

The nature of panel fabrication in a plant provides the opportunity to optimize material usage and reduce material waste. Furthermore, several measures to reduce waste were implemented in 2012. Currently, all lumber and engineered wood for framing is precut by computer numerical control (CNC) saws, which have the ability to optimize cutting for multiple panels. As a result, the waste in the plant is less than with the stick-built method. The waste generated under the current approach is illustrated in Figure 5 to Figure 8.
Usually the floor joists are cut from 60-ft standard length I-Joists, which are purchased directly from manufacturers; accordingly, more than 70% of the total wood product waste generated in the plant is I-joist cut-offs. In the case of the stick-built method, I-Joists are precut by the material supplier before they are shipped to the site, and the waste in houseware is not included in the scope of the stick-built method; to be consistent for panelized and stick-built methods, it is therefore necessary to deduct the corresponding amount of waste associated with this process at the supplier’s warehouse from the waste calculated for panelized construction. Table 4 shows the adjusted waste amounts of the panelized construction method and associated embodied GHG emissions.

To compare panelized with the stick-built method, the waste generated from stick-built construction is ascertained through a literature review. It is found that the construction of a single-family home in North America typically produces between two and four tons of wastes on site (NAHB Research Center, 1996; Laquatra 2005). Mah (2011) conducted an empirical study of construction wastes has been undertaken to investigate the mass and volume of waste generated during the new home construction process. His study noted that typically in stick-built construction there are three waste pick-ups, with the first pick-up coming after the completion of framing. The study included an on-site audit of the first waste pick-ups of five single-family homes under construction. On average, over 1,400 kg of total waste (wood and non-wood) had been generated at a single-family house construction site by the time framing had been completed. Almost 89% of this waste was either dimensional lumber or engineered wood products. The results of Mah’s study are consistent with those of similar studies that have been conducted around North America. Therefore, the results from Mah (2011) that on average 536 kg of lumber waste and 710 kg of engineered wood waste are generated in the framing of one house are used in this research for the purpose of comparison of between the stick-built and panelized approaches.

To evaluate the impact of reduced waste on the sustainability of construction, the amount of waste is used to calculate the embodied energy and emissions of materials using Equation (6) and Equation (7). The results are shown in Tables 4 and 5.

\[ [6] EW = W \times E_W \]

Where: \( EW \) is embodied energy of waste (MJ); \( W \) is the mass of waste (kg); and \( E_W \) is the embodied energy factor of wood product: 10 MJ/kg for dimensional lumber and 15 MJ/kg for engineered wood (Geoff Hammond & Craig Jones, 2011).

\[ [7] ECO_2 = W \times EEF_W \]

Where: \( ECO_2 \) is embodied CO\(_2\) emissions (kg); \( W \) is the mass of waste (kg); \( EEF_W \) is the embodied emission factor of wood product: 0.341 kg CO\(_2\)/kg for dimensional lumber (Meil, 2000), and 0.576 kg CO\(_2\)/kg for engineered wood (Forintek Canada Corp., 1993).
Table 4: Embodied energy and emissions of waste for panelized construction

<table>
<thead>
<tr>
<th>Waste Source</th>
<th>Plant</th>
<th>Equivalent Amount (30%*)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimensional Lumber</td>
<td>Engineered Wood</td>
</tr>
<tr>
<td>Total Amount (kg)</td>
<td>175,981.4</td>
<td>703,925.6</td>
</tr>
<tr>
<td>Production Outputs (ft²)</td>
<td>1,216,866</td>
<td></td>
</tr>
<tr>
<td>Waste (kg/ft²)</td>
<td>0.145</td>
<td>0.578</td>
</tr>
<tr>
<td>Embodied Energy (MJ/ft²)</td>
<td>1.446</td>
<td>8.677</td>
</tr>
<tr>
<td>Embodied GHG Emissions (kg/ft²)</td>
<td>0.049</td>
<td>0.333</td>
</tr>
</tbody>
</table>

* The 30% value refers to the finding that waste in the panel fabrication plant amounts to just 30% of the waste generated by the corresponding scope of work performed on-site in the stick-built method.

Table 5: Waste and embodied emissions of stick-built construction

<table>
<thead>
<tr>
<th></th>
<th>Dimensional Lumber</th>
<th>Engineered Wood</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste (kg/house)</td>
<td>536</td>
<td>710</td>
<td>1,246</td>
</tr>
<tr>
<td>Average Floor Area(ft²/house)</td>
<td>1,600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste (kg/ft²)</td>
<td>0.335</td>
<td>0.444</td>
<td>1</td>
</tr>
<tr>
<td>Embodied Energy (MJ/ft²)</td>
<td>3.349</td>
<td>6.658</td>
<td>10.007</td>
</tr>
<tr>
<td>Embodied CO₂ Emissions (kg/ft²)</td>
<td>0.114</td>
<td>0.252</td>
<td>0.366</td>
</tr>
</tbody>
</table>

5 CONCLUSION AND LIMITATIONS

This study has demonstrated that utilization of a panelized method enhances the sustainability of construction. In particular, this study has investigated the impact of cycle time savings and waste reduction resulting from panelized construction. Based on the operational data, the framing cycle time of panelized construction has been calculated, and the impact on winter heating has been evaluated. The waste generated by panelized construction has been quantified and compared with that of stick-built construction, and the impact on embodied emissions has been evaluated. The results in Table 6 and Figure 9 show that the overall energy intensity, including operational and embodied, is reduced by 202.378 MJ/ft² using the panelized construction method, which represents a 67.77% reduction compared to the stick-built method. Table 7 and Figure 10 show that the overall emission intensity is reduced by 1.758 kg/ft² using the panelized construction method, which translates to a 49.1% reduction compared to the stick-built method. Compared with stick-built construction, panelized construction as a sustainable construction method is demonstrated empirically to reduce energy usage and CO₂ emissions.

This research entails the following limitations: (1) due to the data accessibility, the data on stick-built construction waste was obtained from published research collaborated with the same industry partner, while others was archived from the industry partner’s records for this research; (2) Winter heating is a crucial issue in Canada; however, in other countries and regions, there may not exist the same issue.
Table 6: Energy comparison between panelized and stick-built construction

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Panelized</td>
<td>93.214</td>
<td>3.037</td>
<td>96.251</td>
</tr>
<tr>
<td>Stick-built</td>
<td>288.622</td>
<td>10.007</td>
<td>298.629</td>
</tr>
<tr>
<td>Reduction</td>
<td>195.408</td>
<td>6.970</td>
<td>202.378</td>
</tr>
<tr>
<td>Reduction %</td>
<td>67.70%</td>
<td>69.65%</td>
<td>67.77%</td>
</tr>
</tbody>
</table>

Figure 9: Energy intensity comparison

Table 7: Emissions comparison between panelized and stick-built construction

<table>
<thead>
<tr>
<th>Construction method</th>
<th>Winter Heating CO2 Emissions (kg/ft²)</th>
<th>Waste-Embodied CO2 Emissions (kg/ft²)</th>
<th>Overall CO2 emissions (kg/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panelized</td>
<td>1.707</td>
<td>0.115</td>
<td>1.822</td>
</tr>
<tr>
<td>Stick-built</td>
<td>3.214</td>
<td>0.366</td>
<td>3.580</td>
</tr>
<tr>
<td>Reduction</td>
<td>1.507</td>
<td>0.251</td>
<td>1.758</td>
</tr>
<tr>
<td>Reduction %</td>
<td>46.88%</td>
<td>68.64%</td>
<td>49.10%</td>
</tr>
</tbody>
</table>
Figure 10: CO₂ emissions intensity comparison

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LIFE CYCLE ANALYSIS OF STRUCTURAL STEEL REUSE USING THE ECONOMIC INPUT-OUTPUT METHOD

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Abstract: Reuse of structural steel is not a new concept in civil engineering. However, even though members, and assemblies of members, have been reused for decades, reuse of steel is not a widely implemented practice. Approximately 90\% of demolished steel is recycled and only 10\% of that steel is reused in its current state. The structural steel reuse that does occur is due to the reuse of very large members or from specialty projects. The reason for these low levels of reuse is because the cost of reusing structural steel is too high. Unfortunately, many decision makers are coming to this conclusion without a comprehensive knowledge of the true cost of reuse and recycling. In order to fully understand the additional costs, or savings, associated with steel reuse, a life cycle analysis needs to be incorporated into an economic analysis. In this study, the economic input-output method was used to perform a life cycle analysis of structural steel reuse as it compares to current practices. The economic input-output method provides the benefit of being able to facilitate a quick analysis but is limited by only being able to perform a generalized analysis across the entire industry. The analysis was performed for several metrics, which can be grouped into four categories: greenhouse gases, energy usage, water usage, and hazardous waste generation. Results from the analysis show that there is a significant decrease, upwards of 65\%, for the calculated metrics across each category for reuse. In order to remedy the limitations of the economic input-output method, it is recommended to perform a similar analysis using a process model approach.

1 INTRODUCTION

Steel reuse shows great promise to become a more “environmentally friendly” alternative to creating new steel from virgin resources and recycled scrap steel. Current practices result in only about 10\% of steel being reused as opposed to the nearly 90\% of steel that is recycled, but it is believed that this could increase by up to 150\% if economic conditions were to change, technological advances were to be utilized, or externalities affecting life cycle cost were considered (Gorgolewski, 2006 and Ness et al., 2014). The impact of a product, process or activity is not only limited to economic impact; there are also environmental impacts and social impacts. Life cycle analysis is a tool used to assess the entire impact of a product, process or activity throughout its entire life cycle. This analysis is a necessary step in the decision making phase of any project. The complete impact of a decision throughout its entire economic life cycle needs to be quantitatively understood in order to properly and knowledgeably make a
comparison between proposed alternatives. Performing a life cycle analysis is the only way to truly understand a decision’s full impact, but there are several ways to do this.

2 BACKGROUND

Before being able to quantify the environmental benefits of reusing structural steel, the metrics for assessing environmental impact must be established. These metrics often include carbon footprint, water footprint, and energy use. It is important to note that these metrics need to be determined for the entire life cycle of the process or component and are based on direct and, sometimes more importantly, indirect impacts. A more detailed list of life cycle impacts can be seen in the work of Reijnders (1995), where the focus was on limiting resource use, minimizing pollution, and preserving nature.

2.1 Carbon Footprint

According to Wiedmann and Minx (2008), “… carbon footprint is a measure of the exclusive total amount of carbon dioxide that is directly and indirectly caused by an activity or is accumulated over the life stages of a product.” This definition of carbon footprint does not include any of the other carbon based pollutants or greenhouse gases, such as methane. Wiedmann and Minx argue that this definition is ideal in spite of its limited scope due to its high level of clarity. When selecting a metric for environmental impact it is important that this metric be of significant contribution, clearly defined, and relatively simple to calculate, especially when implementing practices to reduce environmental impact.

2.2 Water Footprint

The industrial sector consumes large volumes of water, but can also pollute even greater volumes downstream (WWAP, 2009). The idea of a ‘water footprint’ associated with each product and process was introduced by Hoekstra (2003) as a very similar concept to ‘virtual water’, originally coined by Allan (1997). Virtual water is the water consumed by the production of every product. It was used in a proposed solution to countries with water shortages by allowing those countries to export their water needs. A water footprint takes this concept a step further by including the water consumed during the entire life cycle of the process or product, rather than just during its production.

2.3 Energy Use

Based on the work by Dincer (1999), energy use is a suitable metric for environmental impact because of the wide range of problems that can be associated with it. Increases in energy use can be correlated to acid rain, ozone depletion, global warming, air pollution, forest destruction, and the production of radioactive materials. This is because many of the bi-products of energy creation have negative effects on the environment. Acid rain is a result of excessive amounts of sulfur dioxide (SO2), nitric oxide (NO), and nitrogen dioxide (NO2) being emitted into the atmosphere, which are all released during the combustion of fossil fuels. Ozone depletion is mostly due to chlorofluorocarbons (CFCs), which are used in air conditioning and refrigeration units but NO and NO2 also contribute. Other gases produced during energy production, including carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), ozone (O3), and peroxyacetylnitrate, are major contributors to the greenhouse gas effect and global warming.

2.4 The Economic Input-Output Method

The economic input-output (EIO) method for life cycle assessment (EIO-LCA) aims to simplify the process of performing a life cycle assessment without having to limit its scope (i.e. exclude minor products and processes). The EIO method takes an aggregate view of a process or product and determines its life cycle impact based on the resulting inputs and outputs into various industry sectors (Hendrickson, Lave, & Matthews, 2006). For example, in order to construct a reinforced concrete building, a certain quantity of steel reinforcing bars will be required. This steel would represent an output from the steel industry and an input to the construction industry.
The EIO method works by first selecting a product or process to be assessed for its life cycle impact. Next, the entire life cycle requirements for the supply chain of this product or process are determined. These supply chain requirements include everything from extracting raw materials to producing the final product. Once the life cycle supply chain has been established, the discharges associated with each activity in the supply chain are summed and the total life cycle impact is presented. Depending on the desired life cycle analysis output, the aforementioned discharges can be economic activity, environmental, social, etc. (Hendrickson, Lave, & Matthews, 2006).

In order for the EIO method to be feasible, the economy needs to be divided into a limited number of distinct sectors. Each sector also needs to have established and quantified relationships with each of the other sectors. This relationship identifies that amount of inputs required from each sector in order to produce one unit of output for the specified sector. Fortunately, these relationships exist because of the work proposed and carried out by Leontief (1970). The discharges per unit of output from each sector are also required in order to convert the supply chain outputs to a specific type of impact, such as environmental impact. For the specific case of environmental impact, these relationships have already been established (Lave et al. 1995, Hendrickson et al. 1998).

The limitations of the input-output method result mostly from uncertainty as outlined by Lenzen (2001) who listed seven types: (1) source data uncertainty, (2) import assumption uncertainty, (3) estimation uncertainty for capital flow, (4) proportionality assumption uncertainty, (5) aggregation uncertainty, (6) allocation uncertainty, and (7) gate-to-grave truncation error. The data used in the input-output method is collected from national surveys and while errors can be estimated, they cannot be quantitatively known. This results in source data uncertainty. The uncertainty from imports arises because the data associated with foreign goods does not necessarily follow that of their domestic counterparts but the foreign data is not necessarily known. Worst-case errors are typically used to adjust imports but this is a simplified approximation. If capital flow tables do not exist, they must be constructed from capital expenditure from varied sources. This is an approximation and, as a result, a source of uncertainty. The proportionality assumption states that there is a linear relationship between the inputs and outputs and that price is uniform across the economy (Hendrickson et al. 2006 & Lenzen 2001). This means that doubling the output will require doubled input from each input and that the cost of electricity is the same whether being purchased by the steel industry or the fabrics industry. Aggregation leads to uncertainty because multiple producers are combined into a single industry without any way of differentiating between them. The final uncertainty associated with the input-output method is the uncertainty that results from the truncation of the gate-to-grave portion of the life cycle. The EIO method only accounts for the production discharges and neglects any operation, maintenance and end-of-life processes.

3 METHODOLOGY

The life cycle analysis performed in this study was undertaken using the economic input-output life cycle assessment (EIO-LCA) tool, developed by the Green Design Institute at Carnegie Mellon University (CMUGDI, 2008). As discussed previously, the EIO-LCA employs an aggregate overview of the life cycle impacts of a sector of industry based on the desired economic output from that sector. This includes the impacts of other sectors providing inputs to the sector of interest. The methodology for this comparison can be defined by three steps (Figure 1): (1) determining a point of reference, (2) defining appropriate sectors and activities, and (3) equating and comparing equivalent economic activities.
Figure 1: Overview of life cycle analysis methodology

The first step in performing a life cycle analysis is determining a point of reference for the comparison. A life cycle analysis serves very little purpose unless the results are compared with results for another, equivalent alternative. For this study, a particular mass of steel was used as a reference. The exact value for the mass of steel is not important because of the linear nature of the EIO-LCA. Another important consideration for the reference point is where along the supply chain the steel is located. The steel could be located, for example, in the ingot phase, the pre-fabrication phase as an individual member, or the post-fabrication phase, as a member ready for delivery to site. For the purposes of this study, the point of reference was selected as the pre-fabrication phase (PoR1 in Figure 2). This means that the steel has been formed into a standard steel section but has not yet been incorporated into a design or structural assembly, thus no end connections or other such details have been applied. A post fabrication phase point of reference (PoR2 in Figure 2) would also be interesting and may be the subject of a future LCA.

Figure 2: Modified process model for reuse with the life cycle analysis point of reference

The second step of performing the life cycle analysis was to identify the relevant sectors that should be used in the EIO-LCA. The data set used for the analysis was the USA 2002 Benchmark (CMUGDI 2008). This is comprised of 428 different sectors and contains the cradle-to-gate interactions required to produce outputs from each of these sectors. Cradle-to-gate means that the life cycle analysis is only complete to the point where the desired output is produced, for example when a steel ingot is produced at the
The production of new steel components was assumed to come from the “iron, steel pipe and tube manufacturing from purchased steel” sector. This is responsible for the production of welded and rolled structural steel shapes (CMUGDI, 2008). The production of reused steel components was assumed to come from economic activity in the demolition industry. Unfortunately, demolition is not a sector included in the USA 2002 Benchmark data so construction of nonresidential manufacturing structures was selected as a surrogate. It is reasonable to consider construction and deconstruction as equivalent processes performed in an opposite manner. Many of the activities in this sector would be present in the removal of structural steel from buildings at the end of their service life. The main difference is that the deconstruction processes also includes activities for steel and cement manufacturing. The activity in these sectors would be present for the case of construction activity but would likely be absent from reuse activities. An adjustment was made to the impacts of the nonresidential manufacturing structures sector by removing the impacts that result from steel and cement manufacturing. With these sectors removed, the impact results will be more representative of reuse activities. For example, Table 1 displays the five highest total energy using sectors required to produce economic output from the “nonresidential manufacturing structures” sector. It is reasonable to presume that a large majority of the energy usage from “Iron and steel mills” would not be required, and can therefore be disregarded, if the structural steel is being reused.

Table 1: Highest energy users from the “nonresidential manufacturing structures” sector

<table>
<thead>
<tr>
<th>Sector Name</th>
<th>Total Energy Usage (TJ)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonresidential manufacturing structures</td>
<td>2.39</td>
</tr>
<tr>
<td>Power generation and supply</td>
<td>1.14</td>
</tr>
<tr>
<td>Iron and steel mills</td>
<td>0.40</td>
</tr>
<tr>
<td>Petroleum refineries</td>
<td>0.26</td>
</tr>
<tr>
<td>Truck transportation</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*values are reported per $1,000,000 of economic output

The final step was to determine the economic output from each sector required to achieve the desired mass of steel as specified in the first step. In order for a meaningful comparison to be made, the end production of each process needs to be the same. This means that the mass of steel that results from current practices and reuse need to be the same. Unfortunately the EIO-LCA method uses economic activity as the scale defining parameter for the analysis so equivalent economic activities for each production method needed to be calculated. The conversion values used in this study can be found in Table 2.

Table 2: Mass to economic activity conversion rates

<table>
<thead>
<tr>
<th>Production Method</th>
<th>Conversion Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Practices</td>
<td>$3.64 / kg</td>
</tr>
<tr>
<td>Reuse</td>
<td>$4.93 / kg</td>
</tr>
</tbody>
</table>

The current practices conversion rate of $3.64 / kg was selected based on the average material price of structural steel sections ranging from 200 mm to 350 mm in depth. The unit prices for these sections were obtained from RSMeans (2009). The reuse conversion rate was selected as $4.93 / kg. This value was based on the average construction cost per unit mass of various industrial steel framing structures. Following similar logic to the selection of the sectors from USA 2002 Benchmark data, the cost of constructing a particular mass of steel is equivalent to deconstructing that same mass. These unit prices were also obtained from RSMeans (2009). Neither price was adjusted for inflation or changes in market value. The accuracy of this study would be increased if current prices were used, but this was deemed unnecessary for this investigation. Together, these values create a new steel to reused steel price ratio of 1:1.35. This comparison is based on the assumption that the steel is in a pre-fabrication state, as
previously stated. It is expected that reused structural steel closer to the installation stage of the supply chain (PoR2 in Figure 2) would result in a more favourable price ratio.

4 RESULTS

The metrics for the previously described comparison were divided into five distinct groups: conventional air pollutants (Figure 3), greenhouse gases (Figure 4), energy consumption (Figure 5), water usage (Figure 6a), and hazardous waste production (Figure 6b). The reported results are based on $1,000,000 of new steel production. A description of each metric can be found in Table 3.

Table 3: Definition of metrics used for life cycle analysis

<table>
<thead>
<tr>
<th>Metric Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>carbon monoxide emissions into the atmosphere</td>
</tr>
<tr>
<td>NH₃</td>
<td>ammonia emissions into the atmosphere</td>
</tr>
<tr>
<td>NOₓ</td>
<td>oxides of nitrogen emissions into the atmosphere</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>particulate matter emissions into the atmosphere with diameter less than 10 microns</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>particulate matter emissions into the atmosphere with diameter less than 2.5 microns</td>
</tr>
<tr>
<td>SO₂</td>
<td>sulfur dioxide emissions into the atmosphere</td>
</tr>
<tr>
<td>VOC</td>
<td>volatile organic compound emissions into the atmosphere</td>
</tr>
<tr>
<td>CO₂ Fossil</td>
<td>carbon dioxide emissions into the atmosphere from fossil fuel combustion only</td>
</tr>
<tr>
<td>CO₂ Process</td>
<td>carbon dioxide emissions into the atmosphere from all processes other than fossil fuel combustion</td>
</tr>
<tr>
<td>CH₄</td>
<td>methane emissions into the environment</td>
</tr>
<tr>
<td>N₂O</td>
<td>nitrous oxide emissions into the atmosphere</td>
</tr>
<tr>
<td>HFC/PFCs</td>
<td>hydrofluorocarbons, perflourocarbons, and sulphur hexafluoride emissions into the atmosphere</td>
</tr>
<tr>
<td>Coal</td>
<td>energy consumed from coal sources</td>
</tr>
<tr>
<td>NatGas</td>
<td>energy consumed from natural gas sources</td>
</tr>
<tr>
<td>Petrol</td>
<td>energy consumed from petroleum sources</td>
</tr>
<tr>
<td>Bio/Waste</td>
<td>energy consumed from biomass or waste sources</td>
</tr>
<tr>
<td>NonFossElec</td>
<td>energy consumed from non-fossil fuel electric sources</td>
</tr>
<tr>
<td>Water Withdrawals</td>
<td>water withdrawn from the environment</td>
</tr>
<tr>
<td>Hazardous Waste</td>
<td>the amount of hazardous waste generated as defined by the Resource Conservation and Recovery Act</td>
</tr>
</tbody>
</table>

Figure 3 through Figure 6 show that, typically, the analysis for structural steel reuse results in significant life cycle impact reduction. Only four out of the 19 metrics investigated resulted in a significantly increased impact due to the reuse process. Table 4 quantifies the comparison of each metric as the percent reduction that results from applying reuse processes as opposed to current practices. Although a benefit is not demonstrated in all metrics of this study, a generalized decrease in the environmental impact can be seen as a result of reuse. The total mass of conventional air pollutants was reduced by 0.25 t, or 1%, the total mass of greenhouse gases in CO₂ equivalent was reduced by over 1500 t, or 75%, and the total energy usage was reduced by over 17 TJ, or 69%.
Figure 3: Life cycle analysis comparison between current practices and reuse for conventional air pollutants

Figure 4: Life cycle analysis comparison between current practices and reuse for greenhouse gases

Figure 5: Life cycle analysis comparison between current practices and reuse for energy consumption
Figure 6: Life cycle analysis comparison between current practices and reuse for water usage (a) and hazardous waste generation (b)

Table 4: Percent reduction of life cycle assessment metrics as a result of reuse

<table>
<thead>
<tr>
<th>Life cycle assessment metric</th>
<th>Percent reduction as a result of reuse*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>-32%</td>
</tr>
<tr>
<td>NH₃</td>
<td>47%</td>
</tr>
<tr>
<td>NOₓ</td>
<td>47%</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>-32%</td>
</tr>
<tr>
<td>PM₂.⁵</td>
<td>20%</td>
</tr>
<tr>
<td>SO₂</td>
<td>69%</td>
</tr>
<tr>
<td>VOC</td>
<td>-20%</td>
</tr>
<tr>
<td>CO₂ Fossil</td>
<td>58%</td>
</tr>
<tr>
<td>CO₂ Process</td>
<td>98%</td>
</tr>
<tr>
<td>CH₄</td>
<td>65%</td>
</tr>
<tr>
<td>N₂O</td>
<td>6%</td>
</tr>
<tr>
<td>HFC/PFCs</td>
<td>77%</td>
</tr>
<tr>
<td>Coal</td>
<td>90%</td>
</tr>
<tr>
<td>NatGas</td>
<td>75%</td>
</tr>
<tr>
<td>Petrol</td>
<td>-90%</td>
</tr>
<tr>
<td>Bio/Waste</td>
<td>36%</td>
</tr>
<tr>
<td>NonFossElec</td>
<td>78%</td>
</tr>
<tr>
<td>Water Withdrawals</td>
<td>65%</td>
</tr>
<tr>
<td>Hazardous Waste</td>
<td>79%</td>
</tr>
</tbody>
</table>

*negative percent reductions indicate an increase as a result of reuse

5 DISCUSSION AND CONCLUSIONS

The economic input-output life cycle analysis results show a clear indication that reuse has the potential to provide significant benefits over current practices. Steel reuse exhibited superior results in nearly every presented metric, given the parameters of this study. When the results are generalized, a 75% reduction in greenhouse gases and a 69% reduction in energy use is expected for steel reuse.
The external costs associated with construction decisions, such as material source, are not often considered in current decision making practices. These costs are not considered because they are not accurately understood and they are not associated with direct costs to the decision maker. Introducing direct costs to the decision maker, through carbon credits for example, would encourage practices that incorporate a broader, societal cost into their decision making process. This work makes progress towards achieving accurate quantification of the societal cost of reuse practices but more work is still required.

6 FUTURE WORK

One of the main drawbacks of the EIO-LCA method is its aggregate scale. This prevents the specific processes, such as the reuse process, from being examined directly. As a result, a number of assumptions and simplifications needed to be made. These assumptions and simplifications may have an impact on the results. As such, these results should only be treated as preliminary.

A more detailed analysis is essential for accurately quantifying the benefits or costs of reusing structural steel. For this analysis, it is recommended to replace the aggregate approach used by the economic input-output method, with a more detailed approach, such as the process model approach.

It is also worth investigating how the externalities identified in this EIO-LCA could be monetized, such as carbon credits, so that the opportunity cost to society of not reusing steel could be understand and could influence future reuse decisions.

Acknowledgements

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References


MEASURING HIGH-LEVEL PROJECT PRODUCTIVITY FOR ALBERTA CAPITAL PROJECTS

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Abstract: This paper contemplates the development of a single high-level productivity metric for Alberta capital projects in order to represent overall improvement over time. The Industry Leaders Roundtable would use this metric to challenge the status quo, and formulate "out of the box" thinking to improve Alberta Megaproject productivity. The measure would be most relevant for the owner; however, owners and industry need to be supportive to make it successful. For this purpose, the proposed study includes comparisons with data held by the Construction Industry Institute (CII) such as COAA (Construction Owner’s Association of Alberta) and CII Performance Assessment Database. This paper establishes selection criteria for input/output variables for the high-level productivity metrics based on the comprehensive review of existing productivity metrics and create a high-level productivity metric. Data are collected from COAA and CII Performance Assessment Database. Descriptive and statistical inferential analyses are conducted for comparison of high-level project productivity between Alberta and U.S. capital projects. The results of this study are anticipated to provide a single high-level productivity metrics with informative quantitative analyses for Alberta projects.

1 INTRODUCTION

Construction industry has been a significant role in Alberta’s as well as Canada’s economy. In 2013, the construction sector represents 10.9% of $338.2 billion (CND) of total gross domestic product in Alberta (Alberta Government, 2015). Over the two decades, the construction industry in Alberta increases from $4.5 billion (CND) to $36.8 billion (CND). Especially, oil sands industry is a big portion of the construction sector in Alberta and more than $102 Billion (CDN) was spent on construction and operation capital necessary to develop oil sands resources (COAA, 2009). While the size of construction industry increases, the productivity performance and improvement in Alberta’s construction industry have been declining. This decline in Alberta is consistent with the decline of construction productivity in North America region over the past three decades (Jergeas, 2009).

For improving performance of construction productivity, academic researchers and industry practitioners have tried to provide effective productivity measurements. In usual, construction labor productivity is measured in actual work-hours per installed quantity. This measurement has been widely adopted in existing productivity studies (Yi and Chan, 2014). However, this productivity measurement focused on micro-level measurement for construction productivity depending on disciplines and workers. In spite of outstanding contributions from the previous studies, a high-level project productivity measurement has been demanding to capture overall improvement of project productivity for capital projects over time. The
Industry Leaders Roundtable in Alberta seeks a comprehensive measurement of high-level project productivity to challenge the status quo, and formulate “out of the box” thinking to improve Alberta capital project productivity.

This paper contemplates and presents possible measurement of high-level project productivity for Alberta capital projects. This paper aims to identify the most appropriate single, high-level project productivity metric for Alberta’s capital projects in order to gauge overall status and trends across the industry based on pros and cons of each measurement. This paper also compares Alberta capital projects’ project productivity with those of U.S. capital projects as a benchmark.

2 RESEARCH BACKGROUND

2.1 COAA-CII Performance Assessment Initiative

As the principal industry association for capital projects in Alberta, the Construction Owners Association of Alberta (COAA) strives to provide leadership to enable its owner members to be successful in their drive for safe, effective and productive project execution. Since 2005, COAA and CII have had a collaborative partnership for the purpose of benchmarking capital projects in Alberta. Building on the collective expertise of COAA and CII, the COAA Benchmarking program has provided a comprehensive performance assessment system comprised of a customized questionnaire, a dedicated database, and a suite of individualized reports for each company submitting project data as shown in Figure 1. This program was funded by COAA with assistance from Alberta Finance and Enterprise, a component of the provincial government of Alberta, and operated by University of Calgary Performance Assessment Lab.

Since 2005, the collective effort of COAA and CII has focused on exploring the performance and productivity concerning the execution of capital projects in Alberta. This collaboration was premised on the extensive experience of CII in researching and benchmarking industrial facilities in the United States and around the world. Extending CII’s reach into Alberta permitted tremendous understanding of the performance of these projects, especially when compared with similar projects in the United States. In the line of this efforts, this study develops a high-level project productivity metric for Alberta capital projects.
2.2 Macro-Economic Level Workforce Productivity

Statistics Canada, Canada’s national statistical agency, measures labor productivity as an economic indicator across the world, which is calculated by real gross domestic product per hour worked. Real gross domestic product (GDP) (or real value-added) is a chained Fisher quantity index of GDP at basic prices. According to the definitions from the Statistic Canada (Statistic Canada, 2015), the number of hours worked in all jobs is the number of all jobs times the annual average hours worked in all jobs. According to the retained definition, hours worked means the total number of hours that a person spends working, whether paid or not. The hours worked generally includes regular and overtime hours, breaks, travel time, training in the workplace and time lost in brief work stoppages where workers remain at their posts. On the other hand, time lost due to strikes, lockouts, annual vacation, public holidays, sick leave, maternity leave or leave for personal needs are not included in total hours worked. Statistic Canada has adopted this measure to calculate workforce productivity as well as international economic organizations and other countries. Figure 2 was created using annual labor productivity by province and industry that Statistics Canada announced (Statistics Canada, 2015).

![Labor Productivity in Construction](chart.png)

**Figure 2: Labor Productivity in Construction Sector (2007-2013)*

*Courtesy by Statistic Canada (2015)

Figure 2 indicates that the labor productivity trend in the construction sector over the past seven years since global economic recession. During the pre-recession (2007-2009), the labor productivity in the construction sector had declined in both Alberta and Canada. After recession, Alberta’s labor productivity in construction sector has been increasing 20.7% from 2009 to 2013 while the labor productivity in Canada tends to be steady during the same period. In 2013, Alberta’s labor productivity in the construction sector was 1.3 times than overall labor productivity in Canada. This remarkable improvement of the labor productivity in Alberta’s construction sector is consistent with the economic development in Alberta’s economy over the last years.

This labor productivity, which is announced by the government, is representing national and regional economic indicator and is used as a fundamental data when the government develops an economic policies and makes capital investment decisions. However, this indicator has a limitation not to show project-level productivity that can be used for improving performance of owners and contractors. Thus, this paper contemplates the measurement of high-level project productivity metrics that can be applied to individual capital projects.

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3 METHODOLOGY

3.1 High-Level Project Productivity Metrics

To develop high-level project productivity measurement, the reasonable input and output need to be defined to meet the purpose of measurement. This study adopts two approaches for exploring high-level productivity measurement in Alberta capital projects.

First, a quantity-based approach is applied which aggregates construction productivity in major construction disciplines including concrete, structure steel, piping, equipment, electrical, insulation, and instrumentation. Construction productivity of each discipline is measured based on actual work-hours per installed quantity. When using this manner, lower productivity values indicate better productivity performance. Using this quantity-based approach, the CII developed project-level engineering and construction productivity metrics to measure high-level project productivity of capital projects. This approach was applied to measure project-level productivity through standardization and aggregation of productivity metrics of engineering and construction disciplines (Liao, 2012; Chanmeka, 2012). Similarly, the project-level construction productivity metric was calculated through the following procedures:

- Transformation: For calculating project-level productivity metric, the productivity data first needs to be assessed on normality of the distribution because the standardization is conducted based on the assumption of normal distribution of the data. This study checked the normality and skewedness on the distribution of productivity values and applied natural log transformation to transform the skewed productivity data for standardization.

- Standardization: The transformed productivity values of the disciplines were standardized to z-score which standard score which means the number of standard deviations. In practice, the absolute value of this metric represents the distance between the productivity value of one project and the population mean of the productivity values in units of the standards deviation. A value is negative when the productivity is below the average, positive when above.

\[
z_i = \frac{p_{ij} - \mu_i}{\sigma_i}
\]

where: \(z_i\) = z score of \(i^{th}\) construction discipline’s productivity; \(p_{ij}\) = the transformed productivity metric value of \(i^{th}\) construction discipline’s \(j^{th}\) project; \(\mu_i\) = mean value of the transformed productivity metric value of \(i^{th}\) construction discipline; \(\sigma_i\) = standard deviation of the transformed productivity metric value of \(i^{th}\) construction discipline.

- Aggregation: Through the standardization of the productivity values, the variability of productivity values in different disciplines was neutralized and calibrated in the same scale suitable for aggregation. The standardized productivity values of construction disciplines are aggregated using work-hours as the weights because work-hours is usually considered as a common parameter amongst different disciplines (Liao, 2012). The standardized productivity values in different disciplines are aggregated using the following equation:

\[
\text{Project Level Productivity Metric} = \frac{\sum_{i=1}^{n}(WH_i \times z_i)}{\sum_{i=1}^{n}WH_i}
\]
where: \( z_i \) = \( z \) score of \( i^{th} \) construction discipline’s productivity; \( WH_i \) = work hours of the \( i^{th} \) construction discipline.

Second, a cost-based approach is also used which considers costs for construction activities as an output. Total site work-hours is considered as hours worked in construction field. All costs have been normalized in terms of currency, location, and time. The normalized cost are value in 2013 Chicago. Similarly, this approach is applied to high-level productivity measurement. The following costs were considered as output.

- The total constructed cost includes all costs, direct and indirect, inherent in converting a design plan for material and equipment into a project ready for start-up or commissioning, but not in production operation; the sum of field labor, supervision, administration, tools, field office expense, materials, equipment, and subcontracts. Therefore, this study uses sum of procurement and construction cost as total constructed cost.
- The construction phase cost includes the costs of construction activities from commencement of foundation or driving piles to mechanical completion. The costs include construction project management, construction labor, and also equipment and supplies costs that are used to support construction operations and removed after commissioning. The CII defined construction direct and indirect costs for detail of typical cost elements in construction phase.
- The equipment cost is the total cost of major equipment. The major equipment is commonly used interchangeably with engineered equipment. It is generally defined as tagged/numbered process or mechanical equipment including drivers.

When using this cost-based approach, larger productivity values indicate better productivity performance because the costs indicate amount of construction works that have been done as output. For calculating cost-based productivity metrics, the following simple equation is applied.

\[
\text{Project Productivity Metric} = \frac{\text{Cost for construction activities}}{\text{Work-hours}}
\]

In addition to that, the ratio of construction phase cost to procurement cost is also considered as a high-level productivity metric. This metric indicates that how much construction cost is larger than procurement cost considering major equipment and large modularization. If major equipment or modularization is larger, the value of this metric would be smaller.

Based on these two approaches for measuring high-level project productivity, this study investigates the following five candidate as high-level project productivity measurement.

1. Project Level Construction Productivity
2. Total Constructed Cost/Total Site Work-hours
3. (Total Constructed Cost – Equipment Cost)/Total Site Work-hours
4. Construction Phase Cost/Total Site Work-hours
5. Construction Phase Cost/Procurement Cost

### 3.2 Data Sources and Collection

This paper uses the data extracted from CII Performance Assessment Database and COAA Major Project Benchmarking Database. The CII Performance Assessment has collected capital projects data into its database through the collaboration with more than 130 industrial partners including leading construction owners and contractors around world. As of 2014, CII Performance Assessment Database suppressed 2,300 projects in its database, exceeding over $300 Billion (USD) of cumulative capital project investment since 1995 (CII, 2014).

By 2014, 60 Alberta capital project data has been collected in the COAA Major Project Benchmarking system which mainly consisted of oil sands projects including oil sands SAGD, oil sands upgrading, oil sands mining/extraction, oil and gas exploration, pipeline, and so on. The project data were extracted in
the databases if the middle point of construction phase of the projects was 2001 and later conducted in United States and Alberta.

3.3 Analysis Methods

Once the high-level project productivity measurements are determined, this study calculates each project productivity metric and compares its mean between Alberta and U.S. projects. To compare the mean of high-level productivity metrics and their distributions between two regions. An independent sample t-test was applied to project productivity comparisons. The independent sample t-test is a parametric test and two-sample test. This analytic method tests if the means between two groups are same or not. Thus, this study applied the independent sample t-test to test if the mean value of project productivity between Alberta and U.S capital project during the given period at 0.05 significant level. If a p-value of the t-test is less than 0.05, the result indicates the mean value of two groups are significantly different. Using this statistical analysis, this paper presents comparing means of project productivity between Alberta and U.S. capital projects.

4 HIGH-LEVEL PROJECT PRODUCTIVITY BENCHMARKS

4.1 Quantity-based High-Level Project Productivity

As a quantity-based high-level project productivity, the project-level construction productivity developed by CII was applied to comparison of project productivity between Alberta and U.S. capital projects. The value of the project-level construction productivity metric indicates that smaller productivity value indicates better productivity performance. In this study, the zero (0) value indicates the mean of productivity values of capital projects built in North America region.

![CII Project Level Construction Productivity](Image)

Figure 3: Project-Level Construction Productivity Trends (2001-2011)

Figure 3 shows the comparison of the results of project-level construction productivity of Alberta and U.S. projects. The average of project level construction productivity in Alberta projects was 0.30 while that was -0.03 in U.S. projects. The 0.3 of the mean values of Alberta projects indicates 0.3 standard deviation above the mean of North America’s construction productivity. On the other hand, the average of U.S.
projects is -0.03 that indicates the average of construction productivity of U.S. projects is below the mean of North America’s productivity. As the results from the t-test, there was a significant difference in the project level construction productivity for Alberta projects (Mean=0.30, SD=0.69) and U.S. project (Mean=-0.03, SD=0.66) at the 0.05 significant level (p = 0.021). This result indicates that Alberta projects’ construction productivity was above the average of capital projects’ construction productivity in North America. Also, the average of Alberta projects’ construction productivity was statistically significantly worse than that of U.S. projects.

4.2 Cost-based High-Level Project Productivity

High-level project productivity values measured by cost-based metrics were compared between Alberta and U.S. projects as can be seen in Figure 4. The value of the productivity metric developed based on cost-based approach indicates that larger productivity value indicates better productivity performance. That is, the larger value indicates that more amount of construction works has been done during one hour.

![Image of box plots showing cost-based high-level project productivity](image)

Figure 4: Cost-based High-Level Project Productivity

- **Total Constructed Cost/Total Site Work-hours**: The project productivity metric “Total Constructed Cost/Total Site Work-hours” means that the sum of procurement and construction cost per one hour worked in a capital project. The mean value of the project productivity of Alberta projects was US $215.58 per hour while that of U.S. projects was US $221.98 per hour. Thus, the U.S. projects’ productivity was slightly better than that of Alberta projects but the t-test results shows that there was no significant difference between Alberta and U.S. projects (p-value=0.793).
• (Total Constructed Cost – Equipment Cost)/Total Site Work-hours: The project productivity metric “(Total Constructed Cost–Equipment Cost)/Total Site Work-hours” means that the total constructed cost excluding major equipment cost per one hour worked in a capital project. The mean value of the project productivity of Alberta projects was US $157.47 per hour while that of U.S. projects was US $157.21 per hour. Thus, the Alberta projects’ productivity was slightly better than that of U.S. projects but the t-test results shows that there was no significant difference between Alberta and U.S. projects (p-value=0.989).

• Construction Phase Cost/Total Site Work-hours: The project productivity metric “Construction Phase Cost/Total Site Work-hours” means that the amount of construction phase cost per one hour worked in a capital project. The mean value of the project productivity of Alberta projects was US $161.75 per hour while that of U.S. projects was US $174.28 per hour. Thus, the U.S. projects’ productivity was slightly better than that of Alberta projects but the t-test results shows that there was no significant different between Alberta and U.S. projects (p-value=0.526).

• Construction Phase Cost/Procurement Cost: The project productivity metric “Construction Phase Cost/Procurement Cost” means that the ratio of construction phase cost to procurement cost for a capital project. The mean value of the project productivity of Alberta projects was 2.99 while that of U.S. projects was US 2.94. The value of Alberta projects (2.99) means that the construction phase cost is about three times more than procurement cost. The larger metric value indicate that the project spent smaller amount of procurement cost including equipment cost compared to other projects. Alberta project procures engineered modules Thus, the Alberta projects’ productivity was slightly better than that of U.S. projects but the t-test results shows that there was no significant different between Alberta and U.S. projects (p-value=0.793).

5 CONCLUSIONS AND PATH FORWARD

This study contemplates a high-level project productivity metrics that can be used for achieving stable planning and engineering to provide the baseline estimates of planned performance. Five measurements for high-level project productivity were developed and investigated through comparison between Alberta and U.S. projects. These metrics can be used to fill the gap between country- and industry-level labor productivity calculated by government and activity- and discipline-level productivity. As the results from the t-test analysis of the productivity between Alberta and U.S. projects, Alberta projects’ project productivity tends to be lower than that of U.S. projects and can be more improved. The relatively lower productivity of Alberta’s capital projects, especially large oil and gas construction projects causes various factors such as the apparent management deficiency in management scope, time, quality, cost, productivity tools, scaffold, equipment, materials, and lack of leadership, and others (Jergeas, 2009).

For capturing high-level project productivity, the measurement requires to be easily understandable and accepted as a measure of macro-efficiency of construction execution, dis-aggregatable to figure out causes, and practical to tract and record. Based on these requirements against high-level project productivity metric, only project-level construction project productivity metric developed at CII can be dis-aggregatable. So, it can be used for the high-level productivity measurement for Alberta capital projects. However, the high level productivity measurement needs to more elaborated and improved for capturing impact of off-site costs and module costs that are very significant component of capital projects. Although the COAA-CII collective efforts lead about 60 Alberta’s projects in the COAA Large Major Benchmarking System, the number of the submitted projects is not enough to create time series trend over the time with statistical significance. Therefore, the more data collection of Alberta’s projects may be required to develop better productivity measurements.
References


REVIEW OF BIM QUALITY ASSESSMENT APPROACHES FOR FACILITY MANAGEMENT

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\textsuperscript{3} p.zadeh@civil.ubc.ca

Abstract: Assessing the quality of information in building information models (BIM) at the time of project handover is critical for owners. Lack of quality information in delivered BIMs can cause significant issues in using BIM for facility management purposes, potentially limiting or preventing their use in building operations. Our studies of numerous BIM projects and deliverables have found that most BIMs created for design and construction today contain significant quality issues including inaccurate, incomplete, or unnecessary information. To make these models useful for building operations requires significant adjustment to the models, which can be very time-consuming and costly. This paper describes different types of quality issues identified through numerous case studies of BIM projects and categorizes them according to different model perspectives (entity, model, and user level) and relevant facility management perspectives (assets, MEP systems, and spaces). We identify the different characteristics of each type of quality issue and then systematically analyze relevant literature in the AEC and computer science domains to put these issues in context. This analysis highlights the ambiguity in characterizing information quality issues in a BIM and demonstrates the need for a comprehensive and consistent formalization of BIM quality.

1 INTRODUCTION

Assessing the information quality (IQ) of building information models (BIM) for facility management (FM) purposes is a critical and challenging task for owners at the time of project handover. Lack of IQ in delivered BIM could have costly consequences for owners, including: manual adjustments to correct and complete the models; laser-scanning of (a part of) the building and related post processing efforts; and delays in the start of FM systems. Currently, researchers and owner organizations have different perspectives about the IQ of BIM, which consequently lead to different approaches to its assessment. Although organizations like U.S. General Services Administration (GSA) and British Standards Institution (BSI) have developed approaches to enforce BIM requirements throughout the project handover (BSI 2014, GSA 2011), such approaches are mainly based on generic checks and do not cover all required IQ characteristics for FM needs. For proper BIM-IQ assessment, it is necessary for owners to have a clear understanding about “what” are the potential quality issues, “which” IQ characteristics are relevant, and “how” to assess them.

The objective of this paper is to contribute to the development of a comprehensive and consistent representation of BIM quality for owners. Through numerous case studies of BIM projects and interviews with FM personnel, we describe different types of quality issues and categorize them according to
different model perspectives (entity, model, and user level) and relevant facility management perspectives (assets, MEP systems, and spaces) in section 2. In section 3, we identify the different characteristics of each type of quality issue and then systematically analyze relevant literature in the AEC and computer science domains. This analysis highlights the ambiguity in characterizing information quality issues in a BIM, demonstrating the need for a comprehensive and consistent formalization of BIM quality for owners.

2 BIM QUALITY ANALYSIS FRAMEWORK FOR FM

The motivation of this study has its roots in numerous case studies of BIM project deliverables and interviews with various FM personnel. In order to systematically analyze the different types of BIM quality issues, we developed an analysis framework considering different FM categories and model analysis perspectives (Table 1). Generally, FM information management systems (IMS) require information related to three essential terms: assets, MEP systems, and spaces. Although MEP systems may be considered a compilation of different assets, there are still differences between asset related and MEP system related IQ issues. Therefore, we divided the observed IQ issues accordingly in terms of assets, MEP systems, and spaces. Furthermore, the BIM-IQ issues can be categorized into different types from different analysis perspectives of model consumption. We determine these perspectives as: 1) entity level, which focuses on the smallest information pieces in a model; 2) model level, which considers the entire BIM as one information package; and 3) user level, which analyzes the information system from the model user’s perspective.

Table 1: BIM-IQ analysis framework for FM

<table>
<thead>
<tr>
<th>FM Categories</th>
<th>Entity Level</th>
<th>Model Level</th>
<th>User Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Asset</strong></td>
<td>Incomplete Assets (Table 2)</td>
<td>Inaccurate Asset Placement (Table 6)</td>
<td>Compliance with BIM Standards (Table 8)</td>
</tr>
<tr>
<td>MEP Systems</td>
<td>Incomplete MEP Systems (Table 3)</td>
<td>Inaccurate Spatial Allocation of MEP Systems (Table 7)</td>
<td>Model Clashes</td>
</tr>
<tr>
<td><strong>Space</strong></td>
<td>Incomplete Spaces</td>
<td>Inaccurate Space Placement</td>
<td></td>
</tr>
<tr>
<td><strong>Issue Type Categories:</strong></td>
<td>Information Incompleteness (sec. 3.1)</td>
<td>Value Inaccuracy (sec.3.2)</td>
<td>Spatial Inaccuracy (sec. 3.3)</td>
</tr>
</tbody>
</table>

The analysis methodology below follows the structure of this framework. Specifically, we go through each issue type to analyze them systematically in correspondence with the related FM category. As the first step of the systematic analysis, we briefly describe each issue type by giving specific examples from a case study project. This description includes the IQ characteristics that are affected as well as their relevance for FM. In the next analysis step, we discuss the relevant literature for each type of quality issue. This includes the terms used by researchers to address these issues, the general topic that they discuss and their proposed approaches for preventing (IQ assurance) or identifying (IQ assessment) such issues. Finally, we evaluate these different perspectives and discuss the potential research gaps for each issue type.

3 TYPES OF QUALITY ISSUES AND RELEVANT LITERATURE

This section presents a systematic analysis of each type of BIM quality issue from the BIM-IQ analysis framework introduced above in Table 1. In this analysis, we start with the entity level perspective and discuss the issue types related to assets, MEP systems, and spaces, and then continue with the model and user level perspectives.
3.1 Information Incompleteness (Entity Level)

Incomplete Assets: Assessing the information completeness of assets means to check if all necessary equipment are represented in BIM. This step is related to the identification of available MEP systems in the building and their completeness assessment (Table 2). Therefore, it is necessary to identify which systems are in the models first and then check which major assets these systems must have. There are two reasons for considering only the major assets and not all of them in this assessment. First, when the available BIM is not representing the as-built situation, like in our case studies, then many assets and details are missing in the available model. As a result, the modeling of the entire missing assets will require a huge amount of effort. Second, an FM-IMS does not necessarily require detailed information for all assets. According to our interviews with FM experts, the fact is that it is not reasonable from a time and resource point of view to consider all single assets in such FM-IMS. Hence, as for information completeness, the models have to contain at least the major assets completely. For this purpose, it is necessary to check the existence of major assets, their quantity and their necessary attributes. For example, Table 2 shows a missing expansion tank in the MEP BIM of our case study project.

Table 2: Incompleteness of modeled assets

<table>
<thead>
<tr>
<th>Short Description</th>
<th>The existence of necessary asset information in BIM for creating intelligent FM-IMSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example</td>
<td><img src="image" alt="Figure 1: The large white expansion tank in the as-is (a) is missing from the MEP BIM (b) of the same space in CIRS." /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>Used Term</th>
<th>General Discussion Topic</th>
<th>Assessment / Assurance</th>
<th>Used Method</th>
<th>Reference</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Completeness</td>
<td>Required BIM objects and properties</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(GSA 2011)</td>
<td>AEC</td>
</tr>
<tr>
<td>2</td>
<td>Completeness</td>
<td>Value of Information for Facilities Management</td>
<td>Assessment</td>
<td>–</td>
<td>(Kasprzak et al.)</td>
<td>AEC</td>
</tr>
<tr>
<td>3</td>
<td>Included Info.</td>
<td>Quality Assurance</td>
<td>Assurance</td>
<td>–</td>
<td>(Kulušjärvi 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>4</td>
<td>Missing Objects</td>
<td>Correctness</td>
<td>Assessment</td>
<td>Survey</td>
<td>(Berard 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>5</td>
<td>Accuracy</td>
<td>Data and Process Requirements</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(Becerik-Gerber et al. 2011)</td>
<td>AEC</td>
</tr>
<tr>
<td>6</td>
<td>Data Richness</td>
<td>Minimum BIM</td>
<td>Assurance</td>
<td>–</td>
<td>(National Institute of Building Sciences 2007)</td>
<td>AEC</td>
</tr>
<tr>
<td>7</td>
<td>Detailed and Comprehensive</td>
<td>Quality of Laser-Scanned Data</td>
<td>Assessment</td>
<td>Photo Analysis</td>
<td>(Tang et al. 2011)</td>
<td>AEC</td>
</tr>
<tr>
<td>8</td>
<td>Completeness</td>
<td>Data Quality</td>
<td>–</td>
<td>–</td>
<td>(Olson 2002)</td>
<td>CS</td>
</tr>
<tr>
<td>9</td>
<td>Completeness</td>
<td>Quality of Raw Data</td>
<td>–</td>
<td>–</td>
<td>(Assaf and Senart 2012)</td>
<td>CS</td>
</tr>
<tr>
<td>10</td>
<td>Completeness</td>
<td>Data Quality Dimensions</td>
<td>–</td>
<td>–</td>
<td>(Wand and Wang 1996)</td>
<td>CS</td>
</tr>
</tbody>
</table>

Table 1 shows that although different researchers discuss such IQ issues in different contexts (“General Discussion Topic”), most of them address this issue type as “information completeness.” However, only a few of them propose specific methods for assessment or assurance of this IQ characteristic. For instance, in (Becerik-Gerber et al. 2011), the authors propose a list of required information for FM that should be captured in BIM during design and construction. This generic list requires information for assets’ description (like type, serial number, criticality, and status), attributes (like weight, power, and energy consumption), manufacturer (like serial, model, and part numbers) as well as the location of the assets (like building, floor, and space). A more comprehensive list of assets can be found in OmniClass Table 21.
(2006). This list follows an object-oriented approach and so provides a hierarchy for each asset type that can have up to seven levels. The examples above and the similar references (GSA 2011, Kulusjärvi 2012, National Institute of Building Sciences 2007, SBCA 2013) show that the main focus of the AEC researchers regarding to the information completeness is on the IQ assurance by using one of the introduced methods above. However, significant issues remain in terms of how to deal with the incomplete models, how to incorporate such checklists and hierarchies and integrate them into the owner’s requirements and how to assess them in a given BIM.

**Incomplete MEP Systems:** It is necessary for FM-IMS to define MEP systems completely in the mechanical BIM (GSA 2011, Kulusjärvi 2012, SBCA 2013, USC 2012). However, our analysis of BIM projects demonstrates that MEP systems are frequently defined inaccurately and incompletely in the mechanical BIM as in our case study (Table 3). This type of IQ issue is very similar to the incompleteness of assets with the difference that in this case one should investigate the entire components of a system or a sub-system.

### Table 3: Incompleteness of system definitions in BIM

<table>
<thead>
<tr>
<th>#</th>
<th>Used Term</th>
<th>General Discussion Topic</th>
<th>Assessment / Assurance</th>
<th>Used Method</th>
<th>Reference</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>Required BIM objects and properties</td>
<td>Assurance Checklist</td>
<td></td>
<td>(GSA 2011)</td>
<td>AEC</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>System BIM</td>
<td>Assurance Checklist</td>
<td></td>
<td>(Kulusjärvi 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>MEP Quality Assurance</td>
<td>Assurance Checklist</td>
<td></td>
<td>(SBCA 2013)</td>
<td>AEC</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>MEPF Specifications</td>
<td>Assurance Checklist</td>
<td></td>
<td>(USC 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>Assurance COBie</td>
<td></td>
<td>(BIM Task Group 2012)</td>
<td>AEC</td>
</tr>
</tbody>
</table>

The information about systems is especially significant for intelligent troubleshooting processes where one does not exactly know which equipment is not working properly as well as for better understanding the consequences when an asset is broken. The completeness check for MEP systems should include the identification of assets without a specific system as well as systems that miss a major asset as a member (either the major asset is not modeled or it is not assigned to the system). As shown in Table 3, even though this IQ issue type and its consequences for the projects are not explicitly discussed in detail among AEC researchers yet, there are few (but important) references that propose IQ assurance approaches to avoid incompleteness in the MEP system definitions. Nevertheless, there is a research demand for evaluation of the assurance methods, and for the assessment of the required system attributes and the relevant system components (assets).

**Incomplete Spaces:** In addition to assets and systems, spaces play also a crucial role in an FM-IMS. The representation of spaces in a BIM can support FM personnel particularly for what-if analyses, decision-making sessions, and routing the service components (Akcamete et al. 2010, Becerik-Gerber et al. 2011, Nepal et al. 2012). However, incomplete space information makes such processes more difficult. Researchers treat incompleteness of spaces in BIMs as an obvious issue that should be addressed. Therefore, this issue type has not been discussed as a separate topic yet and its assessment is usually included together with other building entities as a part of general checks, as in (Kulusjärvi 2012, LACCD BIMS 2010, National Institute of Building Sciences 2007, SBCA 2013, USC 2012).
3.2 Value Inaccuracy (Entity Level)

**Inaccurate Values for Asset Attributes:** In a desired BIM for FM, it is significant that the major assets are defined accurately. That means that the modeled assets must have the required attributes with precise values, their type must be correct and they need to be represented in the model with the correct size. In addition, the asset names must be clear, meaningful and not redundant. Inaccuracies in the attribute values is a very common IQ issue that we also recognized in our observations (Table 4).

### Table 4: Inaccurate definition of modeled assets

<table>
<thead>
<tr>
<th>Short description</th>
<th>Major assets must have the required attributes with precise values, their type must be correct and they need to be represented in the model at the right place with the correct size.</th>
</tr>
</thead>
</table>

### Example

[Image of example: Figure 3: Example of inaccurate information for heat pump #03]

---

Reviewing related literature shows that when AEC researchers discuss the quality of BIMs, they strongly connect it to the accuracy aspect of the IQ and mainly use this term to address IQ characteristics related to the modeled “values”. However, much of the reviewed literature either does not specifically describe their interpretation of this term in more detail, as in (Du et al. 2014, GSA 2011, Kasprzak et al., National Institute of Building Sciences 2007), or the literature describes it in different ways. For example, (Berard 2012) refers to accuracy through different terms like information “precision”, “unambiguity” and “level of detail.” Du et al. (2014) define information accuracy as the degree to which the BIM models precisely reflect the physical real world conditions of a project. (Kulusjärvi 2012) address the accuracy aspect of IQ through the term “correctness.” These examples highlight a certain degree of ambiguity among AEC researchers when they discuss the quality values in a model. In contrast to the AEC researchers, the CS researchers organize these aspects in a different way. For example, (Lee et al. 2002) assign all value-related IQ aspects to the “intrinsic” IQ category. This category covers aspects like correctness,
unambiguous, consistency, precision, reliability, etc. which match mostly with the different interpretations of accuracy in the AEC domain. Nevertheless, there is still a great potential for unambiguous analysis of each of these aspects. In addition, Table 4 shows that the researcher mainly focus on using checklist for accuracy assurance and assessment methods. However, using checklists is a very generic approach and leaves room for different interpretations.

**Inaccurate Values for System Definitions:** In contrast to the completeness of MEP systems, the accuracy of system definitions has not been discussed explicitly in the AEC literature yet. The main reason is that such systems can be considered as a composition of different assets (as system components) and so the value accuracy of asset’ attributes can result in a certain level of accuracy for the related system. Thus, the values of important system attributes can be calculated as summations of related asset attributes, as for system flow, total pressure, electricity voltage, medium type, etc. Therefore, most of the BIM authoring tools offer automated calculations for system attributes. Nevertheless, there are system attributes that describe specifically a system without a direct connection to the system components (Figure 5), like system names, types, classifications, and related documents (specs, sequence of operation, etc.). Thus, this IQ issue type has a high potential for further research to identify the consequences of inaccurate system information for FM-IMSs.

**Inaccurate Values for Space Definitions:** Unlike incompleteness of spaces (and similar to other value inaccuracy issues discussed above), AEC researchers put emphasis on IQ of space definitions. Figure 5(a) in Table 5 shows an example from our case study where the space definition in BIM is inaccurate and incomplete. Figure 5(b) shows how building operation personnel keeps track of changes in the space arrangement with the help of printed PDF floor plans. The space related inaccuracies in the architectural BIM include spaces with incorrect utilization as well as spaces with different names from the actual space names in the building. A similar space related issue is the compliance of the room names with a required nomenclature by the owner. Such compliance is also documented in (Kulusjärvi 2012, LACCD BIMS 2010, National Institute of Building Sciences 2007, SBCA 2013, USC 2012).

![Figure 4: Inaccurately defined system attributes for an air terminal in our case study](image)

![Figure 5: Inaccuracy and incompleteness in space definitions CIRS architectural BIM](image)

<table>
<thead>
<tr>
<th>#</th>
<th>Used Term</th>
<th>General Discussion Topic</th>
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<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>Spatial BIM</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(Kulusjärvi 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>Space Validation</td>
<td>Assurance</td>
<td>COBie</td>
<td>(USC 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>3</td>
<td>Space Requirements</td>
<td>Modelling Requirements</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(LACCD BIMS 2010)</td>
<td>AEC</td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>Quality Assurance</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(SBCA 2013)</td>
<td>AEC</td>
</tr>
<tr>
<td>5</td>
<td>Space Management</td>
<td>Data Requirements for FM</td>
<td>–</td>
<td>–</td>
<td>(Becerik-Gerber et al. 2011)</td>
<td>AEC</td>
</tr>
</tbody>
</table>
3.3 Spatial Inaccuracy (Entity Level)

This IQ issue category is about the inaccuracies in placing the entities in a three-dimensional environment as in BIM. This group of issue types is significant because the spatial placement of entities brings the architectural and mechanical information hierarchies together.

**Inaccurate Asset Placement:** For facility operations, it is very important to find the related spaces for different assets (Asen et al. 2012). Becerik-Gerber et al. (2011) and Cotts et al. (2009) suggest facility managers ensure that the trade mechanics are familiar with equipment location. This highlights the significance of trades’ personal experiences with a facility where an intelligent FM-IMS is not available. Hence, using BIM could be a suitable alternative approach through accurate placements of assets in spaces. This requires both the accurate space definition as well as accurate asset placement in the space according to a spatial hierarchy. This placement is not only about identifying in which space is an asset located but also it is about determining where exactly this asset is placed in the assigned space.

Table 6: Asset placement

<table>
<thead>
<tr>
<th>#</th>
<th>Used Term</th>
<th>General Discussion Topic</th>
<th>Assessment / Assurance</th>
<th>Used Method</th>
<th>Reference</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spatial relationship</td>
<td>Visual Analytics for FM</td>
<td>--</td>
<td>--</td>
<td>(Asen et al. 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>Quality Assurance</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(SBCA 2013)</td>
<td>AEC</td>
</tr>
<tr>
<td>3</td>
<td>Spatial BIM</td>
<td>BIM Requirements</td>
<td>Assurance</td>
<td>Checklist</td>
<td>(Kulusjärvi 2012)</td>
<td>AEC</td>
</tr>
</tbody>
</table>

Finding assets’ exact location is challenging in projects without an as-built model, as in our case study. The reasons are first, mechanical and architectural models are usually separate models and need to be merged and adjusted, and second, it is challenging to assign assets correctly within a wall or ceiling to a space in an automated way. For instance, the height of a room begins from the top of the floor to bottom of the ceiling. Therefore, the challenge is to find the correct space for the assets within the floors’ slab. Figure 6 in Table 6 shows an example of assets within a second floor slab that belong either to the upper space (like diffusers) or to the space below (like light fixtures). Inaccuracy in asset placement in BIMs is a significant issue for creating FM-IMSs. Reviewing related literature shows that this IQ issue type is only marginally addressed in few publications and general expectation is that modelers assure the accuracy of asset-space relation by using a list of certain generic measures. However, a clear IQ assessment approach in this connection is missing.

**Inaccurate Spatial Allocation of MEP Systems:** The relationship between MEP systems and spaces must include both the actual location of system components (assets) in the building as well as the served spaces by each MEP system. This is also emphasized in (Asen et al. 2012) where they describe such relationships as “spatial” for physical relation between assets/systems and spaces, and as “logical” for non-physically related assets/systems and spaces. The spatial relationship between MEP systems and spaces can be considered as a summation of space assignments for individual system components (assets). Thus, through an accurate system definition and correct placement of assets in spaces, this kind of issues can be avoided. The logical relation corresponds to the identification of which space(s) are served through a system (Table 7). This is significant for systems with a central role in a building, which usually serve spaces (mechanical zones) other than the location of their major assets.
Table 7: Spatial allocation of MEP systems

<table>
<thead>
<tr>
<th>Short description</th>
<th>General Discussion Topic</th>
<th>Assessment / Assurance</th>
<th>Used Method</th>
<th>Reference</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Served zones</td>
<td>FM Handover Model</td>
<td>Assessment</td>
<td>COBie</td>
<td>(East et al. 2013)</td>
<td>AEC</td>
</tr>
<tr>
<td>2 Served area</td>
<td>BIM for FM</td>
<td>–</td>
<td>–</td>
<td>(GSA 2011)</td>
<td>AEC</td>
</tr>
<tr>
<td>3 Zoning</td>
<td>COBie.Zone</td>
<td>Assessment</td>
<td>COBie</td>
<td>(Teicholz 2013)</td>
<td>AEC</td>
</tr>
<tr>
<td>4 –</td>
<td>Operation and Maintenance Information</td>
<td>Assessment</td>
<td>COBie</td>
<td>(BIM Task Group 2012)</td>
<td>AEC</td>
</tr>
</tbody>
</table>

Identification of served spaces is very relevant for FM (East et al. 2013, GSA 2011, Teicholz 2013, USC 2012), since such significant systems usually require frequent maintenance and the buildings operators need to know which building parts are affected when a system needs to be maintained. Automated identification of served spaces for MEP systems is more complicated than the location finding challenge above. Our review of related literature in Table 7 reveals that in the discussion about spatial allocation of MEP systems, researchers have been focused so far on the quality assessment measures for BIM mainly using COBie spreadsheets.

### 3.4 Model Incompatibility (Model Level)

Model incompatibility is about the model compliance with BIM standards and is an important IQ issue type from the model level perspective (Table 8). This issue type is about whether or not the information within the model is compatible with specific data structures. In other words, this issue type corresponds to the way the information is organized in BIM and it is related to all FM categories (assets, MEP systems and spaces). This is an important IQ characteristic, since the compliance with a standardized data structure, such as IFC, can shape the modeling process, facilitate information exchange between different BIM authoring tools and as a result can increase the quality of collaboration in a project (Kulusjärvi 2012, LACCD BIMS 2010). In addition to IFC standards, some literature propose the use of BIM exchange standards (like COBie) as alternative benchmarks for model compatibility assessments. For instance, the authors in (East et al. 2013, Kasprzak et al., Teicholz 2013, USC 2012) suggest to perform compatibility checks with COBie standard worksheets as a quality control approach. Moreover, the authors in (USC 2012) propose the compatibility checks with EcoDomus as an alternative to COBie for IQ control purposes. Our literature review results that AEC researchers have comprehensively researched model compatibility with BIM standards (Table 8). However, they address it through very different terms. For example, the authors in (Kasprzak et al.) describe it as “Data & Process Standardization” and propose that the modeled information should be in compliance with specific standards, like the internal standards of the Office of Physical Plant (OPP) at the Pennsylvania State University. This approach is similar to the “Quality Control” checks that the authors in (Messner and Kreider 2013) demand as a part of owner requirements. (Schuette and Rotthowe 1998) address the validation of an information system as the “Language Adequacy” of the model. This emphasizes the importance of this IQ aspect, i.e., the information structure as the “grammar” for organizing data, for the researchers before the BIM era. An alternative approach to check the validation of model data structure is to analyze the warnings that specific BIM artifacts report as described in (Du et al. 2014, USC 2012). An extensive analysis about the warning messages in BIM artefacts is given in (Lee et al. 2015). They divide these warnings into three categories: annotation, information and geometry warnings. The interesting point about such researches is that they do not only propose approaches for assessing IQ issues but also provide analyses to identify the reason of those warnings, which makes this type of researches more valuable.
Table 8: Compliance with BIM standards

<table>
<thead>
<tr>
<th>#</th>
<th>Used Term</th>
<th>General Discussion Topic</th>
<th>Assessment / Assurance</th>
<th>Used Method</th>
<th>Reference</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compliance to Specific Standards</td>
<td>Quality Management</td>
<td>Assessment</td>
<td>Vendor based Applications</td>
<td>(Kasprzak et al.)</td>
<td>AEC</td>
</tr>
<tr>
<td>2</td>
<td>Non-Compliant Elements</td>
<td>Quality Control</td>
<td>Assurance</td>
<td>Using OPP</td>
<td>(Messner and Kreirder 2013)</td>
<td>AEC</td>
</tr>
<tr>
<td>3</td>
<td>Model Quality</td>
<td>BIM Performance</td>
<td>Assessment</td>
<td>Warnings</td>
<td>(Du et al. 2014)</td>
<td>AEC</td>
</tr>
<tr>
<td>4</td>
<td>COBie Compliance</td>
<td>COBie standard worksheets</td>
<td>Assurance</td>
<td>COBie</td>
<td>(USC 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>5</td>
<td>BIM Quality</td>
<td>BIM requirements</td>
<td>Assurance</td>
<td>IFC</td>
<td>(Kulusjärvi 2012)</td>
<td>AEC</td>
</tr>
<tr>
<td>6</td>
<td>Model Control</td>
<td>BIM Integration</td>
<td>Assessment</td>
<td>IFC Analysis</td>
<td>(Manzione et al. 2011)</td>
<td>AEC</td>
</tr>
<tr>
<td>7</td>
<td>Interoperability/IFC Support</td>
<td>Minimum BIM</td>
<td>Assessment</td>
<td>MVD</td>
<td>(National Institute of Building Sciences 2007)</td>
<td>AEC</td>
</tr>
<tr>
<td>8</td>
<td>Language Correctness</td>
<td>Language Adequacy</td>
<td>–</td>
<td>–</td>
<td>(Schuette and Rothowe 1998)</td>
<td>AEC</td>
</tr>
<tr>
<td>9</td>
<td>Compliance to the Model’s Metamodel</td>
<td>Well-formedness</td>
<td>–</td>
<td>–</td>
<td>(Mohagheghi and Aagedal 2007)</td>
<td>CS</td>
</tr>
<tr>
<td>10</td>
<td>Typing</td>
<td>Quality of raw data</td>
<td>–</td>
<td>–</td>
<td>(Assaf and Senart 2012)</td>
<td>CS</td>
</tr>
</tbody>
</table>

4 CONCLUSION

In this paper, we present a novel division of typical IQ issues in BIM for FM into six categories. The information incompleteness and the value inaccuracy have been the subject of many research works, especially in connection with real objects (like assets). Nevertheless, there is still a great research demand for studying different accuracy aspects like value precision and correctness. As for spatial inaccuracy issues, whereas spaces as location of assets have been subject of several studies, there is a demand for future research about the relation between assets/MEP systems and served spaces, which is an essential aspect from FM perspective. System related issues are issues in the semantic of a model. To prevent such issues, researchers propose different instructions and checklist. Nevertheless, an automated method for identification and correction of such issues is a potential subject for future works. IQ issues related to the model incompatibility and uncoordinated information are well-studied fields by AEC researchers. Therefore, it is necessary that the owners deploy these studies to create suitable BIM-IQ strategies and assure the quality of required information for operation phase in the early phases of the project. This research shows the need for further studies on BIM quality and for automated IQ assessment approaches especially at the time of project handover to owners.

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National Institute of Building Sciences. 2007. Transforming the Building Supply Chain Through Open and Interoperable Information Exchanges.


AN AUTOMATED MODEL FOR SELECTING THE OPTIMUM MOBILE CRANE MODEL AND ON-SITE POSITION USING GENETIC ALGORITHMS

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Abstract: Selecting both the optimum mobile crane model for a lift job and identifying collision-free position on site can result in productivity and safety improvements. Planning for lift operations is a task carried out by experienced lift engineers who examine each mobile crane’s lift-capacity specifications as provided by the cranes manufacturer to determine the most suitable mobile crane, configuration settings and a collision-free placing location. In this paper, an automated model was developed that follows a four-stepped algorithm process. First, is an algorithm that acquires the user defined lift requirements and calculates the required crane configuration settings using non-linear trigonometric equations. Second, is an algorithm that selects a crane model from the database of mobile crane models which mostly fits the calculated configuration in terms of crane safety and operation. Third, an algorithm that provides safety and clearance checks for the selected configuration. Finally, Genetic Algorithms are applied to optimize the process and to select the optimum crane model that has the safest configuration settings to use as well as its optimum placing location on site. The model was designed to generate a site layout plan as an output with a Cartesian coordinate system in order to assist the lift engineers in their planning for lift operations. The model was validated through its implementation on a working construction project in Cairo, Egypt. The outcomes highlighted the potential benefit of the model in assisting lift engineers in the planning of lift operations on construction sites and demonstrated its essential features.

1 INTRODUCTION

Heavy lifts planning require the selection of an appropriate type of crane that is capable of carrying, slewing and placing a load without endangering the safety of the crane and the ongoing site operations. In general, mobile cranes are more suitable for typical infrequent heavy lifts such as placing mechanical equipment on building roofs, steel structure erection, etc. The task of selecting a mobile cranes and developing engineered-lift-studies is a crucial part in any heavy lift operation planning. This is due to the fact that, selecting the appropriate mobile crane for a specific lift contributes to the overall project’s productivity; thus, minimizing schedule delays and cost overruns (Hanna 1994). In practice, heavy lifts planning is prepared by experienced lift engineers. Their task is to (1) determine the most adequate crane configuration settings that can safely carry the required load and (2) identify the most appropriate placing location on site that is collision-free with all the nearby structures. A typical mobile crane’s specification has a number of charts including: model geometry and dimensions, lift-capacity charts and boom length range charts. Lift engineers use these charts to determine the best configuration in terms of: operating radius, operating boom angle to ground and the boom length extension which correspond to the weight of the object required to be lifted. Unfortunately, heavy lifts planning is a manual human-based calculation.
which is prone to errors and requires some interpolation and guesswork between charts. Moreover, it does not guarantee the selection of the best mobile crane for the job and its most appropriate onsite location. However, the mobile crane selection and location problem is not new, previous studies have tackled this problem from different perspectives as will be discussed in the next section.

2 PREVIOUS STUDIES

2.1 Mobile Crane Selection

A number of studies have focused on automating the mobile crane selection process by developing models and algorithms that determine the best configuration settings required to safely lift a given load. Al-Hussein et al. (2001) developed a systematic approach algorithm for selecting mobile cranes and calculating the spatial clearances for their locations on construction sites. The work focused more on the development and processing of the algorithm for any type of mobile crane problem. The algorithm was coded with MS-Visual basic and supported by a previously developed crane database named “D-Crane” (Al-Hussein et al. 2000) which was designed to replace the lift-capacity charts for each crane model and rigging accessories. The working principle for the algorithm is that a crane data is retrieved from D-Crane and is processed to determine the near optimum selection of configuration settings which are showed on a user interface.

Moselhi et al. (2004) developed a system that integrates the previously developed algorithms (Al-Hussein et al. 2000 and 2001) with graphics engine to produce 3D animations that act as a simulation tool for a lift planning task. The system demonstrated its capabilities as it assisted crane operators in avoiding potential accidents and reduced the time and cost associated with planning the lift operation on site.

Later in 2005, Al-Hussein et al. developed another algorithm which was not restricted to predefined configurations of cranes’ manufacturers, the objective was to eliminate the guesswork required by practitioners in relation to the limited information pertained in the lift-capacity charts. The developed algorithm continued the work of the previously developed algorithm (Al-Hussein et al. 2001) and provided the optimum crane configuration for a required lift as a range of minimum and maximum values of boom length and radii settings. The algorithm was also developed with MS-Visual basic and the optimization module used MS-Solver. The output of the algorithm was displayed as a 2D-elevation for the range of crane settings.

Wu et al. (2010) developed an algorithm for selecting mobile cranes that considers the lift capacity, geometric characteristics of the crane and the ground bearing pressure which was one of (Al-Hussein et al. 2005) limitations. The algorithm was incorporated in a 3D environment to simulate the crane operation. The crane selection module only covered crawler crane types. The path planning was not considered in the 3D simulation. The proposed algorithm was applied on a working construction project which demonstrated the usability and accuracy of the developed algorithm.

2.2 Workspace planning for the onsite locations of mobile cranes

Most of the previous studies discussed above were mainly concerned with the development of algorithms that automate the selection of the optimum mobile crane configuration settings. However, the collision free-paths and a crane’s workspace considerations in relation to the site plan was not tackled enough.

Tantisevi and Akinci (2009) have modeled the dynamic behavior of mobile cranes during operation in order to identify the possible spatial conflicts. The developed model generated the motion of mobile cranes during construction given some inputs including: building design, schedule, crane load-capacity specifications and information regarding the crane operation. The output of the model generated a 4D simulation of mobile cranes on construction sites that identified the possible spatial conflicts and determined the set of conflict-free site locations where a crane can be placed.

Safouhi et al. (2011) developed an algorithm to determine the optimal location for mobile cranes onsite using a mobile crane’s body working area by defining inside and outside boundary limits as restriction
areas for a crane’s operation. The outside boundary limit was defined as the access areas around permanent structures, while the inside boundary limit was defined as the areas which pertain the crane’s operation due to obstructions such as laydown areas, construction trailers, foundations, etc. The intersection between the inner boundary limit and the outer boundary limit was defined as the feasible area for the crane’s operation. The model used a 2D construction layout plan where facilities and the mobile crane are presented as \((x,y)\) Cartesian coordinates. The algorithm was validated via a case study; the output generated all the feasible locations for a crane to be placed with the ability to rotate 360˚ without its body colliding with any onsite obstruction.

After reviewing the previous works, some findings could be drawn: (1) the previously developed crane selection algorithms used mathematical optimization techniques which adopt differential equations to determine the maximum and minimum values, (2) the mobile cranes’ databases were mostly developed while the original specification charts supplied with each mobile crane model were not considered, (3) the crane’s workspace planning required simulation in a 3D environment to determine the spatial conflicts with the surrounding obstructions.

The objectives of this paper are to develop an automated model that uses the original lift-capacity charts supplied with the mobile cranes, optimize the selection, location and configuration settings of the mobile crane using Genetic Algorithms (GA) while considering the current site mobilization plan.

## 3 METHODOLOGY

A model was developed that is composed of a three components: Inputs, Engine and Outputs as shown in Figure 1. The Inputs component is a site layout plan module which includes coordinates for the site boundaries, the permanent facilities, the temporary facilities and the object required to be lifted. The Engine component, which is the core of the model, is composed of three concurrently working modules: crane’s database, geometry calculator and safety/clearance checks. Each module has its own built-in calculating algorithm and all modules are linked together. GA was used to determine the optimum output from each of the three modules while satisfying a set of constraints. Finally, the Output component generates the most suitable crane to be used, its configuration and the best onsite operating location that is conflict-free. The output is presented on a site layout plan. The developed model was coded on MS-Excel 2010 and was designed with a user interface to facilitate the user inputs and the output reports. GA was used in this model due to the combinatorial nature of the problem in hand. Moreover, GA tend to find global optima in complex spaces compared to traditional mathematical optimization, as presented in the previously developed models that may get stuck in local optima (David 1991).

The working principle of the proposed model is that, at first the site mobilization data which includes the site boundaries, temporary facilities and object to be lifted is input to the model in the form of Cartesian coordinates. At the same time, the Crane Database module generates a crane with all its specifications as placing coordinates as an initial solution to the GA engine. Second, the Geometry Calculator module determines the boom length and working radius that correspond to the required weight to be lifted using a set of non-linear trigonometric equations. The calculated length and radius then flow back to the selected crane’s lift-capacity charts following a search algorithm to select a built-in configuration of boom length, working radius and maximum weight for this setting. The selected configuration then passes to the Safety & Clearance Checks module where a checks algorithm determines any flaws with the selected configuration. If any of the check tests fail, the crane database module selects another crane model and new coordinate points to be the new initial solution for the model and starts over again. If the configuration passes all the check tests, an output report is generated which includes the selected crane model, its configuration, its placing location on site considering the previously input mobilization plan.

### 3.1 Module 1: Site Layout Plan

The site layout plan was modeled in 3-D space where all the facilities, the mobile crane and the object to be lifted were represented in the form of blocks, each defined by nine Cartesian \((x,y,z)\) coordinates as shown in Figure 2.
The site layout was considered to be static, which meant that all facilities were considered to be stationary and occupied spaces. In other words, each facility occupied 9 unique coordinate points in the 3-D space. Hence, the unoccupied grid points represent the domain of all possible coordinates where a mobile crane could be placed. To overcome the limitations of MS-Excel 3-D plots, the model was plotted on three 2-D plots that are interconnected and represent elevations for a 3-D site problem; namely: the (x-y) plan view, the east (y-z) view and the south (x-z) view as shown in Figure 3.

Each block on the plots was defined by its initial coordinates \((x_1, y_1, z_1)\) and its length, width and height. The remaining coordinate points were calculated based on the defined dimensions and the initial coordinates. For example, if L=3m, W=2m, H=3m and the initial coordinates were \((4,3,0)\) then the remaining coordinates shall be \((7,3,0), (7,5,0), (4,5,0), (7,3,3)\), etc.

The mobile crane was also defined as a block with 9 coordinates and with any initial position of \((x_1, y_1, 0)\). The boom was defined as straight line with a start and an end point. The start point was set to be \((x_p, y_p, H_c)\), where \((x_p, y_p)\) are the coordinate points for the crane's pivot and \(H_c\) is the height of the selected crane model from the database. The end point coordinates were set to be \((x_{wc}, y_{wc}, z)\), where \((x_{wc}, y_{wc})\) are the centroidal coordinates of the weight to be lifted.
Figure 3: Representation for the 3-D site problem in the form of three elevations

3.2 Module 2: Crane Database

A database for 10 mobile cranes models with different capacities and from different crane manufacturers such as DEMAG, LIEBHERR, etc, was built as an add-in MS-Excel workbook to the model. For each model a number of specifications were used including lift-capacity charts, crane dimensions, range charts and the crane model’s maximum parameters. Each crane model in the database was coded with a Search Routine Algorithm which acquires the calculated boom length, working radius, lift angle and the total weight to be lifted (which is equal to the rigging accessories weight and the lift weight) from “Module 3: Mobile Crane Settings Calculator” and searches for the best configuration from the lift-capacity charts. For example, assuming that the calculated boom length was 36m, the radius was 21m and the total weight was 12t; the algorithm searches the different databases to determine the best configuration, thus the result could be use Crane#1 named DEMAG AC (120) and selects the configuration that has a boom length = 36m and a radius = 22m where the maximum load for this setting is 13.5 as shown in Figure 4. The determined configuration is then used in both “Module 1: Site Layout Plan” and “Module 4: Clearance Checks”. In the event that the determined crane fails the clearance checks, the algorithm searches again for a different crane with a different configuration.

3.3 Module 3: Mobile Crane Settings Calculator

This module is the engine of the model where all the calculations are made. The algorithm used in this module was the Genetic Algorithms (GA) using Palisade (2009) Evolver™ v5.5 add-in for MS-Excel. Its function was to provide the optimum configuration settings in terms of: (1) the operating radius (R) which is defined as the distance between the centroid of the lift and the center of rotation of the crane, (2) the boom length (L) which is defined as the distance from the crane’s pivot to the centroid of the weight and (3) the lift angle (θ) which is defined to be the boom-to-ground operating angle. The determined configuration settings was then converted to coordinates and presented in “Module 1: Site Layout plan”. Demonstrations of the used variables in the model were represented on a mobile crane schematic diagram as shown in Figure 5.
Both the R and the L can be calculated based on Pythagoras theorem as shown in Equations 1 and 2. The total weight to be carried is the weight of the rigging accessories and the weight of the lift as shown in Equation 3.

[1] \( R = \text{sqrt} \left( (x_{(\text{crane})} - x_{(\text{weight})})^2 + (y_{(\text{crane})} - y_{(\text{weight})})^2 \right) \)

[2] \( L = \frac{(R + P2C)}{\text{Cos} \ \Theta} \)

[3] \( W_{\text{total}} = W_o + W_{\text{rig}} \)

It should be noted that the relation between the \( \Theta \) and the \( L \) and \( R \) are inversely proportional. Thus, \( \Theta \) is considered to be a variable in the model and has a minimum and maximum range as defined in the specifications of the selected mobile crane. Moreover, \( R \) is dependent on the crane initial coordinates and the crane operating orientation which is either over-side or over-front/rear.
The chromosome structure for the GA engine is composed of five genes (variables) as shown in Figure 6; namely: the lift angle (Θ), the initial crane coordinates (x1, y1, 0), the orientation (defined as 1=over-side and 2=over-front/rear) and the crane model number (C#) (number from 1 to 10) as imported from "Module 2: Cranes Database”.

\[
\begin{array}{cccc}
\Theta & x1 & y1 & Ort.
\end{array}
\begin{array}{c}
\text{C#}
\end{array}
\]

Figure 6: GA chromosome structure

Manufacturers recommend practitioners to base their calculations on the shorter working radii as much as possible whereas the outriggers have to be fully extended, since such setting provides stability during operation and reduces the chances of crane overturning.

Therefore, the model’s objective function was to obtain the minimum R that satisfies a set of constraints (Equations 6 to 8), where:

[6] \( R_{\text{min}} \leq R \leq R_{\text{max}} \), where \( R_{\text{min}} \) and \( R_{\text{max}} \) are defined in the lift-capacity chart of the crane selected

[7] \( L_{\text{min}} \leq L \leq L_{\text{max}} \), where \( L_{\text{min}} \) and \( L_{\text{max}} \) are defined in the lift-capacity chart of the crane selected

[8] \( \Theta_{\text{min}} \leq \Theta \leq \Theta_{\text{max}} \), where \( \Theta_{\text{min}} \) and \( \Theta_{\text{max}} \) are defined in the working range chart of the crane selected

3.4 Module 4: Clearance Checks

In addition to the above mentioned constraints, a number of clearance checks were also required to be satisfied for each selected crane; which include:

3.4.1 Carrying capacity check

The selected configuration settings from Module 2 that corresponds to the calculated L and R from module 3 have to satisfy the weight requirements including the object weight and the rigging weight as shown in Equation 9:

[9] \( W_{\text{configuration}} \geq W_{\text{lift+rig}} \)

3.4.2 Crane location is within the site

The calculated crane coordinates have to be within the defined site boundaries. Therefore, the outermost point for the site boundaries \((x_{3[\text{site}]}, y_{3[\text{site}]}, 0)\) has to be bigger that the calculated outermost point for the mobile crane \((x_{3[\text{crane}]}, y_{3[\text{crane}]}, 0)\) as per Equations 10 and 11.

[10] \( x_{3[\text{site}]} > x_{3[\text{crane}]} \)

[11] \( y_{3[\text{site}]} > y_{3[\text{crane}]} \)

3.4.3 Overlap between facilities

There has to be no overlap between the placing position of the mobile crane and the surrounding temporary or permanent facilities, which mean the unoccupied coordinates on the grid can only be assigned to the mobile crane. Also, the crane has to be positioned to have enough clearance spaces between its body and the facilities edge. Therefore, the minimum distance between the mobile crane and any facility can be calculated as the distance between their centroid coordinates, where:

[12] \( d = \sqrt{(x_{C[\text{crane}]} - x_{C[\text{facility}]��})^2 + (y_{C[\text{crane}]} - y_{C[\text{facility}]��})^2} \)

[13] \( \text{min} \; b_{\text{crane}}/2 + \text{min} \; b_{\text{facility}}/2 + 2” > d \)
Where “2**” in Equation 13 is an extra 1 meter allowance from each side of a facility and the crane as a common practice recommendation.

### 3.4.4 Boom to building collision

The operating angle should be sufficient enough to avoid any collisions with the building when planning a lift; therefore, this can be depicted using Equation 14 which requires that the clearance should be bigger than the maximum of either the centroid coordinates location of the weight to the edge of the building. In common practice, usually the minimum clearance is 1 meter from any of the building edges.

\[
\frac{Hr + Hw}{\tan \theta} > \max (\text{Abs}(x_{2(building)} - x_{C(weight)}) \text{ OR } \text{Abs}(y_{2(building)} - y_{C(weight)}))
\]

### 3.4.5 Weight to building intersection

The hook of the crane in the rigging element cannot intersect with the building as shown in Equation 15.

\[
L \sin \theta \geq (Hb - P2G) + Hr + Hw
\]

### 3.4.6 Boom to Weight Clearance

The rigging height has to be tall enough to avoid boom collision with the weight as shown in Equation 16.

\[
\frac{Hr}{\tan \theta} \geq b_{(weight)}/2
\]

### 4 CASE STUDY

The case considered herewith involved the placement of an Air Handling Unit (AHU) on top of an office building project located in Cairo, Egypt. The building was a 6-story high; the mobilization plan for the site was obtained from the Contractor and was input to the developed model. The site mobilization plan was composed of a number of facilities; including: Employer/Engineer’s offices, Contractor’s offices, storage/laydown areas, carpentry workshop and steel workshop. The Contractor’s fleet of owned mobile cranes were also considered and included a number of 4 all-terrain telescopic boom mobile cranes of different capacities. The site layout data was input through the model interface which is divided into 3 sections as shown in Figure 7. The first section is about the permanent facilities which require the user to define site boundaries (length and width), the dimensions and coordinates of the buildings being constructed. The model allows for three buildings to be placed in the layout; however, this case only uses one building; thus, the other input spaces were not used and are shown to be dimmed on the model interface. The second section is about the temporary facilities. The model allows the user to enter 6 temporary facilities; however, in this case only 5 were used. The last section is about the object to be lifted where the user is required to define the object’s dimension, coordinates and the weight in tons, which in this case is the AHU. The objective function was originally set to minimize the radius while satisfying the set of constraints as defined in the model engine. The GA initial solutions’ pool was set to be 100 solutions, the stopping time was set to 15 minutes, the crossover rate was set to 95% and the mutation rate was set to 5%. The model was required to run a number of times to validate its outputs.

### 5 RESULTS

Evolver™ was left to complete its 15 minutes run time, even though the solutions showed to have stopped converging after 10 minutes as shown in Figure 8. The algorithm selected crane model “DEMAG AC (665) 250t” to be used with the configuration of L= 53.6m that corresponds to R= 34m, θ=55.5°, the placing coordinates (43.4,4.6), the outriggers to be fully extended, the counter weight= 100t and the operating zones to be 360°. The outputs were presented in the form plan view, east elevation and south elevation, whereas the calculate parameters were represented on the mobile crane schematic diagram as shown in Figure 9. By further running the model extra number of times, it was concluded that for this optimum configuration, other two optimum placing coordinates could be used, which are: (75.3,27.8) or (60.4,7). By these results, the Contractor had the flexibility to select the onsite placing location for the
mobile crane from these 3 optimum locations (coordinates) in order to minimize any disruptions to the ongoing construction activities that may arise due to the mobile crane’s placing position and operation.

6 LIMITATIONS AND FUTURE IMPROVEMENTS

Although the proposed model demonstrated practicality, yet it had some limitations including: (1) the site layout module was designed to include only 6 temporary facilities and 3 permanent facilities. However, such limitation can be adjusted from the model engine itself, (2) the mobile crane database only considered the telescopic boom cranes without the allowance of an additional jib attachment, and (3) the mobile crane was considered to be a block diagram and the boom a straight line, more detailed variables may need to be included in the model calculations such as the soil bearing pressure, the wind load, etc.

7 CONCLUSION

The task of selecting a mobile cranes and developing engineered-lift-studies is a crucial part in any heavy lift operation planning. In practice, experienced lift engineers develop such studies manually and interpolate between the specifications charts to select the mobile crane to uses while estimating the corresponding onsite position. A model was developed to automate this process and provide the optimum crane selection and onsite position. The model was coded on MS-Excel and ran with GA using Evolver® add-in for excel. A case study for an ongoing construction project in Cairo, Egypt was presented to demonstrate the use of the developed model and illustrate its features. The outcomes demonstrated the
practicality of the model in selecting the optimum mobile crane from a predefined list of a contractor’s fleet of mobile cranes and determined the optimum configuration settings as well as a number of optimum onsite locations. The optimum configurations were exported in the form of a site layout plan.

Figure 9: Model Output report

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QR-CODED CLASH-FREE DRAWINGS: AN INTEGRATED SYSTEM OF BIM AND AUGMENTED REALITY TO IMPROVE CONSTRUCTION PROJECT VISUALIZATION

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Abstract: Design coordination problems are considered as one of the causes of driving project delays. The current normal practice in the Egyptian construction industry is highly dependent on using the traditional 2D CAD software to design and issue construction drawings. The main problem with 2D drawings is that they fail to properly visualize the design intent of the project, hence consuming project time in resolving design coordination problems and in some cases may lead to abortive works. Therefore, this research proposes a workflow that integrates both Building Information Modeling (BIM) and Augmented Reality (AR) using commercially available software to address these problems. The proposed workflow integrates the use of BIM in the design process to produce fully coordinated clash-free 3D models. Later, each exported 2D drawing from this model is imprinted with a unique Quick Response Code (QR-Code). An application reads the QR code using a smart device’s camera and then the clash-free model is displayed on its screen. Users can transform, manipulate or use section planes to easily visualize the design intent behind the produced drawings. A case study was conducted on a project originally designed using a BIM platform to test the applicability of the proposed workflow. Results demonstrated the potential features of integrating a system of BIM and AR to improve the visualization of the design intent after the production of 2D clash-free drawings and improve the design coordination/communication problems.

1 INTRODUCTION

Visual simulation has emerged from the field of computer science, providing planning and analysis tools for the engineering processes by creating dynamic virtual scenes; hence, providing environments where experimentation can be done without the committing real resources or endangering the operational safety. BIM represents the development and use of computer-generated n-dimensional models to simulate the planning, design, construction and operation of a building (Azhar et al. 2008), while AR is the superimposition of computer-generated images over a user’s interface of the real world. In other words, AR allows users to explore and navigate the real world with the virtual objects or models superimposed/blended inside the real view (Behzadan and Kamat 2006). The applications of BIM and AR promise a breakthrough in the way projects are designed, constructed and operated. Even though this technology has been around for some time, developing countries like Egypt are still not familiar with their powerful capabilities. The current on-going practice in the Egyptian construction industry uses 2D-CAD software to generate design and construction drawings. Unfortunately, a few numbers of firms deploy the use of BIM software in their early design stages and use very limited features. BIM is currently used only to (1) design the basic building form as a whole then layout views are generated on 2D-CAD drawings for
each building trade and (2) to export the 3D models to other software specialized in rendering for client presentations. On the other hand, the concept of AR is new and its applications are unexplored and even unknown to many Egyptian construction professionals.

Design coordination and visualization problems are considered to be of the major issues that negatively affect construction projects. Design problems generate seeds for variations and design changes which delay the progress of the works and in some cases may lead to abortive works. Although the design and construction teams do their best endeavors to produce coordinated drawings, failure to coordinate between the different parties and visualize the building components off the 2D CAD drawings remains a problem that needs to be tackled.

2 PREVIOUS STUDIES

BIM has been around for over two decades; however, it only started to become very popular by the beginning of this century as it showed serious potentials in developing and revolutionizing the design and construction processes in the Architecture, Engineering and Construction (AEC) industry. Previous studies have investigated how the use of BIM tools affect projects in all its stages.

Haymaker and Fischer (2001) reported statistics based on 32 major projects where BIM was adopted and the results show that the cost estimation accuracy increased by 3%, up to 7% reduction in the project time and up to 40% elimination of unbudgeted change. Later, a survey was conducted by Azhar et al. (2008) to track the productivity gain by the use of BIM in construction projects. Results showed that the productivity gain ranged from 20% to 30% more, in addition to reduction in Request for Information (RFI) and change orders by a factor of 10% or more.

Another survey was conducted by Becerik-Geber and Rice (2010) for the uses of BIM in the construction industry. The results of their survey concluded that the current top uses of BIM are visualization, clash detection and as-built models. BIM could also facilitate resolving coordination problems using clash detection engines. The 3D coordination process could start right after the model is created in order to detect geometric interferences and clearance interference.

Wu and Chiu (2010) proposed a workspace conflict detection and analysis system using Bentley Microstation software. They created a plugin extension to identify design, damage, safety and congestion conflicts on site. However, Gaungbin et al. (2011) conducted an experiment on 3 software: Autodesk Navisworks, Bentley Interference Manager and Solibri Model checker. The experiment concluded that Autodesk Navisworks’s clash detection module was the best among the rest of software.

Conclusions could be drawn from previous studies that adopting BIM throughout a project’s lifecycle has improved the ways projects were designed and constructed.

Concerning the use of AR in construction, few studies were conducted on the integration of BIM with AR in building design and construction. Wang and Dunston (2006) used AR as an assistant viewer for standard CAD drawings in order to perform a conflict detection tasks. They investigated the time and cost benefits realized when using AR vs using a standard approach (CAD) to solve the conflict in the drawings.

Shin and Dunston (2011) used AR to perform construction inspection tasks, more specifically inspecting a steel column using AR and compare it to the conventional inspection techniques. They developed an AR system composed of a backpack processor that includes a GPS and a helmet with built-in glasses that transposes the model on the glasses screen. The results of the experiment they conducted showed that the device they used to perform inspection satisfied standard tolerance and required faster and simpler setup, hence it was considered promising inspection tool.

Zollmann et al. (2014) discussed in details the technicalities behind transposing a 3D system in the physical environment, which permits monitoring and documenting the onsite construction project progress.
Gheisari et al. (2014) explored the use of BIM and AR for facilities management. The research highlighted the benefits realized to the facility management professionals when using BIM, and indicated that its integration with a handheld mobile augmented reality device (MAR), enhances the current practices for facility management.

After reviewing some of the previous studies conclusions can be drawn that: (1) BIM has proven to improve the ways projects are designed and constructed, (2) implementing AR required the use of electronic devices or tools in order to develop the required system and (3) the integration of BIM and AR in resolving design coordination issues was not tackled thoroughly in literature. Moreover, given the fact that construction projects in Egypt face delays and cost overruns mainly due to design and construction miscoordination, the objective of this paper is to introduce the Egyptian market to an approach considering the use of a BIM and AR in solving coordination problems since the early design stages. The proposed approach provides a simple and cost efficient visualization approach for the project team to tackle the design/shopdrawings complexity and hence increasing the productivity of the project team.

3 THE METHODOLOGY

In order to identify the major problems that negatively impact the progress of any construction project, a number of 40 expert interviews were conducted with industry professionals with experiences ranging from 10 to 20 years in the construction industry profession (including project managers, construction managers, design managers, design team leaders from different trades and site superintendents). The interviewees were required to identify the major problems that negatively affect construction projects. The results generated a number of identified problems which were sorted, grouped, compiled and presented as a percentage scale. For example, the “design complexity” problem (complex building geometries, sophisticated mechanical and electrical systems, etc.) was identified by 34 interviewer which resulted in 34/40 = 85%. All the interview results are presented in the form of a bar chart to give a visual presentation as shown in Figure 1.

![Figure 1: Compiled expert interviews results](image)

The interview results revealed that the design coordination is major a problem that negatively affect the progress of the construction project. This is due to the fact that, coordination between the different trades requires extensive engineering works, which delays the related construction work progress. The design complexity came in second place with a score of 85%. Some experts highlighted that complex designs are difficult to be visualized using the current 2D CAD drawings being used, which results in constructability problems. The communication problems came in third place with a score of 83%.

The results from the expert interviews were used to formulate a workflow that facilitates design management and resolves the coordination problems from the early project stages.
3.1 Proposed Workflow

A workflow approach was developed to demonstrate the systematic procedures that should be followed to assist in solving the design coordination problems and to produce AR-ready design drawings as shown in Figure 2. The developed workflow requires users to use any BIM software equipped with a clash detection module to resolve the coordination problems, as well as any AR software that can generate and read QR/Bar codes.

![Workflow Diagram]

Figure 2: Proposed Workflow
3.1.1 Clashes Identification and Reporting

The process starts by generating a multi-model by amending all the design trades’ models (Architecture, Structure, MEP and Civil). Then, the Design Manager or the BIM coordinator (the reviewer) starts reviewing the model and plans the interference tests. The Clash detective helps in identifying, inspecting and reporting interference clashes between the different design trades in a compiled 3D model. The main objective of clashes detection compared to the traditional design coordination practice is to eliminate the tedious and error-prone manual design review of multiple 2D drawings while reading all of the dispersed information to end up with a complete coordinated model. Typically, clash detection is an iterative process and is dependent on the reviewer’s experience in observing the clashes; thus, a batch of tests needs to be conducted in order to make sure that the model is clash free, such process could take days to complete or even months depending on the project complexity and the number of design trades involved.

After running the required tests, the clash results are generated and the reviewer could generate a clash report based on these results. Clash reports are very handy as they can define clashes in the model by their number, status, type, date found, clash point (coordinates of the clash in the model (x,y,z), item 1 ID and type, item 2 ID and type and the name of the test. The reviewer could then send this clash report by mail to the design team leader in order to fix the clashes in the report. Once the design leader and his team are done fixing the clashes, the reviewer refreshes the model on and checks if there are more clashes occurring. Clash testing runs until all clashes are resolved i.e. the model is almost clash free.

3.1.2 Model Walkthrough

Another step that should follow the clash detection process is the model walkthrough. A model walkthrough can be performed by generating a third-person avatar to walk inside the coordinated model. The main function of the model walkthrough after concluding the clash detection test is to spot the design errors or any further coordination problems by the reviewer’s visual inspection that the clash detection test fails to spot and require the reviewers’ visual inspection to be detected; hence, model walkthrough can be considered as complementary to the clashes identification process.

3.1.3 Imprinting Drawings with QR-Codes

The final step is to implement the AR part by creating unique QR-Codes and markers that resembles each drawing or sheet produced. Each marker should have a unique model attached to it. The purpose of the marker is to enable the end user to superimpose the design intent off the basic 2D drawing. In order to do that, for each construction drawing a QR-code is added; which when detected by a camera (smartphone/tablet camera) superimposes the 3D AR view off the drawing. The proposed position for each QR-Code is to be located within the drawing’s title block or below each drawing in its canvas. It is important to note that the superimposed model can also be a 4D model or a video that illustrates to the users how to construct or assemble the model in consideration. The superimposed AR model could be viewed from each drawing either using a smartphone or a tablet with AR-ready software that reads QR codes.

4 CASE STUDY

A case study was used to test the applicability of the proposed workflow. Three commercially available software were used; (1) Autodesk™ Revit™ 2013 was used to design the BIM, (2) Autodesk™ Navisworks™ Manage™ 2013 was used to review and resolve the design coordination problems and (3) AR-Media™ for Apple™ iPad™ was used for generating the unique QR-Codes and superimpose the models on the screen. The reason for selecting Autodesk products is due to their popularity in the Egyptian market, even though their full capabilities are not taken advantage of by most firms or professionals.

The case study was on an administrative building in a hospital project designed originally designed with Autodesk™ Revit™. The Administration building is a single story building that serves the hospital. The building is composed of administration offices, clerk cubicles space, large storage hall, a dining lounge,
kitchenette and mechanical room and a number of toilets. The building’s exterior is cased with concrete precast panels and lined with gypsum wall cladding from the inside; the partitioning is mainly insulated gypsum board along with some glass storefronts. The perspective view and the ground floor plan for the building are shown in Figure 3.

Figure 3: (Left) building perspective view, (Right) ground level layout

First each design discipline team leader exported their Revit models to the Navisworks™ file format and forwarded them to the reviewer (hereafter called the Design Manager [DM]) who compiled and generated a multi-model as shown in Figure 4. The different design disciplines that were used in this case study were: Architecture, Structure, Electrical, Plumbing, Firefighting and HVAC, which means that 6 BIMs were amended in one multi-model.

Figure 4: The multi-model on the Navisworks™ software interface

Second, the DM executed the clash detection module and specified the batch of tests that were required to be performed. Three clash tests were used in this case which were: (1) Arch vs HVAC, (2) Arch vs
Plumbing and (3) Arch vs Firefighting. The generated results showed that there were 18, 39 and 18 clashes respectively in each of the three defined tests. Selecting the clash number from the clash detection module determines its location and the two elements intersecting as shown in Figure 5. For example, in Clash [7] the DM found that the HVAC pipes were intersecting one of the storefront glass panels inside the model. The DM assigned this clash to the HVAC Piping Team leader with a comment saying “review the placing level of the pipes”.

Figure 5: An output from Arch vs HVAC test showing clash [7] for example where a HVAC pipe and a glass panel intersect

Next, all the resulted clashes from all tests were exported in the form of a clash report. In general, the DM can define all the required fields that are necessary to be shown in the report. In this case, the DM chose the following fields: a picture of the clash, a location of the clash (model coordinates), the clashing elements and the person assigned to resolve the clash as shown in the Figure 6.

Figure 6 - A sample clash report including comments to the assigned person to fix the clash

Since this building was considered to be not that complex and small in size, each of the design discipline trades were given 3 days as a review time to fix their clashes. The DM refreshed model after such review period and re-ran the tests again to review the pending, approved or newly identified clashes.

After almost resolving 95% of the clashes in the multi-model, the DM generated a third-person avatar and performed a walkthrough inside the model. After some time walking with the avatar inside the model and visually inspecting the all the model elements some problems were spotted. For example, it was noticed
that the dimensions of the men’s toilet door were incorrect (1.13 x 0.49m) as shown in Figure 7. Using the review and measurement tools, the problem was redlined and a snap shot was taken and sent to the Architecture design leader who was notified with the problem and was required to check if such door type was misplaced or the type itself was not correctly defined in the model. Other detected items included: misplaced lighting fixtures, some storefront doors were missing, floor finish was missed in toilets, etc.

![Figure 7: Redline on an error in the model when walkthrough was performed](image)

Once the model was clash free and all the files were coordinated with no/minimal problems, the DM notified all the design leaders from each discipline that their models were fully coordinated so that they could start generating the 2D drawings from the BIMs and the QR codes for each design drawing. The QR-Code’s position was proposed to be set within each of the produced 2D drawing’s title block as shown in Figure 8.

![Figure 8 - The proposed location of the QR code for the generated 2D drawing from the BIM](image)

Later during a constructability review session with the attendance of the project’s construction manager and each of the design team leaders, the 2D drawing for the building plan was selected to be used as a test for the system. The AR-Media™ application on iPad was launched, and when pointing the iPad’s camera towards the QR-code, the software automatically read the QR code and the respective model was superimposed on the iPad’s screen as shown in Figure 9. The team reviewed the superimposed model on the iPad’s screen, and implemented some of the manipulation features such as translation, rotation and scaling, cross sectioning, layers management and shadow testing to assess the design and the details for each assembly in the model.
5 RESULTS

The application of the proposed approach has demonstrated its effectiveness in design coordination and visualization in many ways. First for the design team, it assisted in resolving most of the design conflicts by testing the hard and soft interferences of the model elements from different trades using the clash detection module. The conflicts were easily communicated to each reviewer via the clash reports. The avatar walkthrough has also assisted in identifying some design problems that were difficult to be detected using the clash detection module; such as errors in the dimensions of the men’s toilet doors, the storefront partition for one of the spaces being misplaced in a wrong level, etc.). Although the time spent in resolving the coordination issues was longer compared to the traditional method, the proposed workflow has proven to be much more systematic and efficient. Having a fully coordinated model has facilitated the production of the shopdrawings from the model with minimal requirement for the extensive engineering works that are usually performed in the traditional design coordination process. Thus, applying clash detection from the early design stages helped in minimizing the design errors which usually propagate to changes in the drawings and could generate seeds for variations and claims during the construction phase of the project.

Second, the application of the AR has also improved the visualization of the design intent for the whole team. For instance, during the constructability session the construction manager identified some issues in the fixation details of the exterior precast wall casing. These issues were easily communicated to the design team leaders to propose other alternatives and to further elaborate on the design requirements. Clients easily communicated their requirements within the session which was made very clear to the project team. Thus, the application of AR has proven its effectiveness in visualizing the project intent from the 2D drawings and improved the communication between all the team members.

6 CONCLUSION

Design coordination problems are considered as one of the major causes driving project delays. The current normal practice in the Egyptian construction industry is dependent on using the traditional 2D CAD drawings that fail to visualize the design intent, hence consuming project time in resolving design coordination problems. The integration of BIM and AR technologies reveal promising results in tackling the design coordination and visualization problem. In this paper a systematic workflow was proposed that
integrates the use of BIM in the design process to produce fully coordinated clashes-free models and imprinted the generated 2D drawings with QR-Codes. A case study was conducted on a project originally designed using a BIM platform to test the applicability of the proposed workflow. The proposed workflow has shown a number of outcomes. Contractors could generate automatic shopdrawings from the BIM software used and therefore, minimize the number of technical personnel deployed to produce the shopdrawings on site (compared to the traditional approach when using CAD drawings) which shall help in minimizing the direct and indirect costs on the project. Similarly, the Engineer could minimize deploying technical personnel to review the shopdrawings and therefore, minimizing direct and overhead costs.

Applying AR to superimpose the 3D model of the construction drawing at hand provided an innovative approach for implementing AR in construction without being involved in complex coding or buying expensive software. Using a commercially available software makes the process much easier. The application of AR with the drawings helped to better understand the design intent behind the drawing. Consequently, the project team effectively communicated the design. To conclude, the proposed approach provides a simple and a cost efficient method for improved project visualization for the project’s team to tackle the design/shopdrawings complexity and hence increases the productivity of the project team.

References


ENERGY LOSS MODELING OF WATER MAIN BREAKS: A HYBRID
SYSTEM DYNAMICS-AGENT BASED MODELING APPROACH

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Abstract: According to the United States Government Accountability Office Energy-Water Nexus Report, the water pipeline infrastructure system is nearing the end of its service life. Up to 50 percent of water is lost, as evidenced by the 240,000 water main breaks that occur each year, estimated by the American Society of Civil Engineers (ASCE). Water loss in the distribution system leads to additional expenditures for extracting water from natural resources, treatment, pumping, and transporting water into the distribution pipeline network system. Minimizing water losses has the potential to curb the increase in operating costs throughout the distribution system. This paper describes a conceptual System of Systems (SoS) framework for estimating the energy footprint resulting from water main breaks that considers the full cycle of providing drinking water to customers. The paper focuses on the interactions between the water loss in the distribution system and the energy-intensive operational components of the water infrastructure. This paper contributes to the body of knowledge and practice by developing a methodology to quantify the impact of water main breaks on energy consumption and by creating a tool that assists the water utilities as decision-makers in their assessment of the effects of water main breaks on the satisfaction of customers and the revenue loss of water utilities.

1 INTRODUCTION

A 2013 study by the Center for Neighborhood Technology of the Great Lakes states revealed that 6.5 billion gallons of drinking water are lost annually from 63,000 leaking pipes in this region; enough water to meet the demand of 1.9 million consumers for a year (CNT 2013). Water losses cascade into energy loss due to the interdependencies of the infrastructure systems, and leads to additional energy expenditures for extracting water from natural resources and treating, pumping, and transporting water to the end users. Approximately four percent of all electricity generation in the U.S. is used to move and treat drinking water and wastewater (Electric Power Research Institute 2003). For example, the water sector in California consumes 19 percent of the state’s electricity per year (California Energy Commission 2005). Nationwide, the energy bill comprises 40 percent of operation cost for water utilities to provide a clean supply of drinking water for customers (WaterRF 2013). Therefore, minimizing water main breaks through an effective asset management program has the potential not only to reduce the operating and social costs associated with disruption of services to the communities, but also to reduce the energy and carbon footprint resulting from water main breaks.

This paper develops and demonstrates a framework for quantifying the energy footprint resulting from water main breaks that considers the full cycle of providing drinking water to customers. In this study, the energy footprint is a measure of total amount of energy loss in water distribution and supply systems resulted from water main breaks. This framework will investigate the impact of water main breaks on the water supply and distribution system, and assess the interdependencies of the water and energy sectors.
1 BACKGROUND

Extraction and conveyance of water requires a significant amount of energy to transport usable water for the treatment plant. For example, in Southern California, water agencies have to import water from the Colorado River Aqueduct, which requires 2000 kWh/h electricity for pumping (Nuding 2011). In water treatment facilities, the amount of energy used for the treatment process depends on the quality of the water received and the applicable quality standard required for drinking water. Drinking water quality regulations have become more stringent in recent years, requiring advanced water treatment processes, such as UV disinfection systems, which are energy-intensive. Drinking water is then pressurized and pumped through the pipeline distribution network for delivery, which requires additional energy. Figure 1 represents the energy consumption of water supply and distribution components.

Prior research in the water-energy nexus area that addressed the energy needs for water (e.g., American Water Works Association Research Foundation 2007; WaterRF 2011; EPA 2013; WaterRF 2013; U.S. Department of Energy 2014) focused on macro-level analysis of water and energy interactions, including the energy and water demands related to population growth, the development of technology to reduce the energy footprint of the water and wastewater treatment processes, the energy consumption during the rehabilitation and renewal processes, and the improvement of the energy optimization of pumping stations. Additional work has included the quantification of the energy loss of water pipes based on head loss, friction loss, and hydraulics equations (Pelli and Hitz 2000; Colombo and Karney 2002; Filion et al 2004). Cabrera et al. (2010) not only considered the effect of water leakage in distribution systems, but also assessed the energy audit from the resource (reservoir) to the end user. The Reynolds transport equation and integral energy equation were used to develop a mathematical model to evaluate the energy input/output for a water distribution system. These integral energy equations led to calculating the energy loss indicator using leakage; however, it measured only the energy loss in the closed loop of water distribution, not from the water supply systems (extracting and treatment). In addition, the current state of the literature is limited to macro-level analysis of water distribution and supply systems (in the delta level shown in Figure 2), and has not addressed the energy-intensive components of water distribution system in cases of main breaks.

2 METHODOLOGY

In order to better understand the complexity and boundary of the water infrastructure system, a multi-level hierarchical framework for water infrastructure system was developed using the System-of-Systems framework (see DeLaurentis and Callaway 2004), as shown in Figure 2. The alpha (α) level is the base level system and further decomposition does not take place in this context, the beta (β) level is collections of α-level systems, the gamma (γ) level is collections of β-level systems in a network, and the delta (δ) level is collections of γ-level systems. This bottoms-up assesses the interaction between entities in each level, as well as interdependences across levels.
Investigating the dependencies and interdependencies of a complex system requires a theoretical framework including three phases: definition, abstraction, and implementation (DeLaurentis and Callaway 2004). In the forthcoming paragraphs, a discussion on each of the three phases is provided to highlight the purpose of each phase as well as the processes and tasks conducted within each phase.

The first phase, namely definition, intends to ensure that the current problem fits within the overall system characteristics by defining the operational context, status quo, and barriers. In this study, the existing interactions between water and energy infrastructures are defined in order to improve water utilities’ capability by addressing the water and energy loss in water supply and distribution system. Barriers to the possible interactions between water and energy infrastructures can be counted as different managerial and operational dependencies and lack of appropriate communications.

The abstraction phase defines the key entities and their roles. Four main entities can be defined in this phase, which can be grouped under two entity-descriptors, specifically, explicit-implicit and endogenous-exogenous. The four entities that are addressed in this phase are: resources, stakeholders, drivers, and disruptors. Infrastructure resources are the physical entities which are managed, operated and maintained by utilities and acquired by end users. In this study, these resources include water pipes at the alpha level, and the water pipelines network and pumping stations, water treatment plants at the beta level. These resources have an impact on stakeholders. Stakeholders are those who are impacting or are impacted by decisions. Stakeholders include public/private agencies (i.e. water and energy utilities), and users (i.e., water consumers and utility managers). In this study, the drivers are the operation cost (such as energy, cost repair cost, etc.) and the level of service of water infrastructure. Drivers influence the decisions of utility companies to maintain the infrastructure to a certain level of performance. Disruptors are severe events that will reduce the efficiency of the system; in this case, water main break events.

The implementation phase builds upon the definition and abstraction phases. To assess the impact of water main breaks on water and energy infrastructure interdependencies, a number of mathematical models (see Cabrera et al. 2010) must be integrated. Due to the complexity of system, difficulty of integrating these mathematical models, and the level of uncertainty represented by this problem, system dynamic modeling was chosen for conducting the study and to uncover emergent patterns of system
behavior. System dynamics is a methodology that can be applied to analyze the behavior of complex systems with a series of stocks, flows, and feedback loops (Forrester 1991). In this research, the system dynamics component focuses on the interactions between the water loss in the distribution system and the energy-intensive operational components of the water infrastructure. The advantage of using system dynamics modeling to assess the interdependencies is that it allows explaining the endogenous structure of the system, from water main breaks and pipeline characteristics to pumping stations, water treatment, water extraction, and water conveyance, as well as how the different components of the system interact. The closed boundary of the system structure does not imply that the system is unaffected by outside events, such as, traffic load, external corrosion. However, the dynamic behavior is created by interactions within the boundary (Forrester 1999). Figure 3 identifies the boundaries of the system dynamics model and depicts the interactions between system components.

The research methodology was applied to water distribution system in U.S. City A to demonstrate the framework. City A is a Midwestern city with an approximate population of 853,000 in 2013 with an area of 372 square miles and water supply capacity of 79 million gallon per day (US Census 2014; CEG 2013). Water pipeline installation was initiated in 1848 with cast iron pipe (CIP) materials. According to the City GIS database, the current water pipes range in diameter from 0.75 inches to 60 inches. CIP comprises the majority of the installed materials, followed by ductile iron pipe (DIP), polyvinyl chloride (PVC) pipe, steel pipe, asbestos cement (AC), high density polyethylene (HDPE).

AnyLogic 7.0, an object-oriented program, is used to demonstrate the modeling and simulation of the water and energy footprint, as well as the modeling of the interdependent micro-behaviors of the agents toward water main breaks, water loss, and energy loss. The primary components of the system dynamics model include:

- **Stocks**, which represent the variables of the system that change or accumulate over time. Examples of stocks are number of water main breaks, amount of water loss, amount of energy loss, amount of revenue.
- **Flows** represent rates that produce changes in the value of the stocks. These elements introduce changes in the flows to and from the stocks. Examples of flows are frequencies of water main breaks, water loss rates, energy consumption rates.
- **Causal or feedback loops** that represent the dynamic behavior of a system and the causality relationship between the variables and determines the flow of resources from the stocks.

The relation between stock and flow in system dynamics modeling is defined by Equation 1 (Sterman 2001):

\[
\text{Stock} (t) = \int_{s}^{t} [\text{inflow} (s) - \text{outflow} (s)] ds
\]
Where, \( t_1 \) is the initial time, \( t_2 \) is the current time, and the difference between inflow and outflows is the flow rate.

The amount of water loss from water main breaks is based on the AWWA M36 Manual (AWWA 2009). The water loss equation is a function of number of breaks in distribution system, the average flow rates of leaks, duration of leaks, and the average pressure in distribution system, shown in Equation 2 as:

\[
[2] \text{Annual Loss (MG)} = (\text{BR} \times (\text{AFR} \times 60 \times 24 \times \text{TD} (\text{AP} + 70)^{0.5}) / 1,000,000)
\]

Where, MG is million gallons, BR is the number of annual breaks reported by agencies, AFR is the average leak flow rate at 70 psi (gpm), TD is the total duration is days (= awareness duration + repair duration), and AP is the average system pressure (psi).

2.1 Data Analysis

The model input, such as the number of breaks, flow rates, average system pressure, and response time to the water main breaks were retrieved from City A’s GIS database and from literature sources, including AWWA M36 manual, Water Research Foundation, and Environmental Protection Agency (WaterRF 2013; AWWA 2009; EPA 2009). The input variables are the characteristics of three common types of pipe materials, CIP, DIP, and PVC, and three categories of pipe diameters, 6” diameter, 12” diameter, and higher than 16” diameter. The model output variable includes the energy footprint of water main breaks based on the characteristics of the distribution and the main breaks. The average pressure is assumed to be 70 psi for entire water distribution system, based on the City A requirements. The average flow rate for water main breaks is estimated using the pipe diameter and the AWWA M36 Manual as shown in Table 1 (AWWA 2009). The total duration of water loss (awareness duration + repair duration) is retrieved from the GIS database of the City A.

<table>
<thead>
<tr>
<th>#</th>
<th>Pipe Diameter</th>
<th>Average Flow Rate</th>
<th>Average Pressure</th>
<th>Average Failure Duration¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 Inch</td>
<td>46 gpm</td>
<td>70 psi</td>
<td>4 days</td>
</tr>
<tr>
<td>2</td>
<td>12 Inch</td>
<td>111 gpm</td>
<td>70 psi</td>
<td>4 days</td>
</tr>
<tr>
<td>3</td>
<td>&gt;16 Inch</td>
<td>111 gpm</td>
<td>70 psi</td>
<td>4 days</td>
</tr>
</tbody>
</table>

The water loss from main breaks affects the water supply system in order to extract, transport, treat, and pump extra amount of water to customers. The energy rate for extracting water (ground water or surface water) depends on pump efficiency (WaterRF 2013). In this study, it is assumed that the source of water is surface water with the pumping efficiency of medium and production of 20 million gallons per day (MGD), based on the water production rates in City A. The estimated energy consumption of this source water pumping is 2,898 kW/day (WaterRF 2013). Equation 3 is used to calculate the energy consumption of extracting water from resources in the system dynamics model as flows.

\[
[3] \text{Energy Loss of Extracting & Conveyance} = \text{Initial Value} + \frac{d(Energy Loss of Extraction & Conveyance)}{dt}
\]

The amount of energy used for the water treatment process depends on quality of raw water and the quality standard required for drinking water. Drinking water quality regulations have become more stringent in recent years, requiring advanced water treatment processes, which are energy intensive (WaterRF 2013). The types of treatment plant needs to be considered for energy footprint analysis because traditional treatment plants energy consumption is different from advanced treatment plans. This study considered the conventional water treatment plant as a process of treating raw water through rapid mixing, flocculation, sedimentation, filtration, and chlorine stages with the approximate energy intensity of

¹ Time of identification of failure to repair of failure
25,605 Kwh/day (WaterRF 2013). Equation 4 is used to calculate the energy consumption of water treatment plant in the system dynamics model as follows:

\[ \text{Energy Loss of Water Treatment Plants} = \text{Initial Value} + \frac{d(Energy Loss of Water Treatment Plants)}{dt} \]

Energy consumption of pumping stations is a function of the flow, an assumed distribution system pressure head, and assumed pumping efficiency (a measure of pumping system efficiency). In the study, the average pressure of the distribution system is assumed to be 70psi and the efficiency of pump is considered as 65%, based on the commonly observed practice in the water industry (AWWA 2009). Based on these values, the approximate energy consumption of finished water pumping with the pumping efficiency of medium and production of 20 MGD is 21,563 kWh/day (WaterRF 2013). Equation 5 is used to calculate the energy consumption of pumping stations in the system dynamics model as flows.

\[ \text{Energy Loss of Pumping Stations} = \text{Initial Value} + \frac{d(Energy Loss of Pumping Stations)}{dt} \]

Water main break events affect both the water utilities and communities in several ways, such as the social cost for communities and the financial loss for water utilities in repairing breaks. Agent-based modeling (ABM) is used in this study to capture the micro-behavior and emergent behavior outcomes from the activities and interactions between the water utility and consumer agents. ABM models the stakeholders (water utilities and customers) as autonomous agents in order to understand their behaviors toward water main breaks and to assess the potential increases in costs that may be passed on to the users from non-revenue water and energy loss. Figure 4 shows the beliefs, knowledge, and information (BKI) of the water utility and customer agent.

![Figure 4: Representation of environment and agents interactions](image)

### Micro-Behaviors of Water Utility
1. Water main breaks increase operational cost because of repair and renewal.
2. Water main breaks lead to water loss and increase the non-revenue water.
3. Water main breaks leads to energy bill for water supply.
4. Three choices to compensate the revenue loss: increase water rates, federal fund, and local tax.

### Micro-Behaviors of Customer
1. Water main breaks decline the level of services because of interruptions in services.
2. Increase in water rates from water utilities increase the customer complaints.
3. Increase in water rates leads to decrease in water consumption.
4. Decline in water consumption decreases the water utilities revenue.

2 RESULTS & DISCUSSIONS

The proposed methodological framework is used to assess the energy footprint of water main breaks and evaluate the stakeholder’s interactions from the main breaks. This section focuses on the assessment of interdependencies between water and energy infrastructure systems resulting from water main breaks in water distribution system. Figure 5 shows the energy footprint for City A due to water main break events based on different types of pipe materials. This energy footprint includes the energy loss in the water
supply system. The energy loss due to breaks in CIP pipes is higher compared to that in DIP and PVC pipes. This may be related to the aging CIP pipes, which were installed more than 100 years ago in North America. (McKim 1997), and hence show higher rate of breaks. PVC pipes have a lower energy footprint, because of the material’s high resistance to corrosive environments and longer life expectancy (Folkman 2012; Davis et al 2007; Moser et al. 1994).

Figure 5: Energy footprint of water main breaks for each pipe material

Figure 6 shows the energy footprint estimates of water main breaks based on the three different categories of pipe diameters: 6” pipe, 12”pipe, and higher than 16” pipe. 6” diameter pipes in water distribution system have higher rates of energy loss, three times higher than 12” diameter pipes and five times higher than larger than 16” diameter pipes. This is mainly because of higher length of installation and smaller diameter. The small diameter pipes, such as 6” pipes, have a smaller thickness and they are more likely to be affected by the corrosive soil environment and the number of breaks rates for the small diameter pipes are higher (Kettler and Goulter 1985; Loganathan et al 2002).

Figure 6: Energy Footprint of Water Main Breaks for Three Categories of Pipe Diameter

The analysis of this study revealed that as the diameter of the pipes increases (and the thickness increase), the energy footprint decreases. For example, the 6” pipes have a 1523 miles installation in the City A in compare with 12” pipes, which have 936 miles though the city.
Single factor sensitivity analysis was conducted to observe the impact of the different parameters on the energy footprint of the water main breaks. The variable with the highest uncertainty spans the largest range in the tornado diagram. Figure 7 shows the tornado diagram for the citywide energy footprint from water main breaks in City A. The tornado diagram captures the impact of water pipeline characteristics on energy loss of water supply and distribution system. Smaller diameter pipes with the oldest materials types as well as the higher installation lengths have higher energy footprints. PVC pipes with diameters higher than 16" have lower energy footprint rates. 12" PVC pipes and 6" PVC pipes have approximate similar energy footprints.

![Tornado diagram for citywide energy footprint of water distribution system](image)

Figure 7: Tornado diagram for citywide energy footprint of water distribution system

3 CONCLUSION

This paper presented a framework to assess the energy loss of water main breaks to assist in decision making by water utilities in areas of energy cost and operation cost. A hybrid system dynamics-agent based modeling was proposed to evaluate the interaction between water main breaks and energy infrastructure system, as well as the micro-behavior of stakeholders toward water main break events. A system dynamic simulation framework was created and analyzed to estimate the water energy footprint of water main breaks based on the water distribution characteristics. Single factor sensitivity analysis was conducted to identify significant factors affecting the energy footprint of water supply and distribution system in a citywide case. For the case study, 6" CIP pipes were found to be energy-intensive components of water distribution system in case of water main break events, followed by 12" pipe material pipes. Large diameter pipes (greater than 16") were also found to experience lower energy loss due to breaks in water distribution and supply system. The next stage of this research is implementing the agent based modeling to capture the stakeholders behaviors and potential increases in costs that may be passed on to the consumers from non-revenue water and energy loss.

References


APPLICATION OF FAHP AND SHANNON ENTROPY IN EVALUATING CRITERIA SIGNIFICANCE IN PIPELINE DETERIORATION

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Abstract: Water Distribution Networks (WDNs) are the most important element in water supply systems. According to the Canadian Water and Wastewater Association (CWWA), there are more than 112,000 kilometers of water mains in Canada and their replacement cost is estimated to be $34 billion. Another $12 billion is required to service the projected growth. It is important to assess the long-term condition of WDNs to find their respective rate of deterioration in order to prevent disastrous failures and/or sudden shutdowns. Due to the limited data about water mains, condition of pipeline should be estimated based on available data. Therefore, to predict the pipeline condition, importance of each factor should be known. This study aims to calculate the weight of importance of factors that affect deterioration of pipelines. For this purpose, Fuzzy Analytical Hierarchy Process (FAHP) and Entropy Shannon are employed to prioritize the selected factors and calculate their relative weights based on their individual importance. Results show that pipe installation, age and material are the most effective parameters in modeling deterioration. These weights will be used in condition rating models to find the condition of pipelines based on their pipe characteristics, soil and water properties in order to estimate deterioration rate and expected remaining useful life.

1 INTRODUCTION

As Water Distribution Networks age, they experience the problem of deterioration and leakage. The frequency of leaks and breaks increase which result in loss of healthy drinking water. In Qatar, 35% of the drinking water is wasting through leaking only in Doha and 30% is wasting through other area (GWI 2010). Therefore, identifying the deterioration rates and the remaining useful life will help in performing more economical and efficient replacement and maintenance measures. Since in a number of cases, data needed for generating deterioration curves and estimating remaining useful life may be insufficient, prediction models should be employed to forecast the condition of the pipelines based on the available data such as pipe design. This paper utilizes different methods to calculate weight of importance for the most important factors affecting the condition of pipelines in condition rating models. It uses the integration of two methods to take into account the uncertainty and fuzziness of human judgements and decision making. The main objective of this research is to calculate criteria significance in pipeline deterioration in order to be used for future deterioration and remaining useful life models that will be utilized in developing a value-driven optimized intervention plans.
2 BACKGROUND

2.1 Shannon Entropy

In 1984, Claude Shannon proposed a mathematical theory to measure the amount of information content of an information source. In this theory, the term of Entropy, refers to the portion of information content. This portion indicates the uncertainty of both the information source and the random variable and defines how much information is earned when result i is observed. When the raw data of the decision making matrix are identified completely, Entropy method could be used to evaluate the weights. There is more chance of occurrence for each value of i when entropy is higher. Considering P as a random variable and \( P_i \) as the probability, the theory identifies the relationship between Entropy (E) and random variable as for all the m criteria (Shannon 2001):

\[
E_i = S(P_1, P_2, ..., P_n) = -E_0 \sum_{i=1}^{n} P_i \ln(P_i)
\]

Where \( n \) is the total number of possible outcomes. Measuring uncertainty of a random variable \( i \) means that when \( E_i = 0 \), \( i \) would be a certain variable not a random one. Also in case of maximum quantity of \( E_i \), \( i \) is a random variable with a uniform distribution. In this formula, entropy and uncertainty are used for the same concept. In other words, average quantity of information which is collected after the observation of result \( x_i \) in the random variable of \( X \), is entropy. The concept of Shannon Entropy refers to an accepted measure of uncertainty and fuzziness. This is the main reason for choosing this method for calculating the weights. Entropy recently has been used in reliability assessment studies in WDN (Prasad and Tanyimboh 2008, Tanyimboh et al. 2011, Shibu and Reddy 2012) and was used along with AHP in weight determining in Zheng and Tian (2009).

2.2 Fuzzy Analytic Hierarchy Process (FAHP)

AHP gives weights to set of variables by organizing experiences and judgments of individuals into hierarchical structure. This structure illustrates relationships between goal, parameters and sub-parameters. Fuzzy analytical hierarchy process (FAHP) is the fuzzy format of AHP and is a well-known multi criteria decision making technique introduced by Saaty in 1988. It could be said that the ultimate goal of the AHP is collecting the expert's judgment; however it could not reflect the uncertainty in the judgments and knowledge of humans in decision making process precisely. The uncertainty could be modeled using fuzzy logic. Keliner et al. (2005) proposed a fuzzy Markov deterioration process to model failure risk of PCCP, cast and ductile iron water mains. Triangular memberships and fuzzy rules of “if-then” were employed to solve the problem. Condition of the asset was calculated from the present condition and deterioration rate, which had been identified from Markov deterioration process. Makropoulos and Butler (2005) developed a neuro-fuzzy spatial decision support system for pipe replacement prioritization. The model includes fuzzy logic and neural network back propagation algorithm which relates certain characteristics to pipe replacement. Najjaran et al. (2006) presented a fuzzy expert system to assess corrosion of cast/ductile iron pipes from backfill properties. The model comprises subjective and objective parts and two systems were suggested for fusion of the subjective and objective models. This methodology was also used in two other articles of “A Fuzzy Expert System for Deterioration Modeling of Buried Metallic Pipes” (Najjaran et al. 2004) and “Fuzzy-Based method to evaluate soil corrosivity for prediction of water main deterioration” (Sadiq et al. 2004).

Al-Barqawi and Zayed (2006) presented a model using analytic hierarchy process (AHP) for water main conditions assessment. In this model, the effective factors were first recognized; then pair-wise comparisons were performed between each two of the factors, priorities were assigned and condition assessment records were calculated form priority matrices. Rajani and Tesfamariam (2007) proposed an approach for estimating time to failure of cast-iron water mains. The fuzzy membership function employed in this model is triangular fuzzy numbers. This model is identical to one presented in “Estimating Time to Failure of Ageing Cast Iron Water Mains under Uncertainties” (Rajani and Tesfamariam 2005) and “Possibilistic Approach for Consideration of Uncertainties to Estimate Structural Capacity of Aging Cast Iron Water Mains” (Tesfamariam et al. 2006). Al-Barqawi and Zayed (2008) also did another research about an integrated AHP/ANN model to evaluate municipal water mains’ performance. They utilized AHP to calculate the weights and assign a value between 0 (critical) to 10 (excellent) to the condition of
pipeline. Zhou et al. (2009) developed a Fuzzy based pipe condition assessment model which generates pipe condition rating using AHP from fuzzy first-level and second-level condition indicators. Fares and Zayed (2010) presented a hierarchical fuzzy expert system for risk of failure in water mains. The risk of failure varies between 0 (least risk) and 10 (highest risk). The impact factors of the parameters of four categories were evaluated utilizing the Mamadani rule system at first step. Then, they were used to calculate the risk of failure. FAHP is used to solve the hierarchical and multi criteria decision making problems by using trapezoidal and triangular fuzzy numbers. These two mentioned fuzzy numbers are mostly used to reduce the complexity of the problem due to the large number of criteria and decision makers. AHP has some limitations such as subjectivity and it doesn’t consider uncertainty in inputs. FAHP has solved this problem. In FAHP, the experts are asked to enter all possible outcomes of modal, lowest and highest possible values in the pairwise comparison matrix. It means that they are entering the values three times more than they enter in regular AHP which is difficult and time consuming (Fares, 2008).

3 RESEARCH METHODOLOGY

The overall flow of the research process is depicted in Figure 1 and consisted of the following steps: 1) Data collection including questionnaire design, distribution and collection, 2) Data analysis and building the matrix of pairwise comparison, 3) Calculating the weights of importance of factors affecting pipeline deterioration through FAHP and Entropy individually, 4) Integration of weights calculated in previous step to find final weight of importance.
3.1 Data Collection

The survey was performed in Fall 2014. The questionnaire was designed in an online format on Qualtrics website which is a data collection platform. 38 questionnaires were collected from experts around the world to find the weight of importance of each factor in water pipeline deterioration. The years of experience and demographic distribution of these experts is summarized in Figure 2 and 3. In the five-question questionnaire, the experts are asked to identify the relative importance of each criterion in pipeline deterioration both separately and respect to others by using linguistic variables of Table 1.
Table 1: Linguistic variables for the importance weight of each criterion (Chen, 2000)

<table>
<thead>
<tr>
<th>Linguistic Term</th>
<th>Fuzzy triangular Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Low (EL)</td>
<td>(0.0, 0.0, 0.1)</td>
</tr>
<tr>
<td>Very Low (VL)</td>
<td>(0.0, 0.1, 0.3)</td>
</tr>
<tr>
<td>Medium Low (ML)</td>
<td>(0.1, 0.3, 0.5)</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>(0.3, 0.5, 0.7)</td>
</tr>
<tr>
<td>Medium High (MH)</td>
<td>(0.5, 0.7, 0.9)</td>
</tr>
<tr>
<td>Very High (VH)</td>
<td>(0.7, 0.9, 1.0)</td>
</tr>
<tr>
<td>Extremely High (EH)</td>
<td>(0.9, 1.0, 1.0)</td>
</tr>
</tbody>
</table>

3.2 Fuzzy Analytic Hierarchical Process (FAHP)

3.2.1 Pairwise comparison matrix

The very early step for analysis is building the matrix for pairwise comparison and checking its consistency. After that, the relative weights of parameters and sub-parameters were determined (Vahidnia, Alesheikh, Alimohammadi, & Bassiri, 2008).

\[ A = \begin{bmatrix} 1 & W_{12} & \cdots & W_{1n} \\ W_{21} & 1 & \cdots & W_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ W_{n1} & W_{n2} & \cdots & 1 \end{bmatrix} \]

In this matrix, \( W_{ij} \) is the weight of parameter 1 respect to parameter 2. All the arrays in matrix \( A \) are fuzzy triangular numbers of \( (l_{ij}, m_{ij}, u_{ij}) \).

3.2.2 Extent Analysis Method

To analyze FAHP, Larhorn and Pedric (1983) suggested a method which was based on minimum logarithmic squares. This method did not become popular due to its complexity and ambiguity (Nepal, Yadav, & Murat, 2010). After that, Chang (1996) proposed ‘Extent Analysis Method (EA)’ that used fuzzy triangular numbers which becomes more common in FAHP calculations (Nepal et al., 2010) and is used in this study. Considering \( M_1 = (l_{1}, m_{1}, u_{1}) \) and \( M_2 = (l_{2}, m_{2}, u_{2}) \), the arithmetic functions are (Chang 1996):

\[ M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \]
\[ M_1 \times M_2 = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \]
\[ M_1^{-1} = \left( \frac{1}{l_1}, \frac{1}{m_1}, \frac{1}{u_1} \right), \quad M_2^{-1} = \left( \frac{1}{l_2}, \frac{1}{m_2}, \frac{1}{u_2} \right) \]

In this method, the triangular number of \( S_k \) is calculated for each row of the pairwise comparison matrix from below in which \( k \) is row number, \( i \) is alternative and \( j \) is criterion.

\[ S_k = \sum_{j=1}^{n} M_{kj} \times \left[ \sum_{i=1}^{n} \sum_{j=1}^{n} M_{ij} \right]^{-1} \]

Computing \( S_k \), their magnitude should be determined respect to others and the result should be normalized from equation 9.

\[ W_i = \frac{w_i}{\sum w_i} \]

After finding acceptable results, the priority matrices are combined together by multiplying the weight of factors \( (W_i) \) and weight of sub-factors \( (Y_i) \), to calculate the overall scores (Saaty, 1988). Subsequently, Consistency index (CI) which is a degree of deviation from consistency is checked. Afterward, consistency ratio (CR) defined as the ratio of the consistency index (CI) divided by the random inconsistency index (RI) for random comparisons is calculated (Saaty, 1988).
Table 2: Random inconsistency indices (Saaty, 1988)

<table>
<thead>
<tr>
<th>Number of Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0</td>
<td>0</td>
<td>0.58</td>
<td>0.9</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

3.3 Shannon Entropy

The built pairwise comparison matrix for FAHP was used again to perform Shannon Entropy method. Normalizations were performed in Step 1 and entropy was calculated from Step 2. In Step 3, the degree of diversification and weight of importance were computed from calculated entropy.

\[
W_i = \frac{W_{ij}}{\sum_{j=1}^{n} W_{ij}} \quad j = 1, \ldots, n; \quad i = 1, \ldots, n
\]

Compute entropy \( E_i \) as

\[
E_i = -E_0 \sum_{j=1}^{n} W_{ij} \ln W_{ij} \quad i = 1, \ldots, n \quad \text{where} \quad E_0 = \frac{1}{\ln(n)}.
\]

\[
d_i = 1 - E_i
\]

\[
w_i = \frac{d_i}{\sum_{i=1}^{n} d_i} \quad i = 1, \ldots, n.
\]

3.4 Integration of FAHP and Shannon Entropy

After finding the weights of importance from FAHP (\( w_j \)), they can be combined with computed degree of importance from Entropy (\( y_j \)) using equation below.

\[
W_j = \frac{y_j w_j}{\sum_{j=1}^{n} y_j w_j} \quad \forall j
\]

4 RESULTS AND DISCUSSION

The collected responses were analysed and total weight of importance for parameters identified through FAHP are summarized in Table 3. As can be seen, physical factors has the highest effect in deterioration of the water pipelines. Operational and Environmental factors are ranked as second and third important categories in pipeline deterioration. In physical factors, pipe material, pipe installation and pipe age are the first three significant factors. In category of Environmental factors, bedding soil type, seismic activity and backfill material are the most important factors in deterioration of water pipelines respectively. Furthermore, water pressure and O&M practices are the operational parameters that affect the deterioration of water pipelines at most. Computed global weight of importance for each category is multiplied by the local weight of importance of each sub-category to find the total weights of importance for each factor. It can be seen that criteria of pipe material, water pressure, pipe installation, pipe age and bedding soil type are the most important factors in pipeline deterioration in water infrastructure which has been determined by FAHP method. Consistency was checked for the pairwise comparison matrices and results are summarized in Table 3. The pairwise comparison matrix for identifying the global weights is also presented in Table 4.

Table 3: Total weights of importance for all parameters in FAHP

<table>
<thead>
<tr>
<th>Factors</th>
<th>Global weights</th>
<th>Local weights</th>
<th>Weights of importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe material</td>
<td>0.369129</td>
<td>0.178801</td>
<td>0.085314</td>
</tr>
<tr>
<td>Pipe installation</td>
<td>0.369129</td>
<td>0.149646</td>
<td>0.071402</td>
</tr>
<tr>
<td>Pipe age</td>
<td>0.369129</td>
<td>0.146582</td>
<td>0.069940</td>
</tr>
<tr>
<td>Pipe lining and coating</td>
<td>0.369129</td>
<td>0.135983</td>
<td>0.064883</td>
</tr>
<tr>
<td>Pipe wall thickness</td>
<td>0.369129</td>
<td>0.130229</td>
<td>0.062138</td>
</tr>
</tbody>
</table>


Table 4: Pairwise comparison matrix for identifying the global weights

<table>
<thead>
<tr>
<th></th>
<th>Physical Factors</th>
<th>Environmental Factors</th>
<th>Operational Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Factors</td>
<td>(1, 1, 1)</td>
<td>(0.60, 0.78, 0.92)</td>
<td>(0.29, 0.44, 0.60)</td>
</tr>
<tr>
<td>Environmental Factors</td>
<td>(0.08, 0.21, 0.40)</td>
<td>(1, 1, 1)</td>
<td>(0.47, 0.64, 0.78)</td>
</tr>
<tr>
<td>Operational Factors</td>
<td>(0.40, 0.56, 0.71)</td>
<td>(0.22, 0.36, 0.53)</td>
<td>(1, 1, 1)</td>
</tr>
</tbody>
</table>

Table 5: Consistency in pairwise matrices

<table>
<thead>
<tr>
<th>Pairwise comparison Matrix</th>
<th>CI</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global weights</td>
<td>0.58075</td>
<td>1.0013</td>
</tr>
<tr>
<td>Physical factors</td>
<td>0.42589</td>
<td>0.4732</td>
</tr>
<tr>
<td>Environmental factors</td>
<td>0.53143</td>
<td>0.4026</td>
</tr>
<tr>
<td>Operational factors</td>
<td>0.54461</td>
<td>0.4863</td>
</tr>
</tbody>
</table>

The collected responses were also analysed for Entropy method. The entropy, degree of diversification and weight of importance of the deterioration factors were shown in the Table 6.

Table 6: Entropy, degree of diversification and weight of importance of the factors

<table>
<thead>
<tr>
<th>Criteria/ Responses</th>
<th>$e_j$</th>
<th>$d_j$</th>
<th>$w_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe material</td>
<td>0.43974</td>
<td>0.56026</td>
<td>0.066174</td>
</tr>
<tr>
<td>Pipe installation</td>
<td>0.53391</td>
<td>0.46609</td>
<td>0.080345</td>
</tr>
<tr>
<td>Pipe age</td>
<td>0.53840</td>
<td>0.46160</td>
<td>0.081019</td>
</tr>
<tr>
<td>Pipe lining and coating</td>
<td>0.56588</td>
<td>0.43412</td>
<td>0.085155</td>
</tr>
<tr>
<td>Pipe wall thickness</td>
<td>0.58516</td>
<td>0.41484</td>
<td>0.088057</td>
</tr>
<tr>
<td>Dissimilar metals</td>
<td>0.58820</td>
<td>0.41180</td>
<td>0.088515</td>
</tr>
<tr>
<td>Type of joints</td>
<td>0.59528</td>
<td>0.40472</td>
<td>0.089579</td>
</tr>
</tbody>
</table>
\begin{itemize}
  \item Bedding soil type 0.31559 0.68441 0.047492
  \item Backfill material 0.36496 0.63504 0.054921
  \item Soil pH 0.40421 0.59579 0.060827
  \item Seismic activity 0.34103 0.65897 0.051320
  \item Disturbance 0.38311 0.61689 0.057651
  \item Water pressure 0.18103 0.81897 0.027242
  \item O&M practices 0.23985 0.76015 0.036094
  \item Leakage 0.27448 0.72552 0.041305
  \item Water pH 0.29442 0.70558 0.044306
\end{itemize}

\*e_i = entropy
\nd_j = degree of diversification
\nw_j = weight of importance

Since Outputs are not the same in both Entropy and FAHP methods, therefore the final weight will be an integration of both methods. Equation 14 is used to find the weights of importance of the parameters.

Table 7: Weights of factors from Entropy and FAHP

\begin{center}
\begin{tabular}{|l|c|}
\hline
Criterion & Weights of importance \\
\hline
Pipe installation & 0.09101 \\
Pipe age & 0.08989 \\
Pipe material & 0.08956 \\
Dissimilar metals & 0.08896 \\
Pipe lining and coating & 0.08765 \\
Pipe wall thickness & 0.08680 \\
Type of joints & 0.08519 \\
Seismic activity & 0.05146 \\
Bedding soil type & 0.05040 \\
Backfill material & 0.04937 \\
Disturbance & 0.04773 \\
Soil pH & 0.04548 \\
Water pH & 0.03967 \\
O&M practices & 0.03345 \\
Water pressure & 0.03214 \\
Leakage & 0.03124 \\
\hline
\end{tabular}
\end{center}
The weights of importance from FAHP, Entropy method and integration of both methods are illustrated in Figure 4. The factors are organized based on the weights from the integration of both methods. It can be seen that the prediction of weight of importance for most of the criteria are approximately the same in the 3 calculations and the differences are less than 2%. Greater differences are detected in water pressure, dissimilar metals, lining and coating and pipe wall thickness respectively. This confirms that the computed weight of importance for each of the criterion is calculated correctly and shows that more researches and clarifications are required to identify the effects of these criteria precisely.

Figure 4 : Comparison of weights from different methods

5 CONCLUSIONS

As pipelines deteriorate, they are more exposed to failure from internal and/or external causes, therefore knowing the importance of effective factors in deterioration of water pipeline is essential in infrastructure management. This study applies Fuzzy Analytic Hierarchical Process (FAHP), Shannon Entropy and Integration of two methods to determine the weight of importance of the selected factors considering the deterioration process. Results show that physical factors and operational factors are the most and least important category of factors respectively. Pipe specifications such as installation, age, material, utilizing dissimilar metals and lining and coating proved to have the most influence on pipeline deterioration through analysis which should be take into account while designing durable and reliable pipelines. The outcome of this research also reveals consistency between the weights calculated in three highlighted ways except in water pressure, dissimilar metals, lining and coating and pipe wall thickness which brings the need for further investigations on the effect of these factors. The calculated weights of importance from integration of FAHP and Entropy will be used for future development of models for condition rating and deterioration.
Acknowledgement

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AN ONTOLOGY-SUPPORTED TRANSACTION FORMALISM PROTOCOL IN INFRASTRUCTURE MANAGEMENT

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Abstract: Infrastructure organizations use diversified information systems to exchange data (transaction). Presently, data exchange in the area of infrastructure management is accomplished in a manual and ad hoc basis. The growing trend is to transform these manual data exchanges to a computer-to-computer based exchange of information. “How to formalize these data exchanges or transactions?” is the core research question, which was dealt with developing and applying an ontology-supported Transaction Formalism Protocol (TFP). The proposed solution is composed of two parts: ontology and protocol. Two ontologies, the Transaction Domain Ontology and Tangible Capital Asset ontology, were developed using an eleven-step methodology to represent transaction knowledge and Tangible Capital Asset knowledge respectively to support the design and implementation of transactions in infrastructure management. The proposed TFP is an eight-step procedure developed using a four-step methodology from two perspectives: the TFP Specification modelled each step of the protocol as a function for which inputs, controls, mechanisms, tools/techniques, and outputs were defined, whereas the TFP Tool includes a set of forms and guidance developed for specific steps of the protocol. The TFP was applied to develop transaction specifications for the Asset Inventory and Condition Assessment Reporting (AI&CAR) Reporting, which was implemented in the Asset Information Integrator System for the exchange of Tangible Capital Asset information between the municipal and provincial governments. The main contributions of this research work include the development of the two ontologies, protocol, and Asset Integrator Information System.

1 INTRODUCTION

Infrastructure agencies, including shallow utilities own, operate, and manage infrastructure systems using a wide range of information systems, each based on different proprietary data models. Various agencies and utilities interact with each other and exchange infrastructure information to accomplish a wide range of collaborative tasks. As infrastructure agencies increasingly rely on computer-based systems to manage infrastructure data, much of the information that was traditionally exchanged using manual and ad hoc communications can now be exchanged electronically through computer-to-computer data exchange. This allows for more extensive, rapid, and error-free exchange of information, but it requires more formal specifications to govern these data exchanges (i.e. transactions). A transaction is defined “as any communication or interaction between the sender and receiver roles that make up the information flow through a single or collection of a sequenced set of messages” (Zeb and Froese, 2012). Transaction example includes: communications during a disaster response (“Is power available in this area?” “Who is responsible for this section of roadway?” “When will water to be restored to this area?”); coordination between buried utility agencies; aggregation of data from multiple infrastructure management software with regards to the asset inventory and condition assessment reporting and formalized transactions used in the multi-agency situational awareness system wherein the provincial government requires information...
from many other organizations outside the provincial jurisdiction to prepare for and mitigate the impacts of emergency incidents (Stewart, 2010).

Although the inevitable trend in the communication technology is towards increasing computerization, which requires transaction formalization, but there are many challenges that prevent this formalization from being an easy or efficient process. These challenges include: lack of an appropriate process for carrying out this formalization; heterogeneity in data formats, data (class) definitions, and data aggregation (Felio, 2012). These issues were dealt with developing an ontology-supported Transaction Formalism Protocol (TFP) in the domain of infrastructure management.

The TFP is a procedure developed to formalize transactions and create transaction specifications effectively and efficiently. To support the development and application of the TFP, two ontologies were built: the Transaction Domain Ontology (Trans_Dom_Onto), and the Tangible Capital Asset Ontology (TCA_Onto). According to Gruber (1995), an ontology is a “formal explicit specification of a shared conceptualization.” The Trans_Dom_Onto represents transaction related knowledge to support the design, management, implementation of transactions, and development of the TFP. The TCA_Onto represents the Tangible Capital Assets (TCAs) to support the design of message templates in a neutral data format to address message-based interoperability between information systems of the infrastructure organizations. According to PSAB (2009), the TCAs are “non-financial assets having physical substance that are acquired, constructed, or developed and: are held for use in the production or supply of goods and services; have useful lives extending beyond an accounting period; are intended to be used on a continuing basis, and are not intended for sale in the ordinary course of operations.”

The proposed TFP protocol is an eight-step procedure that was developed from two different perspectives. The TFP Specification represents each step of the protocol as a distinct function for which inputs, controls, mechanisms, tools/techniques, and outputs were defined. The TFP Tool is comprised of a set of Excel-based forms and guidance developed for specific steps of the protocol that the transaction development personnel can use to define transaction specifications for IT based solutions.

The proposed TFP was applied to develop transaction specifications for the Asset Inventory (PSAB, 2008) and Condition Assessment (SORP, 2008) Reporting/Tangible Capital Asset (AI&CAR/TCA) Reporting. The formalized transaction specification was implemented in a prototype Asset Information Integrator System (AIIS). The prototype system collects, stores, visualizes, and analyzes the asset inventory and condition assessment information received from different municipalities to help the provincial government to: understand long-term financial needs of municipalities for infrastructure management; develop a consistent and planned approach for funds allocation; and present the case to the federal government for additional funding, if required.

This paper is divided into the following seven sections. Background information and related literature are discussed in section 1 and 2 respectively. Section 3 describes the methodology used, whereas section 4 briefly explains the development of the ontologies and TFP. Application of the TFP is presented in section 5 and evaluation is elucidated in section 6. Conclusions and contributions are discussed in section 7.

2 LITERATURE REVIEW

The literature review is discussed from two perspectives: ontologies in the domain of infrastructure management and related work process and communication formalization standards and methodologies.

Ontologies in infrastructure management—three ontologies in the domain of infrastructure management are of particular importance: Infrastructure Product Ontology, IPD-Ono (Osman, 2007); Infrastructure and Construction Process Ontology, IC-Pro-Onto (El-Gohary, 2008); and Actor Ontology, Actor-Onto (Zhang and El-Diraby, 2009). The IPD–Onto (Osman, 2007) represents infrastructure product knowledge (e.g. pipe, valve, pump, etc.). The IC-Pro-Onto represents process knowledge, e.g. core design and construction processes, management processes, knowledge integration processes, and support processes (El-Gohary, 2008). The Actor-Onto represents knowledge related to various actors and actor-roles in the construction industry (Zhang and El-Diraby, 2009). While these three core formalism
dimensions have been completed, there remains a need to formalize information exchange processes (transactions) to enable computer-to-computer, message-based exchange of information. Transaction formalism involves specifying and defining not only the process, actor and infrastructure system information, but also the specification of information exchange details, which is to be addressed through the development of the Transaction Domain Ontology (Trans_Dom_Onto). In addition, these ontologies do not completely support the design of the message templates that are required to be exchanged in the AI&CAR/TCA Reporting (information transaction). The IPD-Onto doesn't represent a complete set of the infrastructure products, and it was extended in this research in terms of the TCAs to provide payload information for the design of the message templates for the AI&CAR/TCA Reporting, which led to the development of the TCA_Onto. The header information in these message templates, meanwhile, was captured from the Trans_Dom_Onto that was developed as part of this research work.

State-of-the-art standards—some process and communication formalization techniques currently exist in the Architecture, Engineering, Construction and Facilities Management (AEC/FM) industries, but these standards do not fully address the requirements for transaction formalism in the domain of infrastructure management. In the AEC/FM industries, the Information Delivery Manual (IDM) formalizes work processes in the construction industry (IAI-IDM, 2012). It is a requirement specification methodology focusing on model-based exchange of information between different parties using building information models (BIM). The IDM defines information in terms of informational elements (objects and their attributes) rather than informational products (documents), hence the methodology is BIM specific. In addition, the exhaustive nature of the IDM makes it time-consuming to develop and difficult to share with others on projects (Berard and Karlshoej, 2012). Because of the IDM's explicit focus on BIM, it does not meet the requirements for a general communication formalism technique for the infrastructure sector, but it is a very relevant exemplar for this research work, and therefore, some features of the IDM specifications were adopted with modifications. The Model View Definition (MVD) is a methodology developed to formally define a subset of an Industry Foundation Class (IFC) BIM model (IAI-MVD, 2005). The MVD is relevant since it is typically used to formally specify the particular BIM information to be exchanged during a specific type of data transaction, but again, it is BIM specific and it lacks a step-by-step procedure describing how to capture requirements. The Voorwaarden Scheppen Voor Invoering Standaardisatie (VISI), which means “Terms and Conditions for the Implementation of Standardization in ICT” is a Dutch communication management standard developed to define transactions in the AEC/FM industry (VISI, 2011). The VISI standard lacks a step-by-step process to capture transaction requirements and define transactions, and it depends on an Extensible Markup Language (XML) based model representing information in a local context (i.e. the Dutch construction industry). A related standard, the Construction Objects and Integration of Processes and Systems Engineering Method (COINS-EM/CEM), is a Dutch standard developed to create agreements on working methods and organization of production processes and information (Schaap et al., 2008). As with the IDM, COINS-EM/CEM focuses on exchange of model-based/3D object data rather than communication in general, and it also lacks a systematic procedure for requirement specification. Another initiative, the agcXML, focused on developing a set of XML schemas to enable industry experts to exchange electronic building information reliably and efficiently between heterogeneous proprietary software applications to improve interoperability and integration of the information systems (Zhu, 2007). The agcXML doesn’t include a general data transaction specification, it does include a format for transaction use cases and a use case for generic document distribution (Froese, 2007), but does not include a procedure for transaction design.

In summary, none of the standards discussed above fully meet all of the objectives of this research work in terms of developing a step-by-step procedure to define transaction specifications in the domain of infrastructure management. Most of the standards are work-process-centric rather than communication-centric. Most do not address how to assess needs and capture information that is required in a given communication. Most of the standards are IT-expert-centric and are not suitable for the end users. These shortcomings led to the development of the proposed ontology-supported TFP.

3 METHODOLOGY

Methodology to develop ontologies—a ten-step methodology was devised to build the Trans_Dom_Onto and TCA_Onto, which was a hybrid version of the various approaches developed by Fernandez-Lopez et
al., (1997); Uschold and Gruininger (1996); and Noy and McGuinness (2001). (i) Define ontology coverage—purpose, use, and users of the ontologies are defined in this step. (ii) Capture competency questions—a set of competency questions were developed that the ontology should be able to answer. (iii) Generate/create taxonomy—a preliminary taxonomy of various concepts was developed. (iv) Reuse existing ontologies—as long as possible, use was made of the existing ontologies and relevant concepts were captured from existing ontologies. (v) Develop Transaction Domain Kernel Ontology, (Trans_Dom_Kernel_Onto) and Tangible Capital Asset Kernel Ontology, (TCA_Kernel_Onto)—representing concepts at the very abstract level to easily categorize and integrate diversified knowledge in the domain of infrastructure management. (vi) Extend Trans_Dom_Kernel_Onto and TCA_Kernel_Onto to develop Transaction Domain Extended Ontology (Trans_Dom_Extended_Onto) and Tangible Capital Asset Extended Ontology (TCA_Extended_Onto)—abstract concepts represented in the kernel ontologies are extended to develop detailed taxonomies. (vii) Capture ontology—represents explicit declaration of the concepts in terms of soft and hard axioms. (viii) Code ontology—the knowledge represented in both the ontologies was formally coded using Protégé Ontology Editor (Protégé, 2014). (ix) Evaluate ontology—the knowledge represented in both the ontologies was verified using Protégé Ontology Editor and competency questions, and validated through industry experts. (x) Document ontology—the knowledge was finally documented for future use.

Methodology to develop the protocol—the proposed TFP was developed using a four-step methodology devised based on the approach formulated by Adesola and Baines (2005) for the development of business process improvement methodologies. The approach involves reviewing and analyzing current frameworks/methodologies and then selecting the relevant candidates based on the key selection criteria. These steps include: (i) select the candidate standards; (ii) benchmark existing standards; (iii) link and build on existing standards; and (iv) develop the proposed TFP.

4 ONTOLOGY-SUPPORTED TRANSACTION FORMALISM PROTOCOL

The development of the proposed ontology-supported TFP includes two parts: development of ontologies and development of the protocol.

4.1 Ontology Development

4.1.1 Transaction Domain Ontology

To support the design, implementation, and management of transactions in the domain of infrastructure management, the Trans_Dom_Onto was developed. The knowledge represented in the ontology was organized according to the core and support concepts totaling to about 420. The core concepts represent the core building blocks of the transaction domain knowledge in the area of infrastructure management. The core concepts are: transaction, message, actor/actor-role, and information. The transaction is the complete communication between two parties. The message or message template represents the information that is required to be exchanged in a given transaction between the actor-roles. Actors are either organizations or individual that plays a specific role (i.e. sender or receiver) in a given transaction. The information is the discrete processed data that the actor-roles need to exchange to accomplish a transaction successfully. Detailed taxonomies of the core concepts were developed based on the concept of modality (i.e. a specific view of the concept categorization) while the explicit declaration of each concept is presented in Zeb and Froese (2012).

On the other hand, the support concepts support or assist in modelling the core transaction domain knowledge and is the focus of this paper. The support concepts encompass modality, attribute, mechanism, constraint, axiom, and relationship. The modality is a "characteristic that describes a thing and denotes it's belonging to a particular group or category", (El-Gohary, 2008).

According to Osman (2007), an attribute is a characteristic, feature, or property that describes a thing, entity, or concept. The transaction has five transaction attributes. Transaction function attribute—is a characteristic that describes a transaction based upon the function it performs in a given communication. Transaction dependency attribute—is a characteristic that describes a transaction based on the logical,
geographic, and cyber dependencies. Dependencies govern the design and implementation of transactions in practical scenarios. **Transaction performance attribute**—is a property that describes the performance of a transaction in terms of transaction efficiency. **Transaction cost attribute**—is a property that describes the transaction design, implementation, and operational cost. **Transaction control attribute**—is a characteristic that describes the transaction security in terms of transaction authorization.

According to El-Gohary (2008) and Osman (2007), the mechanism is an umbrella concept that has three sub-classes: guide, method, and measure, which includes all the tools and means required to accomplish a transaction successfully. The **guide** is a basic information or instructions needed to support the work of an actor role in all communications. It has the following four sub-classes: theory, best practice, strategy, and algorithm. The **method** is a generic concept that covers all such means, mediums, and techniques used to exchange and store transactions. In the Trans_Dom_Onto, methods for transaction transmission and transaction archiving are represented. According to Osman (2007), the **measure** is an abstract concept used to gauge conformance of an entity's attribute to a pre-defined requirement as prescribed by specifications and codes. It has two types: test and metric. The **test** is used to measure conformance of the characteristics of a physical entity to the desired specification and code requirements. The **metric** is used to gauge conformance of the attribute of an abstract entity with respect to predefined requirements. The metric for the transaction (abstract entity) efficiency (attribute) is represented in the Trans_Dom_Onto. **Objective metric**—captures quantitative measurement of the transaction efficiency. It has two sub-classes: transaction cost savings and transaction time savings. **Subjective metric**—captures qualitative measurement of the transaction efficiency. The quality of a transaction is measured in terms of user convenience (Zott et al., 2000) and transaction righteousness.

The transaction is controlled by a set of transaction constraints, which refer to the conditions, factors, requirements, and obligations that restrict the way transactions are to be designed, implemented, and managed in the domain of infrastructure management. It has two sub-classes: internal and external constraints. The **internal constraints** are the requirements and obligations of the collaboration partners in a given transaction. It is categorized into two sub-classes: user requirement and contractual constraints. The **external constraints** are those constraints that are beyond the control of the collaboration partners. It has two sub-classes: regulatory and environmental constraints.

According to (Osman, 2007 and El-Gohary, 2008), **axiom** unambiguously defines the concept represented in the ontology and constrain its interpretation. According to Gruninger and Fox (1995), axiom specifies unambiguous definitions of the concepts in a specific domain. The transaction axioms were classified as soft and hard axioms. The **soft axioms** define the concepts in plain English Language, whereas the **hard axioms** explicitly define the concepts using a formal language—Ontology Web Language (OWL) based Description Logic Syntax (DL). The hard axioms are of three types. **Subsumption axiom**—explicitly defines classes in hierarchies with parent-child relationship. **Disjoint axiom**—explicitly describes that the concepts are disjointed from each other, which mean an individual as a member of class “x” cannot be an instance of another class. Property restriction axiom—According to Horridge (2009), **properties** describe the binary relationship between the concepts, whereas the **datatype properties** describe the relationships between the individuals and data values, where individuals in OWL represent the instances of a class. In OWL, classes are defined in terms of the property restrictions, which states that “a restriction describes a class of individuals based on the relationships that members of the class participate in” (Horridge, 2009), and therefore, a property restriction represents a class of individuals. The property restrictions are of three types: quantifier restriction (i.e. existential and universal), cardinality restriction (i.e. minimum, maximum, and exact), and has value restriction. A total 1726 axioms were defined in the Trans_Dom_Onto.

According to Osman (2007), **relationships** are the associations between the concepts to enrich knowledge representation. It has the following two types. The **hierarchical relationships** include the generalization-specialization and aggregation-composition relationships. The generalization-specialization relationships—represent is-a or type-of or parent-child relationship between concepts and has two types: hyponymy and hypernymy, (El-Gohary, 2008). The aggregation-composition relationships—are whole-part relationships that represent the relationship between the whole and its parts, which is also known as partonomy (El-Gohary, 2008). It has two sub-classes: aggregation and composition relationships which...
are further classified as meronymy and holonymy. The association or directed association represents other than “is-a” or “part-of” relationships in a knowledge representation. It has the 13 sub-classes: formalize, characteristic, restrict, devise, human function, relational, communicate, reveal, facilitate, cumulate, partake, ingest, and consequence relationship.

4.1.2 Tangible Capital Asset Ontology Development

To support the design of message templates for the AI&CAR/TCA Reporting, the TCA_Onto was developed. The message templates represent header (meta information, e.g. name, from, to, etc.) and payload information (actual information content that actor-roles requires in a given transaction). The header information was captured from Trans_Dom_Onto and the payload information was captured from the TCA_Onto. The knowledge in the TCA_Onto was organized from four different perspectives or modalities. The individual asset represents the TCAs based on the type of the individual asset. According to PSAB (2009) and TCA (2012), individual asset has eight sub-classes: land, land improvement, building, building improvement, infrastructure, machinery and equipment, vehicle, and work in progress. The function based asset includes the TCAs based on the function they perform. Osman (2007) defined six such functions: control, access, protection, measuring, storage and conveyance assets. Commuting and processing was defined as part of this research work. The composition based asset represents the TCAs based on their aggregation in a given infrastructure system. For instance, system, sub-system, and component level (Osman, 2007). The sector based asset classifies the TCAs based on the sector to which they belong. It has two sub-classes: facility and infrastructure sector assets. The infrastructure sector asset has seven sub-classes: transportation, water, wastewater, solid waste management, gas, electricity, and telecom sector assets. The facility and infrastructure sector assets; specifically, the transportation, water, wastewater and solid waste management sector assets were further specialized and extended to develop detailed taxonomies as presented in Zeb and Froese (2014). Development of the detailed taxonomies of the gas, electricity, and telecom sector assets was omitted as these assets are generally not owned and operated by municipal infrastructure organizations and was covered in other existing ontologies. The TCA_Onto represents 345 classes of various TCAs in the facility and four infrastructure sectors. In addition, 1517 axioms were developed to explicitly describe TCAs in the domain of infrastructure management.

4.2 Development of the Transaction Formalism Protocol

The proposed TFP protocol is an eight-step procedure developed to define transactions in the domain of infrastructure management effectively and efficiently. The protocol was developed from two perspectives; TFP Specification and TFP Tool. The TFP Specification was developed from a conceptual perspective where each step of the protocol was modeled as a distinct function for which inputs, controls, mechanisms, tools/techniques, and outputs were defined. The TFP Specification was developed using the IDEF0 modeling technique. The TFP Specification provides the formal “instruction set” for creating transaction specifications as presented in Zeb and Froese (2013). On the other hand, the proposed TFP Tool includes a set of Excel-based forms and some guidance that the transaction development personnel can use to define transaction specifications. These steps are: assess needs—step 1, define As-is transaction map (TM)—step 2, develop To-be TM—step 3, collect information—step 4, design message template (MT)—step 5, review TM and MT—step 6, adopt and implement TM and MT—step 7, and monitor transaction specification—step 8. The forms for the Tool were developed in step 1, 2, 3, 4, 6, and 8. The forms were developed to capture information easily, accurately, and consistently while defining transactions. For step 5 and 7, only guidance was provided on how to perform these steps because no data is required to be captured in these steps. A brief description of these steps is as follows.

- **Step 1**—a comprehensive needs assessment is conducted to identify and select among a set of transactions that has the greatest potential for IT improvement. The assessment criteria include: manual/paper based transaction, criticality, frequency, importance, likelihood of the management, cost of the transaction, and contractual and regulatory requirements.
- **Step 2**—a preliminary As-is TM is developed based on the needs assessment.
Step 3—a To-be TM is developed that is an improved version of the As-is TM incorporating process, information, and mode improvements.

Step 4—required header and payload information is collected in this step.

Step 5—based on the collected information, MTs are defined.

Step 6—the designed TMs and MTs are reviewed for errors; if any, and make changes before implementation.

Step 7—the designed TMs and MTs are implemented in the Asset Information Integrator System.

Step 8—the implemented transaction specifications are monitored for continuous improvements.

5 APPLICATION AREA AND ASSET INFORMATION INTEGRATOR SYSTEM

The proposed TFP Tool was applied to one of the transactions identified through an IT survey (Zeb and Froese, 2012) conducted as part of this research work—AI&CAR/TCA Reporting. The municipal experts completed the needs assessment form using the above-mentioned criteria. The AI&CAR/TCA Reporting transaction was selected because it scored high against the assessment criterion. Despite the fact that the frequency of this transaction is not high, the municipal experts identified it as one of the potential transactions due to three reasons. Compliance with regulatory requirements—newly imposed regulatory requirements require municipalities to report asset inventory information in compliance with the Public Sector Accounting Board reporting requirements-3150 (PSAB, 2008) and condition assessment in compliance with the Statement of Recommended Practices, SORP reporting requirements (SORP, 2008). Manual/paper based transaction—currently, this transaction is manual as human interpretation of the information is required and organizations find it difficult and time consuming to compile, extract, and compare the TCA information. Costly—this transaction is costly in terms of time spent in extracting and comparing information.

The AI&CAR/TCA Reporting is a communication process in which different municipalities report their AI&CAR/TCA information to the provincial government for financial planning and funds allocation. The provincial government collects and analyzes this information to: (i) understand the long-term funding needs of different municipalities for infrastructure management; (ii) develop a consistent and planned approach to fund allocation; and (iii) to present the case to the federal government for additional funding, if required. This reporting also helps municipalities to update asset data on a regular basis, resulting in better management of their infrastructure systems. The AI&CAR/TCA Reporting case study transaction was used in two ways. First, the TFP Tool was applied to formalize this transaction to develop the transaction specification for the application area. Second, the transaction specification for AI&CAR/TCA Reporting was implemented to develop the prototype system—the AIIS.

The proposed AIIS was developed for the reporting of the AI&CAR/TCA information between the municipal and provincial government. Presently, the municipal organizations exchange this information in a manual and ad hoc way in the form of a PDF or Word file due to heterogeneous and inconsistent data formats. To transform to a more computer-based exchange of the TCA information, the AIIS implemented standardized MTs that were defined based on the knowledge represented in the two ontologies developed as part of this research work.

The proposed AIIS is a web-based prototype system that was implemented using the SharePoint platform. This platform was adopted due to its robustness and ease of use (Microsoft, 2012). The proposed AIIS collects the TCA reports received from various municipalities via standardized MTs, as shown in Figure 1, and integrate them with back-end applications (MS Excel, Excel Services within SharePoint, SharePoint Reporting Services, etc.) for further processing and analysis.
Figure 1: Asset information integrator system

6 EVALUATION

The ontology-supported TFP is composed of two parts and, therefore, the evaluation was separately conducted for each part: ontology and protocol.

Ontology evaluation—both the Trans_Dom_Onto and TCA_Onto were evaluated through industry experts using a criteria-based approach (Gomez-Perez, 2001). The criteria used to validate both the ontologies include: completeness (Gomez-Perez, 1996), correctness (Guarino, 1998), and clarity (Gruber, 1995 and Yu et al., 2007). Clarity judges the level to which a knowledge representation is clear and understandable. The class description communication error was used to measure clarity of these ontologies. Completeness judges the level to which a knowledge representation is incomplete. Completeness is measured in terms of incompleteness. Correctness measures accuracy of the knowledge representation from a real-world perspective. The identity error was used to measure the correctness of both the ontologies. The Trans_Dom_Onto was validated through three domain experts using a structured interview approach. Each of them had more than 15 years of experience in different civil engineering fields. They were extremely familiar with the transportation sector while moderately familiar with the water, wastewater, and solid waste management sector. In addition, they were moderately familiar with the data or information modeling and the process of communication formalization. Similarly, the TCA_Onto was validated through three experts. Each of the experts had more than 15 years of experience in managing different types of infrastructure systems. They were extremely familiar with different infrastructure systems being owned, operated, or managed by municipalities. They were moderately familiar with data or information modeling and TCA reporting under PSAB-3150 reporting requirements. Two separate structured questionnaires were presented to the respondents wherein questions were organized according to three assessment criteria: clarity, completeness, and correctness. For each question, a multi-sheet table was developed to reflect various concepts in rows and respondents’ responses in the columns. The respondents were asked to rate a given concept on a scale of 1 (strongly disagree) to 5 (strongly agree) under each of the three assessment criteria. The responses were recorded for each concept reflected in the tables developed for clarity, completeness, and correctness, and an average score was calculated. In both ontologies, the average score ranged from 4 (agree) to 5 (strongly agree), which indicates that all the respondents were in universal agreement on the clarity, completeness, and correctness of the knowledge represented in the Trans_Dom_Onto and TCA_Onto.

Protocol evaluation—the proposed TFP Tool was validated through experts using a criteria-based approach. Adesola and Baines (2005) identified three criteria: feasibility, usability, and usefulness to validate an improvement methodology, which were adopted with modifications to validate the proposed TFP Tool. An additional criterion—generalizability—was also identified, defined, and used to validate the TFP Tool. Feasibility assesses the appropriateness of the TFP Tool in terms of completeness, correctness, and reasonableness. Usability assesses the ability to learn and work with the TFP Tool, which was evaluated using three measures: understandability, applicability, and guidance/supportability.
Usefulness assesses the utility and value of the tool in terms of five measures: effectiveness, efficiency, consistency, changeability/adaptability/customizability, and reusability. Finally, generalizability assesses the applicability of the Tool across a wide variety of communications within AEC/FM and non-AEC/FM industries, using a single measure of generality. A set of questions was framed under each criteria. The experts answers were recorded on an agreement continuum rating system: unable to rate (0), strongly disagree (1), disagree (2), neither agree nor disagree (3), agree (4), and strongly agree (5). Answers were recorded for each question given under feasibility, usability, usefulness and generalizability and average scores were calculated. The resulting average scores ranged from 4 (agree) to 4.8~5 (strongly agree), indicating that the proposed TFP Tool was feasible, usable, useful, and generic.

7 CONCLUSIONS

Presently, data exchange in the domain of infrastructure is performed on a manual and ad hoc basis. The growing trend is to transform this manual data exchange to a more formalized computer-to-computer based exchange of information. To accomplish the paradigm shift, an ontology-supported TFP was developed. The proposed protocol consisted of two parts: ontologies and protocol. To support the design, implementation, and management of transactions in the domain of infrastructure management, two ontologies were developed: the Trans_Dom_Onto and TCA_Onto. Also, the protocol—an eight-step procedure was developed at two levels of abstraction: TFP Specification and TFP Tool. The TFP Specification is a conceptual model that makes a foundation for the TFP Tool. On the other hand, the TFP Tool includes a set of forms and guidance developed for specific steps of the protocol. The TFP Tool was applied in the domain of infrastructure management to develop transaction specifications for the AI&CAR/TCA Reporting, which was implemented in an AIIS. Both the ontologies and protocol were validated through industry experts using criteria based approach. The evaluation results indicate that the transaction development personnel (i.e. transaction analyst, process modellers, software developers, industry experts, and users) can use the protocol effectively and efficiently.

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A DIVIDE-AND-CONQUER ALGORITHM FOR 3D IMAGING PLANNING IN DYNAMIC CONSTRUCTION ENVIRONMENTS

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Abstract: On construction sites, engineers need real-time geometries of workspaces for reducing spatial conflicts between construction activities, monitoring construction progress, and controlling construction quality. The dynamic nature of construction environments, however, poses challenges to collecting sufficient and high-quality geometric data to support such needs. Effective uses of advanced 3D-imaging technologies also rely on engineers’ experiences. Manual imagery data collection often results in missing or low-quality data or unnecessary over-detailed inspection and exponentially long computation time, which may bring extra cost to construction project. To overcome these challenges of 3D data collection, the study presented in this paper proposes a new automatic 3D imaging planning method for guiding efficient and effective 3D imagery (e.g., LiDAR) data collection in dynamic environments. This method first establishes a sensor model of laser scanners, and then establishes a divide-and-conquer algorithm for achieving rapid and precise 3D imaging planning for dynamic construction site. For a given jobsite, this algorithm creates a graph that represent objects or features having specific data quality requirements (e.g., level of accuracy, and level of detail) as nodes, and spatial relationships between these objects as edges (e.g., distance, line-of-sight). A graph-coloring algorithm decomposes such a graph into subgraphs for finding their “local” optimal 3D imaging plans. A solution aggregation algorithm then combines those “local” optimal data collection plans into a complete 3D imaging plan for the complete graph representing the scene. Testing results indicate that the divide-and-conquer algorithm can improve the performance and computational efficiency of 3D imaging planning and producing better results than the conventional 3D imaging planning methods.

1 INTRODUCTION

In construction projects, failing to acquire timely, detailed, and accurate spatial information for decision-making may cause low quality, low productivity, and accidents. On construction jobsites, one key reason of deficient 3D imaging data collection is the dynamic nature of construction projects. Different tasks involve different construction environments, facilities, construction activities, and objects. Moreover, the specific requirement of field data will be changing even in the same task in different environments during different stages of construction. This dynamic nature of construction projects not only requires a variety of 3D data, but also brings difficulty of efficient and effective spatial data collection. The problem becomes more serious when the users of technologies have limited experiences of using imaging systems in changing workspaces. Bad data collection will cause low quality (missing, inaccurate, or less detailed) data, or unnecessary interference of jobsite activities. Reliable sensing method and timely, comprehensive data collection of spatial data is necessary in dynamic construction projects.
Compared to traditional inspection methods (e.g. tapes, laser tapes, Global Navigation Satellite System), 3D imaging technologies, such as laser scanning and structure from motion (SFM), is able to provide fast and comprehensive 3D imageries of construction jobsite. However, currently, construction engineers can only manually plan 3D-imaging process based on their intuition or experiences. This experience-based data collection may not effective or efficient, because 3D imaging data collection is a complicated process that involves 3D space domain and time domain configuration, as well as multiple scanner parameters. On one hand, low quality 3D imaging data may impede effective decision making on the site. On the other hand, redundant data collection is wasting time and causing frequent interferences with construction operations during data collection. In addition, hiring an experienced professional for data collection can be very expensive (thousands of dollars per day). An automatic laser-scanning planning method is thus necessary to configure the parameters of laser-scan data collection (e.g. scan position, parameters on the scanner) systematically according to the dynamic construction information needs in a changing environment while maximizing data collection efficiency. The proposed algorithm will help to reduce the cost caused by decision-making error that result in inaccurate inspection, interruption of construction processes by data collection, and training or hiring laser-scanning professionals.

2 BACKGROUND RESEARCH

3D imagery data quality has great influence on the results of data processing (e.g. more precise result of BIM model). One research provided a sensor model describing how various data collection parameters will influence data quality metrics, e.g. level of detail (TANG and ALASWAD. 2012). Another research proposes a model for estimating edge loss in laser scanned data by considering the impacts of various factors, such as scanning distance, density of data and incidence angle on the edge loss (Tang, Akinci, and Huber 2009).

Researchers studied 3D imagery sensor planning problem in order to capture high quality 3D imagery data. Traditional 3D imagery sensor (e.g. LIDAR) planning focuses on fixed sphere planning about a single object (Latimer et al. 2004; Pito 1996; Son, Park, and Lee 2002; Lee, Park, and Son 2001). In mechanics engineering domain, researchers produced an automatic process planning system based on visibility analysis dealing with free form surface (Fernández et al. 2007). On the other hand, fewer researchers focus on sensor planning problem in construction background. One planning algorithm chose sensing locations based on clustered construction information goals and then generated paths to minimize the transit cost between clusters (Latimer et al. 2004). However, this approach did not clearly show the inspection goal and did not take the data quality requirement into consideration (e.g. LOD, LOA). In another sensor planning approach, researchers used 1m³ cubes to represent the construction to obtain the visibility of any cube, and then next-best-view (NBV) scan planning approach could generate the scan positions (Blaer and Allen 2009). This algorithm also ignored data quality and scan efficiency. A third sensor planning research proposed a scan planning algorithm using the next-best-view idea (Song, Shen, and Tang 2014). The major limitation of directly using next-best-view scan planner was the scan resolution was constant for all the scan positions, which might lead to longer calculation time and redundant data collection in areas where the resolution requirement is low. Therefore, the potential of improving the performance of sensor planning problem in construction area is huge.

3 PROBLEM DESCRIPTION AND TERM DEFINITION OF LASER-SCANNING PLANNING

3.1 Problem Description

The goal of 3D imaging planning is to determine positions and scanner parameters of each scan to ensure the collected 3D image meets inspection requirements with optimal time consumption. We can describe the scan planning problem using the following IDEF0 process model, showing in fig.1. The input includes the inspection goals, i.e. specific areas in the jobsite that field engineers need inspect with certain accuracy. The constraints are sensing model of laser scanner, time, cost, and space limits of the dynamic jobsite. The outputs are the scan positions and scan parameters.
The main challenges of 3D imaging planning are as follows: 1) the measurement model of 3D imaging is not clear. 2) It involves both 3D space domain and time domain; 3) the dynamic nature of jobsite require a high demand for reliable data quality and least possible data collection time. We will focus on these challenges in our proposed method.

![Diagram of IDEF0 process model of laser-scanning planning algorithm]

### 3.2 Feature Point

Feature points are our inspection goals indicate areas we care about in 3D imaging process, which are. For 3D-imaging data collection, obtained imageries should contain all the geometric information in need; on the other hand, we want to avoid imageries containing unneeded dense data that waste time for data collection and processing. For example, engineers tend to avoid densely sampling simple geometries (e.g. flat walls) for saving time to focus on complex shapes, such as edges, openings, and decorations. Therefore, we can ensure the completeness and avoid redundancies of data collection only if we provide prior knowledge about geometric complexity. In this approach, we use “feature points” to symbolise objects or area with such high geometric complexity. For instance, if we know the coordinate of the four corners of a wall, we can determine the direction and size of the wall; if we know the coordinates of two ends of edges, we can determine the edges as well as related walls. Such feature points describing objects with high geometric complexity are feature points.

Feature point information needed for 3D imaging planning consists of 3 terms: 1) coordinates of feature points, 2) the normal vector of the wall each feature point is on, and 3) the level of detail (LOD) requirement of each feature point. The first 2 terms can describe the location of the area with geometrical complexity; the third term can describe the data quality requirement of the corresponding area (detailed description in the next section). For different construction environment and different tasks, the need for feature point information varies, which we will deeply discuss in further study.

Currently we use three sources to obtain feature point information: building information model (or jobsite plan), precious scan data, jobsite photographs. Fig.2 shows the three sources of feature point information: as designed model; previous 3D-imaging point cloud; series of jobsite photographs.
3.3 Level of Detail

3D imaging data collected by a laser scanner is a point cloud. The data quality of a 3D-imaging point cloud consists of two indices: level of detail (LOD) and level of Accuracy (LOA). LOD represents the point density of a certain area in a point cloud, on which this research will focus. Low point density indicates no sufficient information for further data processing and modeling, while an excessively high point density means extra labor and time consuming in data collection.

There is no well-accepted definition of LOD of 3D-imaging point cloud. However, in literature, researchers used two different methods to describe data density of point clouds. The first method was using number of points in fixed area (e.g. 1 square cm, 1 square meter, etc.) to define the data density (Dai et al. 2013). The second method involved two parameters: 1) distance between two adjacent laser dots within a beam path and 2) distance between beam paths (MacKinnon et al. 2009). In our research, we cared about the 3D-imaging data density in both horizontal and vertical dimension, so we defined Vertical LOD and Horizontal LOD using the second method, shown in fig.3:

Vertical LOD: Keep the horizontal rotation of the laser beam fixed, the distance between current laser dot and the next laser dot after rotation $\delta_v$ in the vertical plane.

Horizontal LOD: Keep the vertical rotation of the laser beam fixed, the distance between current laser dot and the next laser dot after rotation $\delta_v$ in the horizontal plane.
3.4 Feasible Area

In our approach, we use the concept “feasible area” to show the relationship between sensor model of laser scanner and the LOD requirement of a feature point. For any given feature point we need to know where to put the laser scanner to acquire point cloud with a required LOD. Thus, the set of qualified scan position is the feasible area of this feature point. To ensure the LOD of every feature point, we need at least one scan position in each feasible area (obviously, we can utilize the overlapping of feasible areas).

The definition of feasible area is the area on the ground where to put the laser scanner with given laser scanning resolution \( \delta_v \) & \( \delta_h \) so that the collected data of certain feature point will satisfy the LOD requirement. For certain feature point, it is obvious that the higher the laser scanner resolution is, the larger the feasible area is.

Without losing generality, we set the coordinate of a feature point as \((0,0,a)\) while the x-z plane represents the wall. If we put the laser scanner at the point\((x,y,h)\), for vertical LOD requirement we have:

\[
[1] \quad s_v = \frac{\delta_v(\sqrt{x^2+y^2}+(a-h)^2)}{\sqrt{x^2+y^2}} \leq LOD
\]

So \(2|a - h| \cdot \delta_v\) is the minimum \(s_v\) that we can obtain at this feature point, which comes from the nature of inequality.

For horizontal LOD requirement, we have:

\[
[2] \quad s_h = \frac{\delta_h(x^2+y^2+(a-h)^2)}{\sqrt{x^2+(a-h)^2}} \leq LOD
\]

So \(|a - h| \cdot \delta_h\) is the minimum \(s_h\) that we can obtain at this feature point.

Fig.4 shows the shape of feasible area of the vertical and horizontal LOD requirement at height=5m, LOD=0.013m (1/2 inch), resolution=1/4:

4 DIVIDE-AND-CONQUER ALGORITHM OF 3D IMAGING PLANNING

4.1 Overview

Using the terms defined in previous chapter, we can rephrase the goal of scan planning in dynamic construction site as follows: to determine optimal scan positions and corresponding scan resolution, so that the scans will cover all the feature point with a required LOD.

Previous approaches consider the jobsite as a whole, so the scan resolutions for all scan positions are fixed. In this case, the search area of possible scan positions maybe quadratically larger, leading to longer calculation time. Moreover, applying high scan resolution for less important area may be redundant...
and causes unnecessary time and labor consumption. To overcome this drawback, we divide the jobsite into parts according to the layout of the feature points, and then generate scan plan for each part. This divide-and-conquer method consists of three steps: 1) divide the whole jobsite into parts, according to the distribution of feature points; 2) generate scan positions and resolution in different parts; 3) completeness checking and generate the global scan plan. Fig.5 shows the framework of this divide-and-conquer algorithm of 3D imaging planning.

4.2 Divide: Feature Points Clustering

4.2.1 Visibility Conflitction Analysis of Feature Points

Visibility analysis means check whether two feature points can be scanned in a single scan. Obviously, two feature points with visibility confliction (cannot be scanned in a single scan) cannot be clustered into the same group. Therefore, the first step of feature point clustering is visibility confliction analysis and generates visibility confliction relationship between any pair of feature points.

![Current state of dynamic construction site](image1)

![Feature points information](image2)

![Feature points Clustering](image3)

![Scanning position detection and resolution configuration in each group](image4)

![Finalizing Scan Configurations](image5)

**Figure 5:** Frame work of divide-and-conquer algorithm of 3D imaging planning

![Figure 6: Using graph theory to cluster feature points: each edge indicates feature points with visual confliction, and different color shows the clustering result.](image6)

In the proposed scan planning algorithm, we used a series of rules assessing the visibility relationship of any pair of feature points. Parameters involved in these rules are distance and relative orientation. For example, two feature point facing the opposite direction and “back to back” (e.g. on different sides of the same wall) are visibility conflict with each other. Another example is: if the distance between two feature points are greater than 5 times of the maximum height of all feature points, these two feature points are visibility conflict, for we need to use extra high resolution to cover such two feature points. Due to the limited space, we do not represent all the visibility checking rules here. We will give detailed discussion in other literatures.

4.2.2 Clustering Feature Points into Groups According to Visibility

We use the following math problem to represent feature points clustering according to visibility confliction condition: A set \{an\} has \(n\) elements. Any element \(a_i\) has a known relationship (‘conflict’ or ‘not conflict’) with any other element \(a_j\) in this set. A minimum positive integer \(m\) is to be found that the set \{an\} can be divided into \(m\) subsets, so that all the elements in the subsets are not conflict with each other, which means any conflict elements are in different subsets.

We apply the feature point clustering problem to graph theory if we use vertices in a graph to show all feature points and edges between feature points to show visual confliction. If we use different color of vertices to show different groups, two vertices connected by an edge cannot be the same color. So the
smallest number of colors needed to color the whole graph, which called the ‘chromatic number’ of the graph, means the least groups to partition the feature point set into without visual confliction. ‘Chromatic number’ is a heavily discussed topic in modern graph theory and there is multiple coloring algorithm available. Fig.6 shows the idea of grouping feature points according to visibility confliction. Different colors indicate different groups.

4.3 Conquer: Scanning Position Detection and Resolution Configuration in Each Group

4.3.1 Framework

The scan position and resolution detection in each group consists of four steps:

1. Determine the sparsest resolution that can scan all the feature points with required LOD. Because we treat the feature points in different group individually, we need to determine the sparsest resolution in current group. Therefore, we can guarantee sensing all feature points in this group. The sparsest resolution is the initial value of the scanning resolution in this group. Due to page limit, we will show the calculation of sparsest resolution for one group in future papers.

2. Use next-best-view (NBV) algorithm to calculate the scan position and resolution. The input of NBV algorithm is the feature point information in this group and the initial resolution. The output of this algorithm is the scan position(s) in this group; the feature points that remain un-scanned in this group (called “garbage”). Section 4.3.2 will discuss next-best-view algorithm in detail.

3. Use higher resolution and check scanning time. The 3D-imaging time of a single scan is the function of resolution. The higher scan resolution means longer scanning time. After calculating scan position(s) with the lowest scan-able resolution, we try higher resolution and process the next-best-view algorithm again check the total scanning time in order to optimize the scan resolution for short scanning time. If we use a higher resolution, we may apply fewer scans and the total scanning time may be shorter than having more scans but using lower resolution. Therefore, if the total scanning time is shortened we repeat this process, until the total scanning time stops shortening.

4. After we process all groups, restore all feature points remain un-scanned as a new group (garbage collection). After generating scan positions in each group, there may be some feature point(s) remain un-scanned called garbage. The reason why we leave some feature points un-scanned is for higher efficiency. For instance, we have 10 feature points in a group. The first scan covers five feature points and the second scan covers four feature points. So there is one feature point remain un-scanned. If we take one more scan just for this feature point, this scan is inefficient. Instead of doing so we consider this remaining feature point as “garbage” and we combine garbage from every group as a new group. Then we can deal with the “garbage” group using next-best-view algorithm.

4.3.2 Next-best-view Algorithm

The next-best-view algorithm will generate scanning position according to the resolution needs of feature points.

1. For each feature point, this algorithm will generate feasible area represented by many small squares of 0.5 by 0.5 meter. Every square is a potential scan position.

2. Then we define the temperature of one square as number of feasible areas that overlapping at this square. The heat map visualizes such temperature across all squares of the whole site. The algorithm first chooses the area consisting of squares with the highest temperature as a scan position. If more than one areas have the equally highest temperature, the algorithm will randomly select one. The algorithm then deletes all the feasible spaces that covers the selected area and update the heat map.
3. After that, the algorithm repeats step 2 in the updated heat map until no more than 7% (empirical) of all feature points left. The positions chosen by such a progressive process will be a scan plan that covers all feature points with satisfied LODs.

### 4.4 Combine: “Garbage Processing” and Finalizing Scan Configurations

Garbage processing deals with a group of feature points consisting of all the remaining feature points from each group using next-best-view algorithm. The framework is the same with section 4.3; however, there are some technical details in difference. “Garbage processing” consists of the following seven steps:

1. Combine feature points remaining un-scanned as a new group

2. Examine whether previous scans has already cover any of the feature points. If so, delete these feature points from the “garbage” group, because the scans in Group A may cover the “garbage” feature points in Group B.

3. Determine the lowest scan-able resolution in “garbage” group.

4. Use the next-best-view algorithm to calculate the scan positions for “garbage” group. If a scan will only cover 2% of total number of feature points, we consider it inefficient and discard this scan. This is a trade-off between data quality and scanning efficiency. In addition, doing this improves the robustness to outlier feature points due to inaccurate data or model.

5. Repeat step 2-3 and process all remaining feature point (either scanned or discarded).

### 5 CASE STUDY AND DISCUSSION

To validate the proposed 3D imaging planning algorithm, we conducted the data collection using the proposed automatic planning method, and compared the quality of the collected data against data collected by an experienced user of laser scanners. This experiment focused on a campus building, ASU McCord Hall. Fig.7 shows the front view photo and google map photo of Arizona State University (ASU) McCord Hall.

![Figure 7: Photos of Arizona State University (ASU) McCord Hall: (a) front view photo, (b) google map photo.](image)

5.1 Feature Point Information Collection

The researchers obtained the building information model of ASU McCord Hall and then picked feature points as follows: corner of the walls, corner of the windows and doors because these points contain important geometry information. Knowing the coordinates of these feature point we will know the layout of
the whole building. Then we manually extract the coordinates of these defined feature points shown in fig.8. Feature point information consists of the 3D coordinates, normal vector, and LOD requirement of each feature point. We set the LOD requirement of each feature point as 25mm (one inch).

![Building information model](image1)

![Feature points extracted from building information model](image2)

Figure 8: (a) Building information model. (b) Feature points extracted from building information model.

### 5.2 3D Imaging Planning

According to feature point information, the 3D-imaging planning algorithm generated the scan positions and corresponding scan resolutions as shown in fig. 9(a).

![Scan planning result generated by proposed algorithm](image3)

Figure 9: Scan planning result generated by proposed algorithm. In (a) we need to choose one scan position in each colored block, while in (b) we use brown stars to show the chosen scan positions.

In fig.9, red circle means the XY coordinates of all feature points, indicating the layout of the jobsite. Color blocks consisting of colored dots are applicable scan positions. We need to take one scan for each separated color block and the scan positions can be any dots in the block. For saving transportation time, we chose the points that close the building. Considering actual environment, brown stars are the actual scan positions, as shown in fig.9 (b). According to the scan planning algorithm, resolution for all scans are the same, being ½. At last, we scanned the building following the scan plan generated by the algorithm.
5.3 Comparing the Automatic Laser Scan Planning against Manual Planning

We acquired the point cloud of ASU McCord Hall through data collection and registration. After manually checking the data quality we found: the LOD of 100% of the feature points are under 0.025m (1 inch). Fig.10(a) shows the overall 3D-imaging point cloud of ASU McCord Hall. Fig.10 (b)–(d) show the neighbourhood of four random feature points. We can see from fig.10 that the data quality satisfied both the horizontal and vertical level of detail. On the other hand, in the 3D imaging data following manual planning, we found only 60% feature points are with required LOD. This result shows that automatic 3D imaging planning algorithm will guarantee the collected data quality.

6 CONCLUSION AND FUTURE STUDY

This paper propose a 3D imaging planning method, output all scan position and resolution that field engineers can follow to accomplish efficient and effective 3D-imaging data collection. Compared to previous data collection planning method, the new 3D imaging planning algorithm not only satisfy the completeness of data collection, but also focus on guarantee the collected data quality. Evaluation results on a campus building show the effectiveness of the proposed algorithm. The 3D imaging plan generated by the algorithm will lead to high quality data collection without time and labor waste.

On the other hand, this paper identified several challenges for the further developments of this scan planning approach: 1) the feature point information generation relies on manual work; also the registration of scanned point clouds is also a manual process, which is time consuming; 2) the algorithm didn’t consider the environment of the jobsite; sometimes the given scan position may not be accessible; 3) we can also integrate the time domain (schedule, or work flow) in to the scanning plan so that the proposed data collection plan will better inform the construction productivity analysis and real-time control. The authors will address these challenges in future studies.

Figure 10: 3D imaging result of ASU McCord Hall. (a) point cloud; (b), (c), and (d) are neighbourhood of three random feature points, showing that the collected data satisfy the LOD requirement (0.025m).

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A SEMANTIC SIMILARITY-BASED METHOD FOR SEMI-AUTOMATED IFC EXTENSION

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Abstract: The Industry Foundation Classes (IFC) schema was designed as a comprehensive data schema to cover information of all phases of a building project and all disciplines of the AEC industry. But due to its limited coverage of details in certain subdomains, the IFC schema needs to be extended for many information processing tasks such as information extraction for automated regulatory compliance checking. Previous IFC extension efforts typically extended IFC in an ad-hoc and subjective manner. A more objective, standardized, and application-independent method for extending IFC is, thus, needed. To address this gap, a new method for extending the IFC schema objectively and semi-automatically is proposed. The proposed method utilizes a semantic relation-based concept matching algorithm to find concepts – from domain documents – to incorporate into the current IFC schema class hierarchy. It utilizes the hypernymy, hyponymy, and synonymy semantic relations. This paper focuses on presenting the proposed semantic relation-based concept matching algorithm: the ZESeM (Zhang and El-Gohary Semantic Matching) algorithm. The ZESeM algorithm was tested on processing concepts from Chapter 12 of the International Building Code 2006. Different semantic similarity computation methods were tested in combination with the proposed ZESeM algorithm. The ZESeM algorithm was evaluated based on adoption rate, which is the number of concepts found by the ZESeM algorithm that are adopted divided by the total number of concepts found by the ZESeM algorithm. An adoption rate of 85.8% was achieved. The proposed semantic relation-based concept matching algorithm offers a more efficient concept matching method for semi-automatically extending the IFC schema.

1 INTRODUCTION

Building projects must comply with various regulations, such as the International Building Code (IBC), the Americans with Disabilities Act, the federal Fair Housing Act, and the Occupational Safety and Health Administration regulations. Due to the large amount of requirements that are covered by these regulations, the manual process of compliance checking is costly, time-consuming, and error-prone (Zhang and El-Gohary 2013). In comparison to manual compliance checking, automated compliance checking (ACC) is expected to reduce the time, cost, and errors of the compliance checking process (Zhong et al. 2012, Eastman et al. 2009). To conduct ACC, building information need to be represented in a computer-processable format.

The IFC schema is the most popular building information modeling (BIM) data schema and is becoming the official ISO standard. It was designed as a comprehensive data schema that covers information of all phases of a building and all disciplines of the architectural, engineering, and construction (AEC) industry to support a variety of tasks during a building life cycle including ACC. However, the IFC still lacks
necessary information (i.e., key concepts and relations) that is needed to perform ACC. Different ways to extend the IFC were proposed and/or utilized in previous ACC efforts, such as creating new project parameters (Nguyen and Kim 2011, Sinha et al. 2013), developing new Information Delivery Manuals (IDM) and Model View Definitions (MVDs) (Nawari 2011), and adding new data items (Kasim et al. 2013). Despite the importance of these efforts, previous extension methods mostly extended the IFC in an ad-hoc and subjective manner (i.e., relying on subjective judgements and case-specific developments), and their resulting extended models usually still suffer from missing essential ACC-related information (Niemeijer et al. 2009, Martins and Monteiro 2013). A more generalized and objective method (i.e., relying on rigorous techniques/algorithms for objective judgments that are consistent across different cases) for extending the IFC is, thus, needed.

To address this gap, the authors developed a new method for extending the IFC schema objectively and semi-automatically. The proposed method utilizes semantic natural language processing (NLP) techniques to extract concepts from construction regulatory documents (e.g., building codes) and insert the extracted concepts into the IFC concept hierarchy. NLP aims to enable computers to understand and process natural language text in a human-like manner (Liddy 2001). One key challenge that is faced when developing an IFC extension method is how to relate concepts with no shared terms (e.g., "outdoors" and "outside horizontal clear space"). To address this challenge, in the framework of the proposed IFC extension method, the authors developed a new semantic relation-based concept matching algorithm: the ZESeM (Zhang and El-Gohary Semantic Matching) algorithm. This algorithm aims to match concepts based on their semantic relations. This paper presents the proposed IFC extension method, with a focus on presenting the proposed ZESeM algorithm and the results of testing the algorithm on processing concepts from Chapter 12 of IBC 2006.

2 BACKGROUND

2.1 Natural Language Processing

Natural Language Processing (NLP) is a subdomain of artificial intelligence that aims to enable computers to understand and process natural language text and speech in a human-like manner (Cherpas 1992). NLP has a wide range of applications, such as text classification (Zhou and El-Gohary 2014), information retrieval (Khhokale and Atique 2014), information extraction (Zhang and El-Gohary 2013), text understanding (Karthikeyan and Karthikeyani 2013), and machine translation (Zhao et al. 2014). The analysis used in NLP is categorized into the following levels: (1) morphology, which is the analysis of meaningful components of the words; (2) syntax, which is the analysis of the structural relationship between words; (3) semantics, which is the analysis of meanings of words; (4) pragmatics, which is the analysis of how language is used to accomplish goals; and (5) discourse, which is the analysis on joining of linguistic units larger than utterance and words (Kumar 2011). NLP analysis in each subsequent level is more difficult than its previous level; and the results of the analysis in each subsequent level is more useful than its previous level. State-of-the-Art NLP techniques performed well at the first two levels and is developing fast at the semantic level.

2.2 Semantic Similarity

Semantic Similarity (SS) is the conceptual/meaning distance between two entities such as concepts, words, or documents (Slimani 2013). Semantic similarity plays an important role in information and knowledge processing tasks such as information retrieval (Rodri guez and Egenhofer 2003), text clustering (Song et al. 2014), and ontology alignment (Jiang et al. 2014). The measurement of semantic similarity between two entities typically requires established relations (directly or indirectly) between the two entities in an underlying structured knowledge model. Taxonomy and ontology are two types of such knowledge models. A variety of SS computation methods are based on the use of these models.

There are two main types of information that are utilized by SS computation methods: (1) shortest path, and (2) least common consumer. Shortest path is the length of the shortest path (counting nodes or edges) between two entities in a structured knowledge model. Least common consumer is the lowest common superconcept of two entities in a structured knowledge model.
Examples of SS computation methods using shortest path information are Shortest Path Similarity and Leacock-Chodorow Similarity (Table 1). Shortest Path Similarity relies solely on the shortest path information to calculate the SS score between two entities. Leacock-Chodorow Similarity, on the other hand, utilizes the maximum depth of the structured knowledge model in addition to the shortest path information to calculate the SS score between two entities.

Examples of SS computation methods utilizing least common consumer information are Resnik Similarity, Jiang-Conrath Similarity, and Lin Similarity. Resnik Similarity utilizes only the information content of the least common consumer of two entities to calculate the SS score between the two entities. Jiang-Conrath Similarity utilizes the information content of the two entities themselves, in addition to the information content of their least common consumer, to calculate the SS score between the two entities. Lin Similarity takes one step further to use the ratio of the information content of the least common consumer of the two entities to the sum of the information contents of the two entities to calculate the SS score between the two entities (Resnik 1995).

SS provides a measure for semantic-level language analysis, which can be used for many applications that require concept matching. For example, for geographic information service matching, Wang et al. (2013) identified the use of SS as a key enabler of matching, and combined two types of SS measures to enhance the matching efficiency for geographic information services. For ontology alignment, Jiang et al. (2014) showed the importance of SS measurement by improving the performance over existing ontology alignment methods through the utilization of a new SS measure. For ontology mapping, Pan et al. (2008) achieved a maximum precision of 80% on ontology mapping using relatedness analysis. Their analysis utilized term-based matching and term co-occurrence statistics. Thus, their method is limited by the corpus used to calculate co-occurrences and may miss concepts that match through general semantic relations because it is difficult for any corpus to capture all semantic relations.

Table 1: Different semantic similarity computation methods and their main information for computation

<table>
<thead>
<tr>
<th>Existing Semantic Similarity Computation Method</th>
<th>Main Information for Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shortest Path Similarity</td>
<td>shortest path between two entities</td>
</tr>
<tr>
<td>Jiang-Conrath Similarity</td>
<td>information content of the two entities themselves, and the information content of their least common consumer</td>
</tr>
<tr>
<td>Leacock-Chodorow Similarity</td>
<td>shortest path between two entities, and the maximum depth of the structured model</td>
</tr>
<tr>
<td>Resnik Similarity</td>
<td>information content of the least common consumer of two entities</td>
</tr>
<tr>
<td>Lin Similarity</td>
<td>ratio of the information content of the least common consumer of two entities to the sum of the information contents of the two entities</td>
</tr>
</tbody>
</table>

2.3 **WordNet**

WordNet is a lexical database of English developed by Princeton University. In WordNet, nouns, verbs, adjectives, and adverbs are grouped into synsets (sets of cognitive synonyms). Each of the nouns, verbs, adjectives, and adverbs category is organized into a subnet. Four types of semantic and lexical relations are used to link the synsets to one another: synonymy, hyponymy (sub-super or is-a relation), meronymy (part-whole relation), and antonymy (Fellbaum 2005). Synonymy is the semantic relation between different concepts who share the same meaning. For example, “girder” and “beam” share the same meaning of “a horizontal structural component for framework of buildings and other structures.” Hyponymy is a semantic relation where one concept is the hyponym (i.e., superclass) of the other. For example, “structural component” is a hyponym of “beam.” Hyponymy is the opposite of hyponymy, where one concept is the hyponym (i.e., subclass) of the other. For example, “beam” is a hyponym of
“structural component.” Meronymy is a semantic relation where one concept is “part of” another concept. For example, “window sill” is a meronym of “window.”

Because of the abundant semantic information structurally represented in WordNet, WordNet could be used as the knowledge model for computing SS scores. However, because the basic element in WordNet is a word (or term) rather than concept, WordNet could only be used to compute term-level SS scores using the above-mentioned SS computation methods. Thus, for the remainder of this paper, the above-mentioned SS computation methods are called term-level SS computation methods.

3 PROPOSED METHOD

To extend the IFC schema objectively, the authors developed a four-step method (Figure 1). The method: (1) extracts regulatory concepts from regulatory documents; (2) selects IFC concepts (i.e., concepts in the existing IFC concept hierarchy) that are most relevant to each extracted regulatory concept; (3) classifies the relationship between two concepts for each pair of extracted regulatory concept and selected IFC concept; and (4) constructs the new concept hierarchy by extending the original IFC concept hierarchy with the classified concept pairs. One thing to note in this four-step method is that once a regulatory concept has been added into the IFC concept hierarchy, the regulatory concept becomes an IFC concept.

For the IFC concept selection, a new semantic relation-based concept matching algorithm was developed: the ZESeM algorithm. The rest of the paper presents the ZESeM algorithm and its testing on extending the IFC concept hierarchy with regulatory concepts from IBC.

The ZESeM algorithm has three main components (Figure 2): (1) a term-based matching mechanism for finding IFC concepts that share term(s) with an extracted concept; (2) a semantic relation-based matching mechanism for finding related IFC concepts to an extracted concept; and (3) a semantic similarity (SS) scoring function for ranking related IFC concepts according to their relatedness to the extracted concept measured by SS scores.
Depending on the part-of-speech pattern of an extracted concept, the first term and last term of this concept are used to search for matched IFC concepts in both term-based and semantic relation-based matching mechanisms. If the extracted concept only has one term or the first term of the extracted concept is not a noun (i.e., singular or mass noun, plural noun, gerund, or proper noun), then only the last term of the extracted concept is used to search for matched IFC concepts. If the extracted concept has multiple terms and the first term of the extracted concept is a noun, then the first term of the extracted concept is used to search for matched IFC concepts, in addition to the last term. The matching term (first term or last term of the extracted concept) is compared with each term of an IFC concept, and the IFC concept is preliminarily selected if it includes at least one occurrence of the matching term of the extracted concept. In both matching mechanisms, stemming is used to ensure that matches in different forms of a word are not missed. For example, through stemming, “foot” could be matched with “feet”, and “reinforcing” could be matched with “reinforced”. In the term-based matching mechanism, the matching is pure term-based (i.e., string match) with stemming applied to both terms. In the semantic relation-based matching mechanism, the matching is based on three types of semantic relations: hyponymy, hyponymy, and synonymy (Fellbaum 2005).

For each extracted concept, term-based matching is applied first. If no matches are found using term-based direct matching, semantic relation-based matching is applied. As such, after the matching is conducted, there are three possible consequences: no matched IFC concept found, one matched IFC concept found, and more than one matched IFC concept found. In the first case, the extracted concept will be abandoned. In the second case, the matched IFC concept is selected. In the third case semantic-similarity based ranking is applied to find the highest ranked IFC concept; the highest ranked IFC concept is then selected.

Equation 1 shows the proposed SS scoring function that was used in the third case. The meaning of each parameter in the function is explained as follows:

1. \( SS_{RF} \) is the SS score between extracted concept \( R \) and IFC concept \( F \).

2. \( SS_{RmFk} \) is the term-level SS score between the matching term \( m \) in the extracted concept \( R \) and the \( k_{in} \) term in the IFC concept \( F \). \( SS_{RmFk} \) is calculated utilizing existing term-level SS score computation methods such as Shortest Path Similarity and Leacock-Chodorow Similarity.
3. \(2k/(n(n+1))\) is a term pair discount factor in which \(k\) is the ordinal number for the term \(F_k\) in IFC concept \(F\) and \(n\) is the length of \(F\) measured in number of terms.

4. \(1/(n)\) is the final discount factor which linearly discounts the summation using the length of the IFC concept.

\[ SS_{RF} = \frac{1}{n} \sum_{k=1}^{n} \left( \frac{2k}{n(n+1)} \right) SS_{termk} \]

The term pair discount factor \(2k/n(n+1)\) is based on the heuristic that in a multi-term concept, the contribution of each term’s carried meaning to the meaning of the whole concept decreases from right to left. The final discount factor \(1/n\) is based on the heuristic that the length of a concept name is related to its level in a concept hierarchy. The shorter the length of a concept name, the more general the concept is; and thus the higher its level in a concept hierarchy.

4 EXPERIMENTAL EVALUATION

The ZESeM algorithm was tested on processing extracted concepts from Chapter 12 of IBC 2006. IBC was selected because of its prevailing adoption in the United States (adopted by 46 states). Chapter 12 of IBC 2006 was then randomly selected. The longest span for each noun phrase in Chapter 12 of IBC 2006 was manually recognized and extracted as a concept. For example, concepts in the list \(L_1\) were recognized and extracted from Sentence \(S_1\). In total, 368 concepts were extracted. WordNet (Fellbaum 2005) was used to define the semantic relations between terms. Five term-level SS computation methods were tested in the ZESeM algorithm for comparison: Shortest Path Similarity, Leacock-Chodorow Similarity, Resnik Similarity, Jiang-Conrath Similarity, and Lin Similarity (Resnik 1995). The term-based matching and semantic relation-based matching mechanisms were evaluated separately. The evaluation was conducted using the measure of adoption rate, which was defined as the number of found IFC concepts that were adopted divided by the total number of found IFC concepts. The evaluation was conducted using a gold standard.

- \(S_1\): “The minimum net area of ventilation openings shall not be less than 1 square foot for each 150 square feet of crawl-space area.”

- \(L_1\): ['minimum_net_area', 'ventilation_openings', 'square_foot', 'square_feet', 'crawl-space_area']

The ZESeM algorithm was implemented using Python programming language (v.2.7.3). The "re" (regular expression) module in python was utilized to implement the matching mechanisms. The hypernymy, hyponymy, and synonymy relations in WordNet were utilized through the NLTK (Natural Language Toolkit) WordNet interface in python. The Porter Stemmer (Porter 1980) was utilized to implement stemming.

5 EXPERIMENTAL RESULTS

The experimental results for term-based matching and semantic relation-based matching are summarized in Table 2. The adoption rate for different term-level SS computation methods ranged from 80.7% to 87.1%. For term-based matching, the highest adoption rate exceeds the lowest adoption rate by 5.1%. For semantic relation-based matching, the highest adoption rate exceeds the lowest adoption rate by 2.2%. Table 3 shows some randomly selected example concepts that were extracted and matched using the different term-level semantic similarity computation methods, for term-based matching and semantic relation-based matching. The matched IFC concepts that were not adopted are shown in italics.
Table 2: Performances of different term-level semantic similarity computation methods on term-based matching and semantic relation-based matching

<table>
<thead>
<tr>
<th>Matching Mechanism</th>
<th>Existing Semantic Similarity Algorithm</th>
<th>Number of IFC Concepts Found</th>
<th>Number of IFC Concepts Adopted</th>
<th>Adoption Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term-based</td>
<td>Shortest Path Similarity</td>
<td>286</td>
<td>249</td>
<td>87.1%</td>
</tr>
<tr>
<td></td>
<td>Resnik Similarity</td>
<td>286</td>
<td>246</td>
<td>86.0%</td>
</tr>
<tr>
<td></td>
<td>Lin Similarity</td>
<td>286</td>
<td>246</td>
<td>86.0%</td>
</tr>
<tr>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>286</td>
<td>244</td>
<td>85.3%</td>
</tr>
<tr>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>286</td>
<td>237</td>
<td>82.9%</td>
</tr>
<tr>
<td>Semantic relation-based</td>
<td>Shortest Path Similarity</td>
<td>114</td>
<td>94</td>
<td>82.5%</td>
</tr>
<tr>
<td></td>
<td>Resnik Similarity</td>
<td>114</td>
<td>93</td>
<td>81.6%</td>
</tr>
<tr>
<td></td>
<td>Lin Similarity</td>
<td>114</td>
<td>93</td>
<td>81.6%</td>
</tr>
<tr>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>114</td>
<td>92</td>
<td>80.7%</td>
</tr>
<tr>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>114</td>
<td>93</td>
<td>81.6%</td>
</tr>
<tr>
<td>Overall</td>
<td>Shortest Path Similarity</td>
<td>400</td>
<td>343</td>
<td>85.8%</td>
</tr>
</tbody>
</table>

6 DISCUSSION

Shortest Path Similarity achieved the best adoption rate for both matching mechanisms. Shortest Path Similarity only utilizes the shortest path between two concepts in a concept hierarchy for SS score computation, whereas Leacock-Chodorow Similarity utilizes both the shortest path between two concepts and the maximum depth of concepts in the hierarchy and other term-level SS computation methods utilize information content of the least common consumer (i.e., the lowest concept in the concept hierarchy that is the superclass of the two concepts). The higher performance of Shortest Path Similarity over Leacock-Chodorow Similarity indicates that the additional information of concept depth did not help in concept matching. The higher performance of Shortest Path Similarity over Jiang-Conrath Similarity, Resnik Similarity, and Lin Similarity indicates the advantage of the shortest path over the information content of the least common consumer in measuring semantic similarity for concept matching. Thus, based on the comparative experimental results of different term-level SS computation methods, the Shortest Path Similarity was selected as the term-level SS computation method in the ZESeM algorithm.

Both term-based matching and semantic relation-based matching achieved good performance of over 80% adoption rate. The examples in Table 3 show the effectiveness of the ZESeM algorithm. The matches between “interior spaces” and “space” and between “square foot” and “feet” show the effectiveness of term-based matching, including the use of stemming. The matches between “floor joists” and “beam”, between “enclosed attics” and “additional story”, and between “cornice vents” and “openings” show the effectiveness of semantic relation-based matching in leveraging the semantic relations between terms to find concept matches that would have otherwise been missed (if only utilizing term-based matching, without the use of semantic information, because those concept pairs do not share any terms).

The processing using term-based matching has larger variation in performance than that using semantic relation-based matching (adoption rate relative difference of 5.1% compared to 2.2%) among the term-level semantic similarity computation methods. Because term-based matching can easily find more candidate IFC concepts to match than semantic relation-based matching, more candidate IFC concepts lead to a higher probability of variability in performance. However, semantic relation-based matching finds semantically related concepts that cannot be found using term-based matching. Thus the combination of semantic relation-based matching and term-based matching finds more matched concepts than using either one of them.
Table 3: Examples of extracted concepts and matched IFC concepts using different term-level semantic similarity computation methods

<table>
<thead>
<tr>
<th>Extracted Concept</th>
<th>Matching Mechanism</th>
<th>Existing Semantic Similarity Computation Method</th>
<th>Matched IFC Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilators</td>
<td>Term-based</td>
<td>Shortest Path Similarity</td>
<td>Cross ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>Ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>Ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resnik Similarity</td>
<td>Ventilating opening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lin Similarity</td>
<td>Ventilating opening</td>
</tr>
<tr>
<td>Interior spaces</td>
<td>Term-based</td>
<td>Shortest Path Similarity</td>
<td>Space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>Space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>Space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resnik Similarity</td>
<td>Space</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lin Similarity</td>
<td>Space</td>
</tr>
<tr>
<td>Square foot</td>
<td>Term-based</td>
<td>Shortest Path Similarity</td>
<td>Feet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>Feet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>Footing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resnik Similarity</td>
<td>Feet</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lin Similarity</td>
<td>Feet</td>
</tr>
<tr>
<td>Floor joists</td>
<td>Semantic relation-based</td>
<td>Shortest Path Similarity</td>
<td>Beam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>Beam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>Beam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resnik Similarity</td>
<td>Beam</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lin Similarity</td>
<td>Beam</td>
</tr>
<tr>
<td>Enclosed attics</td>
<td>Semantic relation-based</td>
<td>Shortest Path Similarity</td>
<td>Additional story</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>Additional story</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>Additional story</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resnik Similarity</td>
<td>Additional story</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lin Similarity</td>
<td>Additional story</td>
</tr>
<tr>
<td>Cornice vents</td>
<td>Semantic relation-based</td>
<td>Shortest Path Similarity</td>
<td>Openings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Jiang-Conrath Similarity</td>
<td>Openings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leacock-Chodorow Similarity</td>
<td>Openings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resnik Similarity</td>
<td>Openings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lin Similarity</td>
<td>Openings</td>
</tr>
</tbody>
</table>
7 LIMITATIONS AND FUTURE WORK

One limitation of this study is that only semantic relation-based matching on unigram (single terms) was used for finding semantically related IFC concepts to an extracted concept. While the combinatorial nature of term meanings [i.e., the meanings of single terms (e.g., “exterior” and “door”) in a concept name are combined to form the overall meaning of the whole concept (e.g., “exterior door”)] renders this unigram method effective, there may be cases where semantic relation-based matching on bigram (pairs of terms) or multigram (groups of three or more terms) could be effective. As such, in future work, the authors plan to extend the semantic relation-based matching mechanism to incorporate semantic relations between bigram and multigram to test whether such bigram or multigram considerations could further improve the performance of concept matching.

8 CONCLUSION

This paper presents a new natural language processing (NLP)-based method for extending the IFC schema objectively. As part of the proposed IFC extension method, a new semantic relation-based concept matching algorithm, called ZESeM algorithm, was developed. The ZESeM algorithm utilizes both term-based matching and semantic relation-based matching to find matching IFC concepts for extracted regulatory concepts. A new function was proposed to compute concept-level semantic similarity (SS) scores between concepts based on their term-level SS scores. The proposed algorithm was tested on finding matching IFC concepts for extracted concepts from Chapter 12 of IBC 2006. The experimental results verify the effectiveness of the proposed concept-level SS function and the proposed ZESeM algorithm in concept matching. An 85.8% adoption rate was achieved. For term-level SS computation, Shortest Path Similarity showed the best performance. One limitation of the proposed method is that only unigram (single terms) semantic relation-based matching was used, while bigram or multigram semantic relation-based matching may further improve the matching performance. In their future work, the authors plan to extend the semantic relation-based matching mechanism to further test the effectiveness of bigram and multigram semantic relation-based matching.

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References


AXIOLOGY-BASED VALUE QUANTIFICATION MODELING FOR BUILDINGS

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Abstract: A report published by the National Research Council of the National Academies identified the research on understanding and quantifying the value of our infrastructure systems to their stakeholders and how this value is impacted by the various planning, design, construction, and operation decisions as a “national imperative”. However, there is still a lack of understanding and formalized modeling of what different stakeholders value (e.g., energy conservation, safety, economic growth) in our infrastructure systems and how to valuate (i.e., quantify the worth) our infrastructure systems based on these values. This paper presents the authors’ work in the area of axiology-based valuation modeling of buildings. “Axiology” is a theory of value (worth) that explores questions such as what are the objects that we value and how to measure the value of these objects. In this paper, the authors propose a mathematical value quantification model for quantifying the degree that a building (and its objects) fulfills stakeholder values based on its properties. The proposed model is primarily theoretically grounded in axiology. It builds on two key notions in Hartman’s formal axiology that (1) object valuation depends on its properties, and (2) valuation has systemic, extrinsic, and intrinsic dimensions. The model was initially validated through a case study. The model offers a way to assess the value of our built infrastructure based on stakeholder values; it could facilitate value-sensitive decision making by embodying stakeholder values into project planning and design towards better synergy between human values and the built environment.

1 INTRODUCTION

A report published by the National Research Council of the National Academies (NRC) identified the research on understanding and quantifying the value of infrastructure systems to their stakeholders and how this value is impacted by the various planning, design, construction, operation, and investment decisions as a “national imperative” (NRC 2009). Similarly, industry organizations and institutes (e.g., SE 2012, NIBS 2012) and individual researchers (e.g., Levitt 2007) have emphasized the need for maximizing the lifecycle environmental, social, and economic value of infrastructure projects. "Potential projects for one type of infrastructure are not evaluated against other projects to determine how the greatest overall value might be achieved” (NRC 2009). The lack of such value quantification methods has led many stakeholders to debate the value of our infrastructure and, in turn, has reinforced the need of value-sensitive decision making (NRC 2009). In order to quantify the value (worth) of an infrastructure, there is a need to understand what stakeholders value (e.g., safety, energy conservation, cost saving), and accordingly, quantify the value (worth) of the infrastructure based on these stakeholder values. Discovering stakeholder values and quantifying the value of infrastructure based on these values are, thus, key prerequisites for facilitating value-sensitive decision making towards maximizing the collective value of our built infrastructure.
Despite the evident need for infrastructure value quantification and value-sensitive decision making, inadequate attention has been given to the theoretical and empirical study of value over the years (Barima 2009). Major gaps still exist in the area of value analysis of built infrastructure: (1) existing value approaches (e.g., value engineering) usually focus on function analyses and define value as a ratio of “function” to its “cost” (Kelly 2007) without a comprehensive interpretation of the concept of “value” based on stakeholder values, (2) existing integrated approaches (e.g., integrated project delivery) promote collaboration with the aim to increase value (AIA 2007), but do not provide a metric for measuring “value” or a well-defined method for value-sensitive analysis. As such, two main knowledge gaps exist: (1) there is a lack of understanding and modeling of what the value (worth) of an infrastructure is, and (2) there is a lack of formalized quantification models that can quantify such value. In the context of built infrastructure development, there is a need to better understand, conceptualize, and reason about “value quantification” in a holistic sense and considering stakeholder values.

To address this need, in this paper, the authors propose a mathematical value quantification model for quantifying the degree that a building (and its objects) fulfills stakeholder values based on its properties. The proposed model is primarily theoretically grounded in axiology. Axiology is a theory of value (worth) that explores questions such as what are the things that we value and how to measure the value of these things (Smith and Thomas 1998). The model builds on two key notions in Hartman's formal axiology that (1) object valuation depends on its properties, and (2) valuation has systemic, extrinsic, and intrinsic dimensions.

2 BACKGROUND

Axiology is a theory of value or worth. It is a study of value concepts, value types, interrelationships, and valuation methods (Allen and Varga 2006). The term “axiology” is derived from the Greek word “axios” meaning value or worth. Axiology aims to answer questions such as how to define and measure the value (worth) of things (Smith and Thomas 1998). Formal axiology is a branch of axiology that was introduced by Robert Hartman. Hartman (1967) proposed to mathematically define the value of “things” in an objective manner based on their properties. He proposed that the value of an object depends on the extent to which its properties correspond to the properties of its concept. According to Hartman, a “good” thing (1) has a concept name, (2) this concept is characterized/defined by a set of properties, and (3) this thing possesses all of the properties in this set (El-Gohary 2010). Hartman also introduced three basic dimensions (types) of valuation (El-Gohary 2010): (1) Systemic Valuation: valuates a “thing” based on a finite number of properties in terms of rigid conformance to a system or a formal construct (e.g., conformance to the definition of circle, or conformance to a regulatory system). Systemic valuation, thus, sees “things” either black or white (e.g., a thing is a circle or not a circle, a person is complying with the law or not); (2) Extrinsic Valuation: valuates a “thing” based on a finite number of properties, but in a flexible way in terms of goodness and badness degrees based on practical aspects, such as functionality, economics, etc. A “thing” has potentially an infinite number of properties, but in practice extrinsic valuation is based on only a few of these properties; and (3) Intrinsic Valuation: valuates a “thing” based on an infinite number of properties in terms of personal judgment based on aesthetical, emotional, or spiritual aspects, etc. A “thing” can be valuated systemically, extrinsically, and/or intrinsically (El-Gohary 2010).

3 APPROACH AND METHODOLOGY

The proposed value quantification model is developed using an axiology-based approach. The model builds on two key notions in Hartman’s formal axiology that (1) object valuation depends on its properties, and (2) valuation has systemic, extrinsic, and intrinsic dimensions. Hartman’s three types of valuation (i.e., systemic, extrinsic, and intrinsic valuation) were adapted to the context of building valuation. In the context of building valuation, both extrinsic and systemic valuation valuate a building (or its objects) based on how good its properties are in fulfilling each of the stakeholder values. Systemic valuation is a rigid valuation that views property goodness as either “black or white” (i.e., a property is either good or bad), while extrinsic valuation is a flexible valuation that views property goodness as a spectrum (i.e., a property is good, fair, bad, etc.). Intrinsic valuation, on the other hand, valuates a building (or its objects) based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. In
developing the mathematical quantification functions of the proposed model, the authors also benchmarked some techniques (e.g., simple additive weighting) of multiple attribute decision making (MADM) approaches and adapted concepts from social welfare theory.

The methodology for developing the proposed model included five main tasks: (1) conducting theoretical studies on formal axiology, (2) identifying and modeling the main concepts for value quantification, (3) identifying potential indicators to measure the goodness of properties, (4) selecting indicators based on a set of well-defined principles, (5) constructing mathematical formulations for value quantification, and (6) conducting a case study for initial validation. In their prior work, the authors presented their research efforts in indicator identification and selection (Zhang and El-Gohary 2014). In this paper, the authors focus on presenting the mathematical formulations for value quantification and its initial validation.

4 PROPOSED VALUE QUANTIFICATION MODEL

4.1 Main Model

The proposed main value quantification model, showing the most abstract value quantification concepts, is depicted in Figure 1. At the highest level of abstraction, a thing is a “stakeholder value”, a “value bearer”, a “value bearing property”, a “property indicator”, a “benchmark of measure”, a “property goodness degree”, a “property value significance”, or a “value fulfillment degree”. A “stakeholder value” is a thing that is of worth, merit, or utility to a stakeholder (e.g., energy conservation, safety, cost saving). The hierarchy of stakeholder values, which includes 50 stakeholder values, is presented in Zhang and El-Gohary (2015). A “value bearer” is an object (e.g., a building or a building element) that holds value. A “value bearer” has one or more “value bearing properties” (e.g., thermal resistance, fire resistance, height). A “benchmark of measure” is a yardstick against which an indicator is measured to define the goodness of a property. A “property goodness degree” is a numeric degree that defines how good/bad a property is in fulfilling a specific “stakeholder value”. A “property value significance” is a quantifiable measure of the importance/relevance of a specific property in fulfilling a specific “stakeholder value” for a specific “value bearer”. A “value fulfillment degree” is a numeric degree indicating how much a value is fulfilled. As per Figure 1, each “function of” relation represents the mathematical function between the different quantification concepts. The following subsections describe how property goodness, property value significance, and value fulfillment are quantified.

![Figure 1: Main value quantification model](image)

4.2 Quantifying Property Goodness

Property goodness indicates how good/bad a property is in fulfilling a specific stakeholder value. Property goodness could be systemic, extrinsic, or intrinsic. Systemic property goodness is “black or white” – a property is either good or bad. Extrinsic property goodness is a spectrum of goodness – a property could be good, fair, bad, etc. Intrinsic property goodness is mostly assessed based on personal
judgment in terms of aesthetical, emotional, or spiritual aspects. The degree of goodness of a property is expressed as a metric-free numerical number called “property goodness degree” (PGD), and is derived based on comparing property indicators (PIs) against well-defined benchmarks. PGD is, thus, a function of PI and benchmark of measure (BOM). Corresponding to the type of property goodness, PGD could be assessed systemically, extrinsically, and/or intrinsically.

Systemic property goodness is assessed systemically. In this type of assessment, a property is either good or bad; the PI either meets or not meets the BOM. Systemic property goodness assessment, thus, results in a dichotomous PGD (either 1 or 0). For example, the PGD of land type (value bearing property) [of a building (value bearer) in fulfilling land pollution prevention (stakeholder value)] is either 1 (if the developer selects a previously developed field for project development) or 0 (if the developer selects a greenfield).

Extrinsic property goodness is mostly assessed extrinsically. In this type of assessment, a property has a spectrum of goodness in terms of how the PI measures up against a BOM. Extrinsic property goodness assessment, thus, results in a PGD that ranges from 0 to 1, which indicates how good the property is. Different extrinsic property goodness assessment functions are defined, depending on the type of assessment: max-best, min-best, or mid-best assessment. Accordingly, PGD is defined based on Eq. 1 to Eq. 3, where PGD_{ijk} = property goodness degree of property i of value bearer k in fulfilling stakeholder value j; PI_{ijk} = property indicator of property i of value bearer k in fulfilling stakeholder value j; BOM_{minij} = minimum benchmark of measure of property i in fulfilling stakeholder value j; and BOM_{maxij} = maximum benchmark of measure of property i in fulfilling stakeholder value j.

When conducting a max-best assessment (Eq. 1), the minimum benchmark represents the lowest degree of goodness, below which the property becomes totally bad; whereas the maximum benchmark represents a high enough degree of goodness, above which a property becomes “good-enough”. Accordingly, (1) when the PI falls below the minimum benchmark, the PGD falls to 0, (2) when the PI falls within the range of minimum and maximum benchmarks, the PGD monotonically increases with the increase of the PI until reaching the maximum benchmark, and (3) when the PI reaches (or is above) the maximum benchmark, the PGD becomes at its maximum of 1. For example, low-emitting material (value bearing property) [of a ceiling (value bearer) in fulfilling indoor air quality improvement (stakeholder value)] can be assessed using max-best assessment, where a higher percentage of compliant low-emitting material (PI) indicates better/more low-emitting material until it reaches 100% (maximum benchmark).

\[
[1] \text{PGD}_{ijk} = \begin{cases} 
0 & \text{if } PI_{ijk} < BOM_{minij} \\
\frac{PI_{ijk} - BOM_{minij}}{BOM_{maxij} - BOM_{minij}} & \text{if } BOM_{minij} \leq PI_{ijk} < BOM_{maxij} \\
1 & \text{if } PI_{ijk} \geq BOM_{maxij}
\end{cases}
\]

When conducting a min-best assessment (Eq. 2), the minimum benchmark represents a high enough degree of goodness, below which a property becomes “good-enough”; whereas the maximum benchmark represents the lowest degree of goodness, above which the property becomes totally bad. For example, water consumption (value bearing property) [of a water closet (value bearer) in fulfilling water conservation (stakeholder value)] can be assessed using min-best assessment, where a lower amount of water usage per flush (PI) indicates better water consumption until it falls to 1.28 gpf (minimum benchmark).

\[
[2] \text{PGD}_{ijk} = \begin{cases} 
1 & \text{if } PI_{ijk} \leq BOM_{minij} \\
\frac{BOM_{maxij} - PI_{ijk}}{BOM_{maxij} - BOM_{minij}} & \text{if } BOM_{minij} < PI_{ijk} \leq BOM_{maxij} \\
0 & \text{if } PI_{ijk} > BOM_{maxij}
\end{cases}
\]

When conducting a mid-best assessment (Eq. 3), there is a certain range within which the property becomes “good enough”; when the PI falls within that range, the PGD is at its maximum. The PGD
decreases when the PI falls out of this range until it becomes totally bad, when the PI reaches the minimum or maximum benchmark (both representing the lowest degree of goodness). For example, thermal comfort level (value bearing property) [of a living room (value bearer) in fulfilling thermal comfort improvement (stakeholder value)] can be assessed using mid-best assessment, where the thermal comfort level is the best when the air temperature is within a range of 69 °F to 73 °F (good enough range).

\[
P_{D_{i,j,k}} = \begin{cases} 
0 & \text{if } PI_{i,j,k} < BOM_{min_{i,j}} \\
\frac{BOM_{min_{i,j}} - PI_{i,j,k}}{BOM_{max_{i,j}} - BOM_{min_{i,j}}} & \text{if } BOM_{min_{i,j}} \leq PI_{i,j,k} < BOM_{max_{i,j}} \\
1 & \text{if } BOM_{max_{i,j}} \leq PI_{i,j,k} \\
0 & \text{if } PI_{i,j,k} \geq BOM_{max_{i,j}} 
\end{cases}
\]

Intrinsic property goodness is mostly assessed intrinsically. In this type of assessment, a property is assessed flexibly based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. Stakeholders can directly assign a PGD within the range of 0 to 1 based on their personal judgment of the goodness of the property. For example, a stakeholder can directly assign a PGD of 1 to a white interior wall color if white is his/her most favorite color for a wall. The detailed methodology for assessing intrinsic property goodness is beyond the scope of this paper.

4.3 Quantifying Property Value Significance

Property value significance (PVS) represents the significance, importance, or relevance of a specific property of a specific value bearer in fulfilling a specific stakeholder value. Properties may have different significances to value quantification. Determining the PVSs for the various building properties may not be easy or apparent. PVSs could be determined extrinsically and/or intrinsically.

Using extrinsic PVS determination approaches, PVSs are determined in a flexible and objective manner based on norms, relative impact of property, expert opinion, etc. Selecting which approach to use for extrinsic PVS determination depends on the type of property, the type of PVS, and the availability of data. A norm-based approach determines PVSs based on weightings embedded in applicable norms, such as standards, advisory practices, rating systems (e.g., LEED, BREEAM). For example, the PVSs of recycled material, reused material, and regional material (value bearing properties) [of a wall (value bearer) in fulfilling material conservation (stakeholder value)] can be directly obtained from LEED, which uses “credit weighting” to represent the point allocation between different credit categories. The LEED credit weightings for “material reuse”, “recycled content”, and “regional materials” are equal (2 points for each) (USGBC 2009). Accordingly, the three properties are assigned equal PVSs of 0.33 (after normalization). Because norm-based data are well-established by an authority or advisory body, a norm-based approach is preferred for PVS determination, if relevant norm-based data (e.g., score/point weightings) are available. Other approaches should be used when such data are not available.

An impact-based approach determines PVSs by evaluating the potential impacts of each property with respect to a set of impact categories. For example, disability adjusted life years (DALY) weighting (Blanc et al. 2008) can be used to determine the significance of environmental-related properties (e.g., air pollutant emissions) of a value bearer (e.g., a building or a building element) in fulfilling the environmental values (e.g., air pollution prevention) by assessing their potential impacts on human health using existing assessment tools (e.g., IMPACT 2002+). For example, particulate matter (PM) emissions (value bearing property) of a building (value bearer) affect human health more severely than lead emissions (value bearing property) (Blanc et al. 2008) and, thus, has a higher PVS (0.98) than that of lead emissions (0.02).

An expert-based approach determines PVSs based on expert opinion. It is a suitable approach to use when norm-based data are not available or when it is difficult to assess the potential impact of the
properties. For example, the PVS of sound resistance and sound absorption (value bearing property) [of a wall (value bearer) in fulfilling acoustical performance improvement (stakeholder value)] can be determined by soliciting acoustical consultant/expert opinion using a budget allocation process (BAP). In BAP, an expert is given a set of properties of a value bearer in fulfilling a specific stakeholder value. The expert is asked to allocate a “budget” of one hundred points to the individual properties in the property set, based on their expert judgment of the relative PVSSs of the respective properties. To ensure objectivity and correctness in PVS determination, it is important to select experts with knowledge and expertise in the specific technical domain related to the type of value bearer and stakeholder value (e.g., expertise in acoustical performance of buildings).

Using intrinsic PVS determination approaches, PVSSs are determined in a flexible and personal manner based on personal stakeholder judgment in terms of aesthetical, emotional, or spiritual aspects. For example, the significance of color (value bearing property) [of a wall (value bearer) in fulfilling aesthetics (stakeholder value)] is determined based on the personal opinion of the stakeholders. Similar to intrinsic property goodness assessment, stakeholders can directly assign a numerical number between 0 to 1 to a PVS based on their personal judgment of the significance, importance, or relevance of the property of the value bearer in fulfilling their own stakeholder value. The detailed methodology for intrinsic PVS determination is beyond the scope of this paper.

4.4 Quantifying Value Fulfillment

Value fulfillment represents how much a value is fulfilled. It depends on how good/bad the properties fulfill the value (i.e., PGD) and how significant the property is in fulfilling this particular value (i.e., PVS). “Highly good” properties (e.g., net-zero energy consumption), in comparison to “good” properties, tend to contribute to the fulfillment of a stakeholder value in extra higher degrees. Thus, to quantify value fulfillment of each stakeholder value, a value fulfillment degree (VFD) is defined by aggregating the PGDs and PVSSs of individual properties, while taking into account the extra higher level of contribution of highly good properties. The VFD function, thus, is composed of two sub-functions: (1) a property goodness aggregation (PGA) function that aggregates the PGDs and PVSSs of individual properties, and (2) a high property goodness (HPG) function that rewards states of HPG.

The PGA function aggregates the PGDs and PVSSs of individual properties to define how much a value is fulfilled by these properties. The PGA function uses simple additive weighting. Simple additive weighting is one of the most widely used MADM methods (Andresen 2000). A simple additive weighting function is a linear aggregating function that allows for compensability (i.e., possibility of offsetting a disadvantage on some criteria by a sufficiently large advantage on another criteria) among criteria (OECD 2008). Simple additive weighting is suitable for value fulfillment quantification for three reasons. First, when aggregating PGDs and PVSSs for individual properties to define the VFD of a stakeholder value, properties of one value bearer are compensatory in value fulfillment. For example, for fulfilling material conservation (stakeholder value), a floor (value bearer) with small amount of recycled material (value bearing property) can be compensated with large amount of reused material (another value bearing property). Second, a simple additive weighting method is able to provide an aggregated VFD (numerical number) for each value bearer. This allows further aggregation of the VFDs and for valuating a value bearer irrespective of the existence of other alternatives. Third, research shows that simple additive weighting methods yield “extremely close approximations” to other non-linear aggregating methods (e.g., generalized means) while remaining easier to understand (Andresen 2000).

The HPG function rewards states of HPG because of its higher contribution to the fulfillment of stakeholder values. The HPG function adapts concepts from social welfare theory. Social welfare theory is the study that assesses the collective welfare of a society or a group by combining individual opinions, preferences, interests, or welfare (Feldman and Serrano 2006). When calculating the degree of value fulfillment during value quantification, the aim is to find a good/satisfactory overall state of the aggregated value bearing properties based on the goodness degrees and value significances of the individual properties. This is analogous with social welfare assessment in which a social welfare function is used as a measure of the aggregated well-being (the good or satisfactory state) of a group based on the allocation of requisites (such as income) among the individuals of that group. However, unlike social welfare
assessment in which states of poverty are undesirable (and thus penalized), in value assessment states of “wealth” (i.e., states of high goodness of individual properties (“highly good properties”) such as net-zero energy consumption) are valued (and thus rewarded). While “highly bad properties” (e.g., 15 min fire rating) are also undesirable (not valued) during value quantification, such states of badness are already eliminated during regulatory compliance assessment. As such, for defining the VFD, two lines are established: “high property goodness (HPG) line” and “high property badness (HPB) line”. The HPG line represents the state of high goodness for a property, and is above the minimum benchmark and below the maximum benchmark. When the PGD of a property is at/above the HPG line, such property contributes to the fulfillment of a stakeholder value in an extra high degree. The HPB line represents the state of the property being highly bad and is usually at (or below) the minimum benchmark established by regulatory requirements. An HPB line is, thus, unnecessary in well-regulated societies that establish minimum requirements in the form of regulations, codes, standards, etc.

The HPG line could be assessed extrinsically or intrinsically. Systemic property cannot have HPG states because it could only be either good or bad. Similar to extrinsic property goodness assessment, extrinsic HPG line assessment assesses the state of high goodness in terms of how it measures up against a BOM, which could use max-best, min-best, or mid-best assessments. Accordingly, the HPG line is defined based on Eq. 4 to Eq. 6, where HPGL\textsubscript{ij}= high property goodness line of property i in fulfilling stakeholder value j; HGBOM\textsubscript{ij}= high goodness benchmark of measure of property i in fulfilling stakeholder value j; BOM\textsubscript{minij}= minimum benchmark of measure of property i in fulfilling stakeholder value j; and BOM\textsubscript{maxij}= maximum benchmark of measure of property i in fulfilling stakeholder value j. Eq. 4 to Eq. 6 are used for max-best, min-best, and mid-best assessment, respectively.

\textbf{[4]} \quad \text{HPGL}_{ij} = \frac{\text{HGBOM}_{ij} - \text{BOM}_{\text{minij}}}{\text{BOM}_{\text{maxij}} - \text{BOM}_{\text{minij}}} \quad \text{BOM}_{\text{minij}} \leq \text{HGBOM}_{ij} < \text{BOM}_{\text{maxij}}

\textbf{[5]} \quad \text{HPGL}_{ij} = \frac{\text{BOM}_{\text{maxij}} - \text{HGBOM}_{ij}}{\text{BOM}_{\text{maxij}} - \text{BOM}_{\text{minij}}} \quad \text{BOM}_{\text{minij}} < \text{HGBOM}_{ij} \leq \text{BOM}_{\text{maxij}}

\textbf{[6]} \quad \text{HPGL}_{ij} = \begin{cases} \frac{\text{HGBOM}_{ij} - \text{BOM}_{\text{minij}}}{\text{BOM}_{\text{maxij}} - \text{BOM}_{\text{minij}}} & \text{BOM}_{\text{minij}} \leq \text{HGBOM}_{ij} < \text{BOM}_{\text{minij}}' \\ \frac{\text{BOM}_{\text{maxij}} - \text{HGBOM}_{ij}}{\text{BOM}_{\text{maxij}}' - \text{BOM}_{\text{maxij}}} & \text{BOM}_{\text{maxij}}' \leq \text{HGBOM}_{ij} < \text{BOM}_{\text{maxij}} \end{cases}

Similar to intrinsic property goodness assessment, intrinsic HPG line assessment is a flexible and personal high goodness assessment that is conducted based on personal stakeholder judgment in terms of aesthetic, emotional, or spiritual aspects. The detailed methodology for intrinsic HPG line assessment is beyond the scope of this paper.

The HPG function is a measure of the extent of high goodness in the set of properties of the value bearer. The function estimates the degree of HPG in the whole set by considering how far each PGD is above the HPG line. HPG is then rewarded by the HPG function, using a coefficient α, because of its higher contribution to the fulfillment of stakeholder values. The coefficient α defines the extent of rewarding HPG; and is a numerical number between 0 and 1. An α of 1 represents a full extent of reward, while an α of 0 represents no reward at all.

The VFD function is an addition of the PGA function (which ranges from 0 to 1) and the HPG function (which ranges from 0 to 1), thereby making the HPG acting as an “extra bonus”. The VFD function is defined in Eq. 7, where VFD\textsubscript{jk}= value fulfillment degree of stakeholder value j by value bearer k; n = total number of properties that contribute in fulfilling stakeholder value j; PGD\textsubscript{ijk}= property goodness degree of property i of value bearer k in fulfilling stakeholder value j; PVS\textsubscript{ij}= property value significance of property i in fulfilling stakeholder value j; α = a coefficient for rewarding high property goodness; and HPGL\textsubscript{ij}= high property goodness line of property i in fulfilling stakeholder value j.

\textbf{[7]} \quad \text{VFD}_{jk} = \sum_{i=1}^{n} \text{PGD}_{ijk} \times \text{PVS}_{ij} + \alpha \sum_{i=1}^{n} \text{PVS}_{ij} \times \max[0, (\text{PGD}_{ijk} - \text{HPGL}_{ij})]
5 CASE STUDY

A case study was conducted to initially validate the proposed value quantification model. A duplex apartment building model was used in this case study. It is one of the common Building Information Model (BIM) published by buildingSMART alliance (a council of the National Institute of Building Sciences) for evaluating model or software functionality and applicability (buildingSMART 2015). The case study focused on analyzing the value fulfillment of the exterior wall system of the building. The exterior wall system is designed using concrete block with brick veneer. The detailed information on the design of the exterior wall system is summarized in Table 1. A set of stakeholder values were selected for this case study analysis, including: (1) material conservation, (2) indoor air quality improvement, (3) acoustical performance improvement, and (4) fire safety.

Table 1: Exterior wall systems design

<table>
<thead>
<tr>
<th>Element</th>
<th>Concrete Block Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural framing</td>
<td>8&quot; x 8&quot; x 16&quot; Concrete block</td>
</tr>
<tr>
<td>Interior sheathing</td>
<td>5/8&quot; Type X gypsum board</td>
</tr>
<tr>
<td>Insulation</td>
<td>3&quot; Fiberglass board rigid insulation</td>
</tr>
<tr>
<td>Substrate</td>
<td>1-5/8&quot; Metal Stud layer</td>
</tr>
<tr>
<td>Thermal/air layer</td>
<td>1&quot; Air space</td>
</tr>
<tr>
<td>Membrane layer I (weather barrier)</td>
<td>Asphalt felt paper</td>
</tr>
<tr>
<td>Membrane layer II (vapor retarder)</td>
<td>Polyethylene sheet</td>
</tr>
<tr>
<td>Exterior cladding (veneer)</td>
<td>Brick veneer</td>
</tr>
</tbody>
</table>

Table 2: Stakeholder values, properties, property indicators, benchmarks of measure, and high goodness benchmarks of measure

<table>
<thead>
<tr>
<th>Stakeholder Value</th>
<th>Property</th>
<th>PI</th>
<th>Unit</th>
<th>PIs of the Wall</th>
<th>BOM Min</th>
<th>BOM Max</th>
<th>BOM Reference</th>
<th>HGBOM Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material conservation</td>
<td>Recycled material</td>
<td>Percentage</td>
<td>%</td>
<td>77.75</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>50 USGBC 2013b</td>
</tr>
<tr>
<td></td>
<td>Reused material</td>
<td>Percentage</td>
<td>%</td>
<td>5.5</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>25 USGBC 2013b</td>
</tr>
<tr>
<td></td>
<td>Regional material</td>
<td>Percentage</td>
<td>%</td>
<td>35.43</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>50 USGBC 2013b</td>
</tr>
<tr>
<td>Indoor air quality improvement</td>
<td>Low-emitting material</td>
<td>Percentage</td>
<td>%</td>
<td>85.23</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>90 USGBC 2013b</td>
</tr>
<tr>
<td>Acoustical performance improvement</td>
<td>Sound resistance</td>
<td>STC*</td>
<td>NA</td>
<td>61.9</td>
<td>45</td>
<td>70</td>
<td>ICC 2012</td>
<td>55 USGBC 2013a</td>
</tr>
<tr>
<td></td>
<td>Sound absorption</td>
<td>NRC**</td>
<td>NA</td>
<td>0.05</td>
<td>0</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Fire safety</td>
<td>Fire resistance</td>
<td>Fire rating</td>
<td>hour</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>ICC 2012</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*STC stands for sound transmission class rating
** NRC stands for noise reduction coefficient
The results of the model-based analysis, including the PIs, BOMs, HGBOMs, PVSs, PGDs, and VFDs, are summarized in Tables 2 and 3. A 0.5 α coefficient was used in the analysis, which represents a mid-extent of rewarding high property goodness. The results of the VFDs of material conservation, indoor air quality improvement, acoustical performance improvement, and fire safety are 0.442, 0.852, 0.738, and 1.000, respectively. These results indicate that this concrete block wall fulfills material conservation value in a low degree, fulfills indoor air quality improvement and acoustical performance improvement in a relatively high degree, and fulfills fire safety in an extremely high degree. This value quantification results could provide decision makers with a sound numerical measurement as a basis for decision making, for example when making trade-offs (e.g., which values to fulfill in priority) or selecting design alternatives.

Table 3: PGDs and PVSs of the properties and VFDs of the stakeholder values

<table>
<thead>
<tr>
<th>Stakeholder Value</th>
<th>Property</th>
<th>PGDs</th>
<th>PVSs</th>
<th>VFDs</th>
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<td>Indoor air quality improvement</td>
<td>Reclaimed material</td>
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<tr>
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<td>Low-emitting material</td>
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<td>0.738</td>
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<tr>
<td>Fire safety</td>
<td>Fire resistance</td>
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<td>1.00</td>
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</table>

6 CONCLUSIONS AND FUTURE WORK

This paper presents an axiology-based mathematical value quantification model for quantifying the value fulfillment of one value bearer based on one stakeholder value. A value fulfillment degree (VFD) function is proposed for value quantification. The VFD function identifies the fulfillment degree of each stakeholder value based on the goodness of the properties and the significances of the properties in fulfilling particular stakeholder values. In doing so, a highly good property is rewarded in the function because of its higher contribution to the fulfillment of stakeholder values. Property goodness is a measure that defines how good a property is in fulfilling a specific stakeholder value, which is assessed systemically, extrinsically, or intrinsically. Property value significance is a measure that represents the significance, importance, or relevance of a specific property of a specific value bearer in fulfilling a specific stakeholder value, which is determined extrinsically or intrinsically. The model was initially validated through a case study, which demonstrates the applicability of the model in quantifying the VFDs of material conservation, indoor air quality improvement, acoustical performance improvement, and fire safety (stakeholder value) of a concrete block exterior wall system (value bearer).

In their future/ongoing research, the authors will further explore value aggregation that includes three types of aggregation: (1) subvalue aggregation (along a stakeholder value hierarchy): mathematically aggregating the subvalues (e.g., resource conservation, pollution prevention) to define the supervalue (e.g., environmental value), (2) object value aggregation (along an object hierarchy): mathematically aggregating the values of the parts (e.g., wall, ceiling, floor, etc.) to define the value of the whole (e.g., building), and (3) collective value aggregation (along a stakeholder hierarchy): mathematically aggregating the values of individual stakeholders to define the collective value of the group of stakeholders.

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References


INFRASTRUCTURE CONDITION ASSESSMENT BASED ON LOW-COST HYPER-SPATIAL RESOLUTION MULTISPECTRAL DIGITAL AERIAL PHOTOGRAPHY

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Abstract: Infrastructure condition information is critical for effective asset management. Infrastructure managers are tasked with regularly assessing asset conditions to make effective maintenance, repair, and rehabilitation decisions. Currently there are two types of methods broadly adopted for infrastructure condition assessment: on-site evaluation methods and airplane-based observation methods. On-site evaluation methods are expensive, labor-intensive, time-consuming, potentially dangerous to inspectors, inconsistent, and requiring specialized staff on a regular basis. Airplane-based observation methods can provide reliable overall condition information for ground infrastructure assets such as roadways, bridges, dams, or buildings, but the spatial resolutions of 0.075-meter (3-inch) to 1-meter are insufficient to examine detailed asset conditions such as individual cracks on a pavement surface or on a bridge. Using roadway pavement assets as an example, this research explored the utility of hyper-spatial resolution (3-millimeter) multispectral digital aerial photography acquired from a low-altitude unmanned remote sensing system to permit characterization of detailed surface distress conditions. With the help of orthogonal regression analysis, detailed pavement surface distress rates manually estimated from hyper-spatial resolution multispectral digital aerial photography were compared to reference pavement distress rates manually collected on the ground. The results show that the hyper-high spatial resolution imaging techniques provide detailed and reliable data suitable for informing infrastructure system management decisions. These results open the way for the future application of low-cost hyper-spatial resolution digital aerial photography for automated assessment of detailed infrastructure system condition.

1 INTRODUCTION

Infrastructure condition information is critical for effective infrastructure system management (Zhang and Bogus 2014). Decisions involving maintenance, repair, and rehabilitation of infrastructure systems require accurate and current information describing the conditions of these systems and their components (Maser 2005). This information is required not only to characterize current conditions but also to project future performance and remaining life (Maser 2005). Therefore, infrastructure managers are tasked with regularly assessing asset conditions to make effective maintenance, repair, and rehabilitation decisions.

Currently, infrastructure management agencies use either on-site evaluation or airplane-based observation methods for infrastructure condition assessment. On-site evaluation methods are labor-intensive, time-consuming, and potentially dangerous to inspectors (Maser 2005). Airplane-based observation methods can provide reliable overall condition information for ground infrastructure assets...
such as roadways, bridges, or buildings (Zhang and Bogus 2014), but the spatial resolutions of 0.075-meter (3-inch) to 1-meter are insufficient to examine detailed asset conditions such as individual cracks on a pavement surface or on a bridge. In recent years, unmanned remote sensing systems (URSS) have emerged as an important platform for hyper-spatial resolution aerial data collection. URSS can fly lower to the ground than traditional airplanes, and thus allow for more detailed data to be collected without specially-designed, cost prohibitive sensors (e.g. LiDAR). Using roadway pavement assets as an example, this research explored the utility of hyper-spatial resolution (3-millimeter) multispectral digital aerial photography (H-DAP) acquired from a low-altitude URSS, in this case a tethered weather balloon, to permit characterization of detailed surface distress conditions. Detailed pavement surface distress rates manually estimated from H-DAP were compared to reference distress rates manually collected on the ground to assess the feasibility and potential utility of automated approaches.

2 BACKGROUND

The ability to assess the condition of infrastructure systems (e.g. roads and bridges) rapidly and accurately is critical to making decisions within any infrastructure management systems (Maser 1988; Karaa 1989). Infrastructure condition data are collected and used by infrastructure management agencies to determine the serviceability of infrastructure systems and to help make decisions on the distribution of limited resources for maintenance, repair, and rehabilitation.

Traditionally, infrastructure assessment is performed with “boots on the ground” by having experts visually inspect the condition of infrastructure systems with subjective judgment (Aktan et al. 1996) or by using vehicle-mounted electronic sensors to automatically detect the infrastructure conditions (Hudson and Uddin 1987). This type of assessment method is classified as on-site evaluation and still broadly used by infrastructure system management agencies. In recent history, one might still remember structural engineers scaling the Washington Monument in Washington, D.C. after the 2011 earthquake to determine the structural integrity of the monument (Figure 1). On-site condition assessment can collect detailed infrastructure condition data. However, on-site methods are expensive, labor-intensive, time-consuming, potentially dangerous to inspectors, requiring specialized staff on a regular basis, and data collected by different inspectors can exhibit a high degree of variability (Maser 2005; Bogus et al. 2010).

Figure 1: Post-earthquake assessment of Washington Monument (Source: NPS.gov)

Another method to assess infrastructure conditions is using remote evaluation methods. This technology is typically deployed on airplanes that fly over infrastructure systems. This type of assessment method is classified as airplane-based observation evaluation and is becoming more and more popular (Jensen and Cowen 1999). The resulting images (Figure 2), which typically have spatial resolutions ranging from 0.075-meter (3-inch) to 1-meter, can be used to evaluate the overall condition of infrastructure systems rapidly and inexpensively (Zhang and Bogus 2014). There are limitations, however, on the spatial resolution of these images which can limit the ability to detect and assess small defects, such as cracks on a pavement surface or on a bridge (Guo 2010).

The intellectual significance of this research is that it addresses the limitations inherent in both the “boots on the ground” method and the aerial data collected from airplane-based technology by using a novel middle ground approach of data collection for detailed infrastructure condition assessment. The proposed
The methods uses an unmanned airborne system (UAS), which can fly lower to the ground than traditional airplanes, and thus allow for more detailed infrastructure condition data to be collected without specially designed, cost prohibitive sensors. The improved detail associated with the data holds the potential to provide much better condition assessment of infrastructure systems at dramatically reduced cost when compared to on-site (i.e. manual methods or automatic methods) approaches.

Figure 2: Routinely available airplane-based observation images for infrastructure condition assessment; this image has a spatial resolution of 0.1524-meter (6-inch).

In recent years, UAS have emerged as an important platform for collection of hyper-spatial resolution aerial data (i.e., sub-centimeter ground sampling distances) – a trend that is all but certain to continue. For now, due to a wide variety of regulatory and safety concerns, the legal use of UAS is severely restricted in the United States. In anticipation of an established regulatory environment and availability of UAS for routine infrastructure condition assessment, this research used a tethered helium weather balloon system to simulate the collection of hyper-spatial resolution aerial image data from untethered UAS. The process of measuring spatial properties from aerial photography or images is referred to as “photogrammetry”. Aerial triangulation (AT) is the basic photogrammetric method for analyzing aerial images to determine X, Y, and Z ground coordinates of individual points based on measures take from a series of overlapping aerial photographs (Zomrawi et al. 2013). AT traditionally requires the identification of thousands of control points linking images to one another and to a reference dataset to enable least squares estimation of the optimal triangulation model. New computation approaches (e.g., structure-from-motion, graphic processing unit based image processing) have enabled automation of traditional AT to permit routine estimation of 3-dimensional surface structure and subsequent orthocorrection of large datasets at approximately the spatial resolution of the input images (Zhang et al. 2011; Zomrawi et al. 2013). When coupled with hyper-spatial resolution image data such as that collected by low altitude UAS, this technology holds the potential to permit the estimation of horizontal and vertical measurements at sub-centimeter scales (Zhang et al. 2011), and ultimately, the detection and assessment of infrastructure damages at finer scales than has traditionally been possible by airborne survey.

Hyper-spatial resolution aerial data have been used to facilitate research in many fields, such as archaeology, intertidal ecology, marine ecology, zoology, emergency management, vegetation and soil monitoring, and topographic mapping (Scoffin 1982; Aber et al. 1999; Fraser et al. 1999; Guichard et al. 2000; Aber et al. 2001; Sklaver et al. 2006; Wundram and Loffler 2008; Marzolff and Poesen 2009; Smith et al. 2009; Verhoeven 2009). However, previous studies regarding application of H-DAP to detailed infrastructure condition assessment are limited. The only published research on this topic was performed by Chen et al. (2011). This research shows the potential to use H-DAP to evaluate crack-level infrastructure condition, but the assessment ability is limited to inch-level large cracks on bridge pavements because the spatial resolution of the used aerial images is 0.0254-meter (1-inch).

Using roadway flexible pavement (i.e. asphalt concrete) assets as an example, we explore the application of H-DAP to detect and assess detailed infrastructure condition. Key items for evaluating flexible pavement distress were identified from United States Department of Transportation Highway Performance System (HPMS) Field Manual, including rutting (item 50), alligator cracking (item 52), and transverse cracking (item 53). Rutting is an unrecoverable longitudinal surface depression in both wheel paths (Cordova et al. 2009). Alligator cracking is interconnected cracks resembling chicken wire or alligator skin (Cordova et al. 2009). Transverse cracking is cracking that is predominantly perpendicular to the pavement centerline. Transverse cracking is a result of pavement expansion and contraction due to
temperature changes, as well as shrinkage of asphalt binder with aging (Cordova et al. 2009). With AT, it is possible to generate sub-centimeter scale mosaicked orthophotos and digital surface models (DSMs) for standardized evaluation of detailed infrastructure condition, potentially reducing the cost and duration of assessment while improving the comparability of results.

3 METHODOLOGY

Using H-DAP acquired from a low-cost UAS as input, AT was used to generate 3-millimeter spatial resolution mosaicked orthophotos and same spatial resolution DSMs for pavement surfaces. Key metrics (HPMS Field Manual 2010) used to measure flexible pavement distress, including cracking length, cracking area percentage, and rutting depth, were measured from the orthophotos and DSMs and then compared to ground reference data measured manually using standard protocols (Cordova et al. 2009).

3.1 Data Acquisition and Preparation

A low-cost unmanned remote system was developed to simulate the collection of image data from other untethered low-altitude UAS that are now common in the marketplace. This system includes a tethered helium weather balloon with customized rigging. The sensor affixed to the balloon rigging is a small-format Canon digital camera (SX260 HS). This camera has a 12 megapixel detector array collecting in the visible blue, green, and red wavelength via Bayer array sampling, a rugged cased with protected lens, built-in GPS unit, and intervalometer capability. A firmware enhancement application known as the Canon Hack Development Kit (CHDK), was employed to permit more control over the operation of the Canon SX260 HS digital camera, including shutter speed, shutter lag, aperture size, and intervalometer.

Data were collected for ten sites (i.e. road sections) on US Highway 66 and New Mexico Highway 0333 near the City of Albuquerque, NM. Approximately 200 overlapping hyper-spatial resolution aerial images were acquired for each site at about 40 meters above ground level (AGL). The ground area covered by each frame is approximately 20-meter by 15-meter and the ground sampling distance is approximately 2-millimeter. A Real Time Kinematic (RTK) surveying system was used to collect the horizontal and vertical coordinates of the ground control points (GCPs) on the pavement surface with a National Oceanic and Atmospheric Administration (NOAA) Online Positioning User Service (OPUS) reported root mean squared error (RSME) of 0.004-meter horizontally and 0.006-meter vertically. Sixteen GCPs were collected along with detailed photos of each GCP for each site.

A reference data set was collected by a trained two-person crew at each of the preselected data collection sites. Crew members performed manual (i.e., visual) evaluation with safety precautions (e.g. safety training and high visibility garments) based on the standard protocol adopted by the HPMS Field Manual. Both inspectors assessed pavement distresses (rutting, alligator cracking, and transverse cracking) independently and the results are the average value of the two independent evaluations. In accordance with the HPMS Field Manual, rutting and shoving depth was measured for only the rightmost driving lane for both inner and outer wheel paths at three locations along the wheel path within each site and then the depth averaged for each wheel path. The HPMS Field Manual requires reporting the percent area of total alligator cracking to the nearest 5%. In addition, the HPMS Field Manual requires reporting an estimation of relative length in feet per mile (feet/mile) of transverse cracking.

3.2 Aerial Triangulation (AT)

After excluding blurry and oblique images, approximately 150 overlapping hyper-spatial resolution aerial images were used for each site. The commercial software Agisoft was selected as the tool to perform AT as it permitted minimal human intervention at a low cost. Among the sixteen GCPs collected for each site, ten were used to calibrate the AT process while the remaining six were reserved to evaluate the horizontal and vertical accuracy of the orthophotos and DSMs. For each site, millions of control points were identified from the input overlapping images to build a dense cloud, and then a triangulation irregular network (TIN) mesh was generated based on the identified control points. Orthophotos and DSMs were exported as raster datasets in TIFF format at a spatial resolution of 3-millimeter. Orthophotos and DSMs are generated in a single processing routine and are therefore tightly co-registered. Orthophotos were
used to assess the horizontal accuracy while DSMs were used to assess the vertical accuracy. The accuracy assessment results (RMSE) show that the overall horizontal accuracy for all data collection sites is 0.004-meter, while the vertical accuracy is 0.006-meter. The number of overlapping images used and accuracy information for each data collection site is reported in Table 1.

Table 1: Images Frames and Accuracy of Orthophotos and DSMs for Each Site

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Image Frames</th>
<th>Horizontal Accuracy (in meters)</th>
<th>Vertical Accuracy (in meters)</th>
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<tr>
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<td>0.006</td>
</tr>
<tr>
<td>Site 2</td>
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<td>0.004</td>
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<td>Site 9</td>
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<td>0.005</td>
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<tr>
<td>Site 10</td>
<td>189</td>
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<td>0.004</td>
</tr>
<tr>
<td>Overall</td>
<td>1591</td>
<td>0.004</td>
<td>0.006</td>
</tr>
</tbody>
</table>

3.3 Rutting Depth Measurement

In manual evaluation, rutting depth was measured with a wooden bar and a measuring tape. The actual measured points are the lowest points as visually determined by inspectors. DSMs exhibit the modeled 3-dimensional pavement surface. Points and polygons were created on DSMs to simulate the locations of the actual measuring points and wooden bars for rutting depth measurement. The actual measuring points and the locations of the wooden bars are shown in Figure 3.

The minimum scale of the measuring tape used for manual inspection was 0.001-meter. The length and width of the wooden bar is 1.22-meter (48-inch) and 0.02-meter (0.8-inch). With the actual field measured point (as photographed) as the center, two polygons (one on either side of the field measured point) with a size of 0.61-meter (20-inch) by 0.02-meter were created to simulate the location of the wooden bar. Using the polygon as the boundary, the DSM pixels were extracted and the highest measured points were identified to correspond to the field method of rutting depth calculation. Figure 4 illustrates the method used to calculate rutting depth from the DSM.

As shown in Figure 4, we consider the two highest points of the rutting section points A and B and the two measured points of the rutting section Points C and D. The distance from Point C to Point D is the rutting depth. Points A, B, and C will have the same height if the heights of Points A and B are equal. However, under most circumstances the heights of A and B are different. Therefore, a weighted average method was used to estimate the height of Point C.
\[ [1] \text{HC} = \frac{(HA \times DA + HB \times DB)}{(DA + DB)} \]
\[ [2] \text{RD} = \text{HC} - \text{HD} \]

In Equation 1, HC represents the height of Point C, while HA and HB represent the heights of Point A and Point B, respectively. DA represents the horizontal distance from Point A to Point D, while DB represents the horizontal distance from Point B to Point D. In Equation 2, RD represents the rutting depth. HA and HB were determined based on the DSMs, while DA and DB were determined based on the orthophotos.

3.4 Alligator Cracking Measurement

As required by the HPMS Field Manual, alligator cracking should be reported as the percent of total alligator cracking section area to the nearest 5% at a minimum. In the manual evaluation protocol (Cordova et al. 2009), pavement inspectors pace off the cumulative length of alligator cracking and mark the location of occurrence in 1 or 2 wheel paths. For example, typically the width of the driving lane is 3.66 meters (12 feet), and therefore, for a 1.6 kilometer (1 mile) section, the total area is 5886 square meters (63360 square feet). If the total length of alligator cracking paced off by inspectors is 152 meters (500 feet) in both wheel paths and the width of the evaluated alligator cracking is 0.61 meters (2 feet), the total area of the alligator cracking is 185 square meters (2000 square feet). Therefore, the reported area percentage should be 5 percent (2000/63360 = 3.2 percent which should be rounded up to the nearest 5 percent). In order to simulate the alligator cracking measurement prescribed by the HPMS, polygons were created to represent the whole pavement surface section used for manual evaluation and the boundary of the occurred alligator cracking. The polygon defining the manual evaluation zone was used to calculate the total area while the polygon defining the alligator cracking was used to calculate the total area of alligator cracking, and then the percent of alligator cracking was calculated by comparing the two polygons. The usage of polygons to determine the area percentage is shown in Figure 5. It should be noted that both actual percentage and rounded percentage were calculated for each site, but only rounded percentage was used for the following analyses.

3.5 Transverse Cracking Measurement

According to the HPMS Field Manual, pavement inspectors should count the number of transverse cracks extending at least half the lane width (1.83 meters [6 feet] or longer cracks) to estimate the total length of cracking in terms of feet per mile (or meters per kilometer) normalized by the total length of the manual evaluation zone. In order to simulate the transverse cracking measurement, any transverse cracks longer than 1.83 meters (6 feet) were digitized in a GIS as polylines to facilitate the calculation of the total length of transverse cracking (Figure 6). The same polygon created in alligator cracking measurement representing the whole pavement section was used to measure the total length of the evaluation zone.

3.6 Measurement Result Comparison

Rutting depth, alligator cracking area percent, and transverse cracking length measured from the DSMs and orthophotos were compared to manual evaluation results to examine the feasibility of using the H-DAP derived outputs to detect and assess the pavement surface distress metrics. Linear regression analyses revealed that the H-DAP derived measurement and the manual measurement for all three
distresses fit closely to the regression lines. Therefore, a paired-t test was not performed to examine if the H-DAP derived measurement and the manual measurement are statistically different from each because these data clearly violate the assumption that there is no linearity between the two groups of sample values (Carroll and Ruppert 1996). Pavement surface distresses measured from these two methods were compared with orthogonal regression analysis because it does not assume independence between variables. Orthogonal regression examines the linear relationship between two continuous variables and is often used to test whether two instruments or methods are measuring the same thing (Staiger and Stock 1997). For both linear regression and orthogonal regression, the dependent variable is the reference distress rate measured by manual method. This also makes the usage of orthogonal regression appropriate because unlike linear regression, both the independent and dependent variables in orthogonal regression contain measurement error (Carroll and Ruppert 1996).

![Figure 5: Alligator cracking boundary within entire manual evaluation boundary; blue polygons are the alligator cracking area while the red polygon is the entire manual evaluation zone; areas for these polygons can be calculated within the geographic information systems (GIS) and therefore, alligator cracking area percentage can be determined.](image1)

![Figure 6: Transverse cracking and entire manual evaluation polygon boundary; the red polygon is the entire manual evaluation zone, while the blue polylines are the transverse cracks; lengths of these transverse cracks and the length of the manual evaluation zone can be calculated within the GIS and therefore, transverse cracking length normalized by the total evaluation zone length can be calculated.](image2)

4 RESULTS AND DISCUSSION

The manually-evaluated and H-DAP derived rutting depths are summarized and exhibited. It should be noted that the results are organized by inner and outer wheel paths for each data collection site (See Table 2 for details). Table 3 summarizes the manually-evaluated and H-DAP derived alligator cracking area percent and transverse cracking length.
Therefore, instead of using a paired-test, orthogonal regression analysis was used in this study because it does not assume independence between variables. Interpretation of the
orthogonal regression results should be focused on the CI. It indicates that the measurements from the manual method and H-DAP method are not statistically different if zero is contained in the CI for the intercept and one is contained in the CI for the slope. Results revealed that there is no evidence showing that distress rates measured by manual method and H-DAP method are statistically different.

Table 4: Linear Regression and Orthogonal Regression Results

<table>
<thead>
<tr>
<th>Distress</th>
<th>Regression</th>
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<th>P Value</th>
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<th>R²</th>
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<td></td>
<td>Linear</td>
<td>Intercept DSM Depth</td>
<td>-0.00004</td>
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<td>(-0.0012387, 0.00114)</td>
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<tr>
<td>Rutting</td>
<td>Orthogonal</td>
<td>Intercept DSM Depth</td>
<td>1.00770</td>
<td>&lt;0.0001</td>
<td>(0.934107, 1.08128)</td>
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</tr>
<tr>
<td></td>
<td>Orthogonal</td>
<td>Intercept DSM Depth</td>
<td>1.00770</td>
<td>&lt;0.0001</td>
<td>(0.934107, 1.08128)</td>
<td>N/A</td>
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<td>DSM Depth</td>
<td>1.00770</td>
<td>&lt;0.0001</td>
<td>(0.934107, 1.08128)</td>
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<td></td>
<td>Orthogonal</td>
<td>Oregonphoto Area Percent</td>
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<td>(0.78988, 1.01129)</td>
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<td>Oregonphoto Length</td>
<td>0.9943354</td>
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<td>&lt;0.0001</td>
<td>(0.96896, 1.01971)</td>
<td>0.9990</td>
</tr>
</tbody>
</table>

Ultimately, these results show that H-DAP method works as effectively as the manual evaluation does. Given the horizontal and vertical accuracy of the DSMs and orthophotos, the discrepancy between manual method measurement and the H-DAP method measurement could be from either method. Distresses measured by different inspectors have been shown to exhibit a high degree of variability (Bogus et al. 2010) because this method relies on subjective visual observation, suggesting that manual assessments will naturally exhibit variability. These results can be interpreted to indicate that H-DAP based method is at least as accurate as manual methods.

5 CONCLUSIONS

We present a novel approach for detailed infrastructure condition assessment using H-DAP acquired from a low-altitude URSS. Using roadway pavement assets as an example, results indicate that pavement surface distress conditions measured by manual methods and the H-DAP method are not statistically different from each other and that the proposed method is likely more accurate than manual methods. In the near-term, the proposed H-DAP method could be used to measure infrastructure conditions in situations where field inspectors cannot evaluate except with considerable labor costs (e.g. sections in remote areas) or where vehicles cannot access, but in the longer-term, the proposed method is capable of completely replacing field infrastructure condition assessment due to its high accuracy, potential for full automation, and dramatically reduced long term cost.

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References


EX-ANTE ASSESSMENT OF VULNERABILITY TO UNCERTAINTY IN COMPLEX CONSTRUCTION PROJECT ORGANIZATIONS

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Abstract: Modern construction projects are operated in extremely uncertain environments. Uncertainties affect the performance of projects. Despite an extensive body of literature in the area of performance assessment, there is a gap in knowledge pertaining to an integrated methodology for ex-ante evaluation of vulnerability of project organizations to the impacts of uncertainties. The objective of this paper is to address this gap in knowledge by creating a framework for ex-ante assessment of vulnerability in construction project organizations. In the proposed framework, construction project organizations are conceptualized as complex meta-networks and analyzed using dynamic network analysis. Accordingly, the impacts of the uncertain events (e.g., late design deliverables, equipment breakdown, safety accident and injury, and severe weather conditions) are translated into perturbations in different node entities (i.e., human agent, information, resource and task) and the corresponding links in project meta-networks. These uncertainty-induced perturbations cause transformations in the project topological structure, and thus, negatively affect the efficiency of project organizations’ meta-networks. The extent of the variation in the efficiency is used as an indicator of a project organization’s vulnerability to uncertainties. The application of the proposed framework is shown in a numerical example related to a tunneling project. Various scenarios related to different uncertain events were simulated to quantitatively investigate the vulnerability of the project and evaluate the impacts of different planning strategies on mitigating vulnerability. The results demonstrate the capability of the proposed framework for quantitative assessment of vulnerability and evaluation of planning strategies in construction projects. Hence, it provides a tool for proactive evaluation and mitigation of vulnerability in construction project organizations.

1 INTRODUCTION

Modern construction projects are complex and are executed in highly uncertain environments. Similar to other complex systems, construction project organizations have a greater likelihood for successful performance if they are less vulnerable to uncertainties. Despite a growing body of literature in the areas of performance assessment and risk analysis in construction projects, our understanding of the determinants of performance vulnerability in complex construction projects remains limited. First, the existing studies (e.g., Baloi and Price, 2003; Zou et al., 2007) mainly focus on identification of risks and uncertainties affecting the performance of construction project organizations. However, a better understanding on the extent and severity of performance variation in a project which also depends upon the vulnerability of the project organization is missing. Second, the majority of the existing risk and uncertainty assessment approaches (e.g., Nieto-Morote and Ruz-Vila, 2011) in construction projects are rather subjective and do not provide a robust quantitative basis for ex-ante evaluation of planning strategies to reduce the
vulnerability of project organizations to uncertain events. Third, the existing methods for performance assessment and risk analysis in construction projects do not capture the complex interactions between human agents, information, resources, and tasks in project organizations. Capturing these complex interactions is a critical step toward development of an integrated methodology for performance assessment in complex construction projects (Zhu and Mostafavi, 2014). To address these methodological limitations and gaps in knowledge, an integrated framework for ex-ante assessment of vulnerability in complex construction project organizations is proposed in this paper.

In the proposed framework, project organizations are conceptualized as dynamic multi-node and multi-link meta-networks composed of different node entities (e.g., agents, information, resources and tasks) and their interdependencies. Accordingly, the uncertain events in construction projects are translated into perturbations in the node entities and links of the meta-network. Then, using stochastic simulation, the impacts of uncertainty-induced perturbations on the performance of project organizations are captured based on the changes in the efficiency of the meta-network. Finally, the proposed framework enables ex-ante evaluation of different planning strategies and their significance in mitigating vulnerability.

2 A FRAMEWORK FOR ASSESSMENT OF PROJECT ORGANIZATION’S VULNERABILITY

There are four components in the proposed framework: abstraction of project meta-network, translation of uncertainty-induced perturbations, vulnerability assessment, and evaluation of planning strategies. Figure 1 shows the four components in a workflow for integrated vulnerability assessment in complex construction projects. The details of each component are explained in this section.

![Figure 1. A Framework for Integrated Vulnerability Assessment in Construction Projects](image)

2.1 Abstraction of Project Meta-network

Complex construction projects are systems-of-systems consisting of interconnected networks of human agents, information, resources and tasks (Zhu et al., 2014). The ability of project organizations to cope with uncertainty is an emergent property that arises from the interactions between different entities. Hence, for evaluating the vulnerability of a project organization to uncertainty, different entities and their interconnections should be properly abstracted. In order to facilitate the abstraction of the entities and their interactions in complex project organizations, Zhu and Mostafavi (2014a; 2014b; 2014c) proposed conceptualization of project organizations as systems-of-systems or meta-networks (Carley 2003). The meta-network of the construction project organization is composed of four types of node entities (i.e., agents, information, resources, and tasks) and ten types of links, as shown in Figure 2. To abstract the node entities and their interconnections, the first step is to identify the task nodes. A task node is an entity...
with a measureable outcome. In construction project, a task node could represent decision making, information processing or production work. A task is being implemented by one or more agent nodes which utilize information and resources to complete the task. After identification of the task nodes, the agent nodes can be identified. An agent node is an entity that implements the task. It could be an individual, a crew, or a team depending on the nature of tasks. Then, information and resource nodes can be identified accordingly based on the requirement of the tasks. The interdependencies and relationships between different node entities build the links in the project meta-network. Each type of links represents one type of relationship (e.g., agent-information link represents who knows what, agent-task link represents who is assigned to what task). One type of links and their corresponding nodes form an individual network [e.g., social network of agent-agent relationships (AA), assignment network of agent-task relationships (AT)]. Different networks are interconnected as a whole in the project meta-network. Changes in one node entity or network cascade into changes in the other node entities and networks.

![Nodes and Links in Project Meta-Networks](image)

**Figure 2. Nodes and Links in Project Meta-Networks**

### 2.2 Translation of Uncertainty-induced Perturbations

Conceptualizing project organizations as meta-networks provides a novel perspective for understanding the uncertain events and their corresponding impacts on the performance. According to the principles of network science, perturbations in networks affect their topological structures and stability (Dalziell and McManus, 2004). Using the theoretical underpinnings of network science, in the proposed framework, the impacts of uncertain events are translated into perturbations in the node entities and links in a project organization’s meta-network (Zhu and Mostafavi, 2015). Table 1 summarizes three main types of perturbations in construction projects (i.e., agent-related perturbations, information-related perturbations and resource-related perturbations) and examples of events corresponding to each type of perturbation. One uncertain event may cause perturbation in a single node entity (i.e., single-effect event) or multiple node entities (i.e., multi-effect event). For example, equipment breakdown on a jobsite may lead to a single-effect event, while the failure of the power system may cause multiple perturbations in different resource node entities. In the proposed framework, each uncertain event is abstracted using two attributes: its perturbation effect and likelihood of occurrence. The perturbation effect depends upon the node entities and links impacted due to the uncertain events. The likelihood of an uncertain event is determined using historical data or other probability encoding techniques (Clemen and Winkler, 1999).

<table>
<thead>
<tr>
<th>Types of perturbation</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent-related perturbation</td>
<td>Staff turnover, safety accident or injury, dereliction of duty</td>
</tr>
<tr>
<td>Information-related perturbation</td>
<td>Late design deliverables, unclear scope/design, limited access to required knowledge, miscommunication</td>
</tr>
<tr>
<td>Resource-related perturbation</td>
<td>Counterfeit/defective materials, equipment breakdown, late delivery of material</td>
</tr>
</tbody>
</table>

*Table 1: Perturbations in Project Meta-networks*
2.3 Vulnerability Assessment

The vulnerability of the project can be measured based on the extent of the changes in the relevant topological measure (i.e., task completion measure) of the meta-network before and after a perturbation (Holme et al. 2002, Criado et al. 2005). The greater the change in the topological measure due to uncertain-induced perturbations, the greater the vulnerability of the network. More specifically, network vulnerability denotes the decrease of network efficiency due to a selected removal of nodes or links. For example, a network is moved from its equilibrium state $N$ to $N'$ due to exposure to uncertain event(s) $\mathcal{E}$. The corresponding vulnerability of the network to this exposure then can be defined using Equation 1:

$$[1] \nu(\mathcal{E}) = \varphi(N) - \varphi(N')$$

where $\varphi$ denotes the performance efficiency (i.e., functionality) of the network. There are different approaches to assess the performance efficiency of a network depending upon its type. In project organizations’ meta-networks, efficiency could be measured based on the percentage of tasks that can be completed by the agent assigned to them (i.e., based on whether the agents have the requisite information and resource to do the tasks) (Carley and Jeff, 2004). Equations 2-4 show the procedure for computation of information-based task completion. In Equations 2-4, binary matrices are generated based on the abstraction of the project meta-network (e.g., $AI$ represents a binary matrix representing the agent-information relationships, with agent node entities as the row and information node entities as the column). Similarly, resource-based task completion can be calculated by replacing matrices $AI$ and $IT$ with matrices $AR$ and $RT$ in the equations. The overall performance efficiency of a project organization’s meta-network is the average of information-based task completion and resource-based task completion values (Equation 5).

Hence, the vulnerability of a project organization to uncertain events can be obtained using Equation 1 and by assessing performance efficiency of the meta-network (from Equation 5) prior and after perturbations. The value of vulnerability ranges from 0 to 1. A higher value means that the project organization is more vulnerable to the uncertain events.

$$[2] Need = [(AT' \times AI) - IT']$$

$$[3] S = \{i | 1 \leq i \leq |T|, \exists j: Need(i, j) < 0\}$$

$$[4] Information \, based \, task \, completion = (|T| - |S|)/|T|$$

$$[5] \varphi(N) = (Information \, based \, task \, completion + Resource \, based \, task \, completion)/2$$

2.4 Evaluation of Planning Strategies

In the proposed framework, different planning strategies are translated to the addition/removal of node entities and/or links in the project organization’s meta-network. Table 2 provides examples of planning strategies and their reflections in the project organization’s meta-network related to task assignment, decision-making authority, as well as resource management. These different planning strategies can be translated to changes in the node entities and links in the meta-network. The same project could exhibit different levels of vulnerability under different planning strategies. The effectiveness of planning strategy is measured based on the reduction of vulnerability.

$$[6] effectiveness \, of \, planning \, strategy \, p = (\nu_p - \nu)/\nu$$

where $\nu$ denotes the vulnerability of the project to the uncertain events in the base scenario, and $\nu_p$ denotes the vulnerability of the same project to the uncertain events with alternative planning strategies.
Table 2: Examples of Different Planning Strategies in Construction Project Organizations

<table>
<thead>
<tr>
<th>Planning Strategies</th>
<th>Reflection in the Project Meta-networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Assignment</td>
<td></td>
</tr>
<tr>
<td>Division of labor</td>
<td>One agent or crew is assigned to one task</td>
</tr>
<tr>
<td>Generalization of labor</td>
<td>Agents or crews can be assigned to multiple tasks</td>
</tr>
<tr>
<td>Decision-making Authority</td>
<td></td>
</tr>
<tr>
<td>Centralized</td>
<td>Reservation of decision making power at top level</td>
</tr>
<tr>
<td>Decentralized</td>
<td>Decision making authority is distributed</td>
</tr>
<tr>
<td>Resource Management</td>
<td></td>
</tr>
<tr>
<td>Redundancy</td>
<td>Backup resources are prepared for key resources</td>
</tr>
<tr>
<td>No redundancy</td>
<td>No backup resources</td>
</tr>
</tbody>
</table>

3 NUMERICAL EXAMPLE

A hypothetical case related to a tunneling project is used here to illustrate the application of the proposed framework. In this example, a tunneling project constructed using New Austrian Tunneling Method (NATM) was modeled. Compared to the conventional tunneling method, which uses the suspected worst rock condition for design, NATM saves cost by adjusting the initial design during the construction phase (De Farias et al., 2004). In NATM, rock samples are collected by the geologist team during the early stage of design. After doing laboratory tests on the rock samples, the test results are compared with the rock quality designation index and the rock mass classification can be identified. The initial design is then conducted based on the identified rock type. The excavation crew performs excavation into the tunnel face based on the initial design, followed by loading explosives and blasting. Before blasting, the safety supervisor performs the safety inspection on the site and issues the safety approval. Right after the excavation work, the support installation crew starts working on the jobsite. Support installation crew applies shotcrete and installs the initial support (e.g., rockbolts, lattices girders or wire mesh) as the initial lining process. Measurement instrumentations are installed to observe the rock deformation behavior after the initial lining. The geologist team reads the data from the instrumentations and reports the rock deformation information to the designer. The designer team then makes the decision on whether a revision on the initial design is needed. The decision depends on whether the rock deformation is within the acceptable range. If no revision is necessary, a final lining process composed of traditional reinforced concrete is conducted; otherwise, the designer team revises the initial design for both initial lining and final lining. In this case, the support installation crew will use the revised design to implement the initial and final lining. The whole tunneling project is constructed in sections. At the end of each section, the project manager reviews the initial design, revised design, as well as the rock deformation, to assess the risks, and makes a decision on the step length for excavation of the next section. For example, if a relatively large deformation is observed, the project manager will decrease the step length to prevent the chance of collapsing. This tunneling project involves multiple dynamic and complex processes. A high level of interdependence exists between different agents, resources, information and tasks. Uncertain events could have negative ripple impacts on the project performance. For example, if a miscommunication happens between the geologist team and design team about the rock deformation information, not only will the task of revising design be directly affected, but also the succeeding tasks (e.g., installation of the final lining may not be performed appropriately due to lack of information related to revised design).

3.1 Integrated Vulnerability Assessment

The proposed framework was used for ex-ante analysis of vulnerability in the case study project. The four components of the proposed framework were all conducted in the context of the case. ORA-NetScenes 3.0.9.9 was used as the network analysis and modeling platform.

Abstraction of Project Meta-network

First, the meta-network of the project organization in the case study was abstracted. The project’s meta-network includes 36 node entities (of four different types) and 118 links (of ten different types) in total. Table 3 provides examples of different node entities and links in the tunneling project meta-network.
Translation of Uncertainty-induced Perturbations

Potential uncertain events, their effects, and the likelihood in the case project were identified. The potential events include single-effect events related to agent, resource, and information (e.g., geologist or designer turnover, delay in obtaining rock deformation data, or excavator breakdown), as well as events with multiple effects (e.g., power system failure or severe weather). Each uncertain event was translated to perturbations in the project's meta-network. For example, if a turnover in the design team happens, the designer node is isolated in the project's meta-network (i.e., with no links to project resource or information). Thus, the design tasks cannot be completed successfully. The likelihood of uncertain events was identified based on three levels of uncertainty: low (10%), medium (20%), and high (50%) (van der Gaag et al., 2002). Table 4 depicts the identified uncertain events, their perturbation effects, and likelihood in the case. For example, the level of uncertainty related to the late delivery of material was identified as high, which implies that, for each type of material used in this project (i.e., explosive, initial support, concrete and reinforcement), there was 50% likelihood of late delivery.

Table 3: Examples of Node Entities and Links in the Tunneling Project's Meta-Network

<table>
<thead>
<tr>
<th>Types</th>
<th>Examples in the tunneling project case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent (A)</td>
<td>geologist team, designer team, excavation crew, project manager, etc.</td>
</tr>
<tr>
<td>Information (I)</td>
<td>rock condition, initial design, rock deformation, revised design, etc.</td>
</tr>
<tr>
<td>Resource (R)</td>
<td>concrete, boomer, initial support, power system, excavator, etc.</td>
</tr>
<tr>
<td>Task (T)</td>
<td>lab test, excavation, apply shotcrete, revise design, etc.</td>
</tr>
<tr>
<td>Link</td>
<td></td>
</tr>
<tr>
<td>A-A</td>
<td>geologist team reports to designer team</td>
</tr>
<tr>
<td>A-I</td>
<td>excavation crew knows initial design information</td>
</tr>
<tr>
<td>A-R</td>
<td>geologist team uses measurement instrument</td>
</tr>
<tr>
<td>A-T</td>
<td>designer team is assigned to conduct initial and revised design</td>
</tr>
<tr>
<td>I-I</td>
<td>revised design information depends on rock deformation</td>
</tr>
<tr>
<td>I-R</td>
<td>initial design is needed for choosing initial support material</td>
</tr>
<tr>
<td>I-T</td>
<td>rock deformation is needed for deciding step length</td>
</tr>
<tr>
<td>R-R</td>
<td>concrete is used by shotcrete machine</td>
</tr>
<tr>
<td>R-T</td>
<td>loader and trucks are needed for mucking</td>
</tr>
<tr>
<td>T-T</td>
<td>safety inspection is conducted before blasting</td>
</tr>
</tbody>
</table>

Vulnerability Assessment

The perturbations related to the uncertain events were simulated as independent random events in the case study. Using Monte-Carlo experimentation, 30 runs of the simulation model were implemented. Since the likelihood of one event occurring does not affect the likelihood of the other events occurring, multiple uncertain events happen in each run of the Monte-Carlo simulation randomly. In each run of simulation, the vulnerability of the project organization to the perturbations of the uncertain events that occurred in that run was assessed. Then, a probability distribution related to the vulnerability of the project organization under the identified uncertainties (i.e., uncertain events, their effects, and likelihood) in this case was obtained from the outcomes of the total 30 runs.

Table 4: Uncertain Events in the Tunneling Project’s Meta-Network

<table>
<thead>
<tr>
<th>Uncertain Events</th>
<th>Perturbation Effect</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-effect Event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dereliction of duty</td>
<td>Agent-related perturbation</td>
<td>Medium</td>
</tr>
<tr>
<td>Staff turnover</td>
<td>Agent-related perturbation</td>
<td>Low</td>
</tr>
<tr>
<td>Inadequate information</td>
<td>Information-related perturbation</td>
<td>Medium</td>
</tr>
<tr>
<td>Equipment breakdown</td>
<td>Resource-related perturbation</td>
<td>Medium</td>
</tr>
<tr>
<td>Late delivery of material</td>
<td>Resource-related perturbation</td>
<td>High</td>
</tr>
<tr>
<td>Compound-effect Event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power system failure</td>
<td>Multiple resource-related perturbation</td>
<td>Medium</td>
</tr>
<tr>
<td>Severe weather</td>
<td>Agent and resource-related perturbations</td>
<td>Low</td>
</tr>
<tr>
<td>Economic fluctuation</td>
<td>Agent and resource-related perturbations</td>
<td>Low</td>
</tr>
</tbody>
</table>
Evaluation of Planning Strategies

In the base scenario of the tunneling project studied, planning strategies of the generalization of labor, centralized decision making, and non-redundancy in resource management were adopted. To investigate the influence of different planning strategies on the project vulnerability, three comparative planning scenarios were developed. For comparative analysis, in each scenario, only one aspect of the planning strategy was different from the base scenario. In the first scenario, the planning strategy pertaining to task assignment was changed. In the base scenario, there was only one single agent node for the geologist team and one agent node for the designer team. Tasks of laboratory tests and observing rock deformation were both assigned to the same geologist agent, and tasks of conducting initial design and revised design were both assigned to the same designer agent. In scenario 1, two more agent nodes were added as geologist and designer. Thus, division of labor was achieved (i.e., tasks of laboratory tests and observing rock deformation were assigned to the different geologists, and tasks of conducting initial design and revised design were assigned to the different designers). In the second scenario, the planning strategy pertaining to the decision-making authority of the step length was changed. In the base scenario, the designer should report the corresponding information (e.g., initial design, revised design and rock deformation) in the current section to the project manager and wait for the project manager to make the decision on the step length for the next section. In scenario 2, the decision-making authority related to step length was given to the designer at the lower level, since he/she already holds all the required information for making the decision. Thus, in scenario 2, the project manager node and its corresponding links were removed from the project’s meta-network. In the last scenario, the planning strategy of redundancy in resources was adopted. In the base scenario, no redundancy was considered in the resource management strategy. In scenario 3, nodes of the additional electrical power system, shotcrete machinery, and boomer were added as backup resources. These resource nodes were linked with other related nodes in the project’s meta-network so that they could be used by the corresponding agents for specific tasks. Figure 3 shows all the meta-networks (without any perturbation) related to the four scenarios. Since different planning strategies were translated to different topologies of the project organization’s meta-network, differences in the numbers of nodes, links, as well as the network densities of meta-networks under different planning strategies can be observed. For each scenario, vulnerability assessment was conducted following the same procedures. The effectiveness of different planning strategies was then evaluated.

Figure 3. Meta-networks of the Tunneling Project under Different Planning Strategies
3.2 Results

Figure 4 shows the results related to one run of vulnerability assessment for the tunneling project in the base scenario. In this specific run, no multiple-effect uncertain events happened. However, several single-effect uncertain events happened simultaneously. The safety supervisor left the position and the support installation crew failed to complete the tasks in the project. The geologist didn’t have access to the latest version of rock quality designation index, which led to difficulty in accurately determining the rock type. Also, there was a delay in the delivery of materials to the jobsite, including explosive, initial support, concrete and reinforcement. Finally, the boomer equipment which facilitates the tasks of applying shotcrete and installing support didn’t function properly during the project. In this specific circumstance, the project meta-network was pushed away from its original stable state, as shown in Figure 4. The network efficiency was decreased from 1 to 0.625, which means after the perturbations mentioned above, only 62.5% of the tasks could be completed if no adaptive or restorative actions were taken. Thus, the project vulnerability to the uncertain events assessed in this run is 0.375.

Figure 5 shows the results of vulnerability assessment in the total 30 runs of the Monte Carlo simulation for the base scenario. Figure 5(a) is a boxplot for the vulnerability values in different runs. Each data point shows the vulnerability obtained in one run. The interquartile range box indicates that 25% of the vulnerability values in the 30 runs are less than 0.3645, and 75% of them are less than 0.5. The boxplot also suggests the values of vulnerability obtained in the 30 runs are normally distributed. Figure 5(b) shows the bell curve of the distribution. With the mean value (0.4111) and standard deviation (0.1092) of the 30 samples, the average vulnerability of the project organization to the uncertainties in the case can be predicted. For example, with a 95% confidence interval, the average vulnerability of the tunnelling project under the base scenario to the identified uncertainties is between 0.3703 and 0.4519. A higher level of vulnerability implies more possible losses when facing uncertainties. Thus, construction project companies can use the results of the ex-ante vulnerability assessment to predict the possible disturbance magnitude of project against uncertain events and develop corresponding contingency plans.

Figure 4. Changes in Network Efficiency in One Run of Monte Carlo Simulation for the Base Scenario

Figure 5. Project Organization’s Vulnerability for the Base Scenario
The other component of the analysis was to evaluate the effectiveness of different planning strategies in reducing vulnerability of project organization to the uncertainty-induced perturbations. Figure 6 shows the vulnerability of the tunneling project in different scenarios related to planning strategies. The interval plots in Figure 6 depict the mean values of multiple runs of the Monte Carlo simulation for each scenario with a 95% confidence interval. The effectiveness of the planning strategies related to task assignment, decision-making authority and resource management was evaluated by calculating the decreases of the project organization’s vulnerability in different scenarios. From the results, it is obvious that division of labor adopted in scenario 1 is the most effective planning strategy which decreases the vulnerability of the project organization in the base scenario by 16.57%. This is due to the fact that when each agent or agent crew is assigned for one specific task and role, the impact of perturbations on single agent node is limited. The planning strategy of considering redundancy in resource also shows the capability in reducing the vulnerability of project organization. Compared with the base scenario, the mean value of the vulnerability assessed in the samples of scenario 3 is reduced by 12.16%. When the planning strategy of resource redundancy is considered, the project organization becomes more robust especially against resource-related perturbations, as the backup resource could help to maintain the efficiency of project network. The planning strategy related to decision-making authority doesn’t show significant effectiveness in this case. The vulnerability is decreased only by 0.34% in average when adopting the planning strategy of decentralized decision-making authority in scenario 2 compared with the base scenario. As a conclusion, in this tunneling project, the planning strategies of division of labor and redundancy in resource have the most significant impact on reducing project organization’s vulnerability. This kind of information can help the decision makers to select the most effective planning strategies from a list of options in order to decrease the vulnerability of the project organization. Adopting alternative planning strategies usually implies more input into the project (e.g., hiring more agents, ordering backup resource). Knowing the effectiveness of alternative planning strategies provides the basis for the decision makers to conduct cost benefit analysis and make the final decision on whether to adopt certain planning strategy or not.

![Project Organizational Vulnerability under Different Planning Strategies](image)

### Figure 6. Project Organization’s Vulnerability under Different Planning Strategies

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>StdDev</th>
<th>95% CI</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Scenario</td>
<td>30</td>
<td>0.4111</td>
<td>0.1092</td>
<td>(0.3703, 0.4519)</td>
<td>-</td>
</tr>
<tr>
<td>Comparative Scenario 1</td>
<td>30</td>
<td>0.343</td>
<td>0.1186</td>
<td>(0.2987, 0.3873)</td>
<td>16.57%</td>
</tr>
<tr>
<td>Comparative Scenario 2</td>
<td>30</td>
<td>0.4097</td>
<td>0.1267</td>
<td>(0.3624, 0.4570)</td>
<td>0.34%</td>
</tr>
<tr>
<td>Comparative Scenario 3</td>
<td>30</td>
<td>0.3611</td>
<td>0.1235</td>
<td>(0.3150, 0.4072)</td>
<td>12.16%</td>
</tr>
</tbody>
</table>

### 4 CONCLUSION

Traditional methods of risk analysis in construction projects are based on qualitative, descriptive and reactive approaches. In this paper, an integrated framework for ex-ante assessment of vulnerability to uncertainties in complex construction project organizations is proposed. The proposed framework provides
a novel approach for quantitative assessment of project vulnerability based on the theoretical underpinnings of network theory. It provides a quantitative basis for ex-ante assessment of vulnerability and evaluation of planning strategies. The results of the integrated vulnerability assessment can be used for analysis of the benefits of alternative planning strategies and selecting the most effective planning strategies for reducing vulnerability under uncertainty. The application of the proposed framework will facilitate a paradigm shift toward ex-ante assessment of performance vulnerability in complex construction projects. It enhances the design and management of project organization toward proactive reduction of vulnerability. It also will enable creation of novel theoretical constructs for a better understanding of the links between planning strategies, complexity, and vulnerability in construction projects. This understanding will provide prescriptive findings and flexible strategies that lead to predictive assessment and proactive management of performance in construction projects.

References


AUTOMATED MONITORING OF HARDHATS WEARING FOR ONSITE SAFETY ENHANCEMENT

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² Department of Civil and Environmental Engineering, Myongji University, South Korea

Abstract: Construction is one of the most dangerous job sectors over the world. Any accidents that happen on the construction sites will bring the sufferings to the workers and their families and incur the delays and costs to the projects. Therefore, it is necessary for the contractors to monitor potential site safety issues and comply with existing safety regulations all the time. One of fundamental safety regulations is hardhat wearing. The wearing of the hardhats is always mandated and should not be violated anytime on the construction sites. In this paper, a novel method is proposed to facilitate the monitoring of whether any persons on the construction sites are wearing hardhats as required by the safety regulations. The method is built upon computer vision techniques. Under the method, human bodies and hardhats are first detected in the video frames captured by real-time on-site construction cameras. Then, their pair-wise matching is found. For those persons without the matching of the hardhats, they are identified as not wearing hardhats. The proposed method has been tested on real site videos. The test results showed that multiple persons could be monitored even if they are not wearing any real-time location sensors or tags. The test results demonstrate the potential of using live streaming or time-lapse construction site videos to facilitate the safety monitoring work on construction sites.

1 INTRODUCTION

Construction has been identified as one of the most dangerous job sectors. CBC News (2012) once reported that a total of 700 deaths occurred in the construction industry from 2008 to 2010, which almost accounted for 23.3% of all workplace fatalities. Also, the Association of Workers’ Compensation Boards of Canada (AWCBC) mentioned that there were more than 27,000 time-loss injuries in the construction industry each year from 2009 to 2010 (AWCBC, 2011). In order to provide a healthy and safe working environment for construction workers, several onsite safety regulations have been established by the governments. They specify the contractors’ responsibilities and duties on the construction sites, including the appropriate use of appropriate personal protective equipment (PPE). The contractors must ensure that the regulations are enforced. In Quebec, this job is assigned to onsite safety inspectors, called construction site health and safety management guarantors. The guarantors need to take every necessary measure to ensure the general contractors comply with the safety regulations.

Hardhats are one type of important PPE. Any individual person must wear a hardhat, when they enter to a construction site. For example, the Safety Code for the Construction Industry mandates that “any person on a construction site shall wear a certified safety hat in accordance with CSA Standard” (Quebec, 2014). The similar guideline or regulation could also be found in the OSHA (Occupational Safety & Health Administration). It stipulates that “Employees working in areas where there is a possible danger of head
injury from impact, or from falling or flying objects, or from electrical shock and burns, shall be protected by protective helmets” (OSHA, 2012). Therefore, it is one of top priorities for the safety inspectors to check and confirm all employees and site visitors wear hardhats all the time on the construction sites.

However, the statistic data indicated that that most workers who suffered impact injuries to the head were not wearing hardhats, even when performing their normal jobs on their regular worksites. The Bureau of Labor Statistics once noted that "hardhats were worn by only 16% of those workers who sustained head injuries, although two-fifths were required to wear them for certain tasks at specific locations" (OSHA, 2006). The reasons for not wearing hardhats could be various, such as discomfort while wearing hardhats, disassociation with the safety issues, etc. For example, workers might take off their hardhats to cool off, when the temperature is high.

Therefore, it is necessary for the safety inspectors to monitor all persons on the site to wearing hardhats all the time. In order to facilitate the inspectors' monitoring work, this paper proposed a novel method for checking whether persons on the construction sites are wearing hardhats or not. The proposed method is built upon the live streaming or time-lapse construction site videos with computer vision techniques. It mainly include the detection of human bodies and the detection of hardhats. When the human bodies and hardhats are detected, their pair-wise matching is performed, so that those persons without wearing hardhats could be identified.

The effectiveness of the proposed method has been tested with real site videos. The test results showed that the method could monitor the wearing of hardhats on multiple persons simultaneously. These persons do not have to be tagged. This nature makes the method affordable to be used at most construction sites. The proposed method is expected to facilitate the safety inspectors' work and enhance construction site safety. The site safety enhancement could bring several benefits to the contractors, including increasing workers' productivity and reducing project direct and indirect costs due to the cost saving from preventing construction accidents.

2 RELATED WORK

2.1 RTLS-based Site Safety Enhancement

The enhancement of onsite construction safety has been increasingly received attentions of researchers and industrial practitioners. Several research studies have been initiated for the purpose of adding an extra level of proactive safety measures using real-time location systems (RTLS). These RTLS typically relied on the remote sensing techniques, such as radio frequency identification (RFID), global positioning system (GPS), wireless local areas networks (WLAN), and ultra-wide band (UWB).

Most RTLS have been used for proximity warning. Ruff (2007) compared different RTLS in his report for evaluating and implementing proximity warning systems on surface mining equipment. Moreover, Teizer et al. (2010) presented their findings of using Very-High Frequency (VHF) active Radio Frequency (RF) technique to warn ground workers and equipment operators once they are too close in proximity. In the work of Carbonari et al. (2011), they relied on UWB tracking data to implement a proactive virtual fencing system, and demonstrated its capability of reinforcing safety management policies. Also, Chen and Teizer (2013) integrated the real-time GPS and UWB location data into a virtual reality environment representing a construction site for monitoring construction safety.

In addition to the use of RTLS for the proximity warning, the systems could also be adopted for other purposes related to construction safety enhancement. Kelm et al. (2013) designed an RFID-based portal to check whether the workers' personal protective equipment (PPE) complied with the corresponding specifications. Aguilara and Hewageeb (2013) developed an IT based safety management system using web cameras, barcodes and RFID tags installed on construction equipment.

However, existing RTLS come with limitations, when they are used for monitoring the wearing of hardhats on construction workers. First, in order to check whether construction workers are wearing hardhats, it is at least necessary to attach a tag or sensor on each person and hardhat. In addition, the RTLS are mainly
used for real-time location tracking. Therefore, it is difficult to use the RTLS to identify whether the hardhats are appropriately used, considering that workers might take off their hardhats and put them aside while doing their jobs.

2.2 Video-based Site Safety Enhancement

Live streaming or time-lapse video cameras are increasingly placed on construction sites, considering their acceptable return on investment (Bohn and Teizer, 2010). For example, Hydro-Quebec has recently decided to install video cameras on their construction sites to facilitate the monitoring of daily construction activities. The live streaming or time-lapse videos collected by the cameras record project ongoing construction activities on the construction sites. Therefore, they are useful for monitoring construction site safety issues. Abeid and Arditi (2002) relied on live streaming or time-lapse videos collected on construction sites to investigate construction accidents. Liaw et al. (2012) used the live stream or time-lapse videos to create safety training and education media resources.

So far, several research studies have been initiated to investigate the potentials of live streaming or time-lapse videos to create onsite safety alert systems built upon computing techniques. For example, Steele et al. (2003) once proposed to mount a stereo camera on the rear of an off-highway dump truck, and the stereo videos could help the truck driver identify possible on-site obstacles on the mining site. In addition to mounting stereo cameras on the equipment, the cameras are also placed on the site to capture and analyze workers’ unsafe actions, considering these actions might result in accidents. Han and Lee (2013) and Han et al. (2013) relied on Kinect-style cameras to monitor whether construction workers on a ladder are leaning too far to one side or reaching too far overhead to prevent the falls from the ladders.

Similar to the work presented in this paper, Giovanni et al. (2009, 2011) designed a vision-based system to support the workers’ safety by checking the presence of those workers without wearing hardhats on construction sites. In their work, they first used a pedestrian classifier with covariance descriptors to recognize construction workers in video frames, and then used the head and hard-hat detectors. However, there is one major limitation in their system. The system could not function correctly, when the workers on construction sites wear white hardhats. The failure of the detection of white hardhats makes the system generate a lot of false alerts. As illustrated in Figure 1, the safety alert issued by their system (Giovanni et al. 2009, 2011) was false, since the person identified as not wearing a hardhat (red box) was actually wearing a hardhat.

![Figure 1: Failure of detecting white hardhats](image)
3 OBJECTIVE AND SCOPE

The overall objective of this paper is to evaluate the safety issue of whether individuals on construction sites are wearing hardhats as required by existing safety regulations could be monitored with live streaming or time-lapse videos. If any individual on the construction site is not wearing a hardhat, an alert will be produced to ask for the onsite safety inspector's attention. This way, it could facilitate the routine inspection work performed by the onsite safety inspector.

This paper only focuses on the wearing of hardhats, considering the hardhats are one type of important personal protective equipment (PPE) items on the construction sites. They could protect the workers from impact and penetration hazards as well as from electrical, shock and burn hazards. Although the hardhats are play an important role on head protection, individual persons on the construction sites might still be careless about wearing the hardhats, even including construction workers themselves. Moreover, it is difficult for a safety inspector to monitor whether each individual person on the construction site is wearing the hardhat all the time.

4 PROPOSED METHODOLOGY

In order to achieve the objective mentioned before, a novel vision-based method is proposed for monitoring any individual persons who are not wearing the hardhats on the construction sites (Figure 2). The method includes three steps, as illustrated in Figure 2. The human bodies and hardhats are first detected based on their histogram of gradient (HOG) features. Then, their pair-wise matches between the detected human bodies and hardhats are found based on their geometric and spatial relationships. If a human body detection region has no corresponding hardhat detection match, it means that the person in the human body detection region is not wearing a hardhat. Therefore, this human body detection region is highlighted for the onsite safety inspector's attention.

![Diagram](image)

Figure 2: Proposed methodology

4.1 Human Body Detection

The purpose of the human body detection is to locate individual persons on the construction site, such as engineers, labourers, carpenters, etc., in video frames. In order to speed up the human detection process, the background subtraction proposed by Macfarlane and Schofield (1995) is first used to extract the moving blobs in the video frames. The moving blobs are further analyzed with the morphological operations (i.e. dilation and erosion) to remove the small sized ones. Then, the human body detection is limited to the remaining blobs as the foreground regions.

As for the detection of human body in the foreground regions, the detection includes two stages as suggested by researchers such as Dalal and Triggs (2005) and Felzenszwalb et al. (2010). First, a large number of positive training samples (human body images) and negative samples (non human body images) are collected and used for the supervised training of a support vector machine (SVM). Once the training is completed, the detection of human bodies in the test video frames works by sliding a search window across the foreground regions. The HOG feature is extracted from each window and classified by the SVM as a human body or not.
4.2 Hardhat Detection

Hardhats are typically made of fiberglass and rigid plastic. On the one hand, the colors of the hardhats could be white, brown, green, blue, orange, red, etc. to indicate the roles (e.g. managers, engineers, superintendents, and laborers) of the wearers on construction sites. Considering the colors could vary, it would be difficult to rely on the color information as detection cues. On the other hand, most hardhats have similar cap-style shapes. They are rigid and do not have deformations.

Therefore, hardhat detection here is similar to the detection of human bodies. The HOG features of the hardhats are extracted from the video frames as the detection cue, especially considering that the HOG feature is capable of describing detailed shape information in an efficient way. Moreover, the effectiveness of the HOG features has been well-proven in many research studies for shape-based object detection. The hardhat detection includes two stages. First, hundreds of construction site images with different poses of hardhats are collected as a training database, where the hardhat HOG features are calculated and input into an SVM for the supervised training. The training results are compiled into a hardhat detection model. In order to detect hardhats in a video frame, the HOG features extracted from the test frame are input to the detection model, and the best possible placements of the hardhats could be determined. The detection model here only uses the HOG features without color cues. Therefore, it could detect the hardhats with different colors.

4.3 Human Body and Hardhat Pair-wise Matching

After the detection of human bodies and hardhats, the detected hardhats should be matched to the detected human bodies to find out those persons who are not wearing hardhats on the construction sites. The matching here is mainly based on the spatial relationships between the detection regions of the hardhats and human bodies. Typically, the detected hardhat should be located in the upper area of the detected human body region, if the person in the detected human body region is wearing a hardhat. If there is no matching that could be found on that person, it indicates that the person is not wearing a hardhat. Then, a safety alert is produced to ask for the safety inspector's attention. One example of the pair-wise matching between the detected human bodies and hardhats could be found in Figure 3. In the figure, the matches of the hardhats for three persons in the right could be successfully found. As a contrast, the pair-wise matches of the hardhat for the two persons in the left could not be found, since they are not wearing hardhats.

5 IMPLEMENTATION AND RESULTS

The method was implemented and tested with real site videos captured by a Canon VISXIA HF S100 at a project site in Atlanta. The site was managed by Barton Malow Company. The test videos includes a total...
of five persons. Three of them were wearing hardhats on the site and two were not wearing hardhats for
the evaluation purpose. The test video was 166-second long, and recorded with 20 frames per second
(fps) containing 3,320 frames. The resolution of the videos is fixed at 768 pixels by 432 pixels.

5.1 Results of Human Body Detection and Hardhats Detection

Figure 4 illustrates the results of detecting human bodies and hardhats in the test video frames. Most
human body detections made by the method are correct, although the method missed some human body
detections (i.e. the persons in the video frames are not detected by the method). The correct detection of
human bodies is more important than the missed detection in terms of monitoring whether a person is
wearing a hardhat or not on the construction site. If the method could only successfully detect a person
every 10 frames, the miss rate is high, but it is still able to monitor whether the person is wearing a
hardhat once in a second. On the other hand, if the correct detection rate is low, it increases the chances
of false alarms. For example, if the method misrecognizes tree branches as a human body, a false alarm
will be issued, since the hardhat could not be detected in the detection region of that ‘person’.

![Figure 4: The detection of human bodies and hardhats](image)

Compared with the human body detection, most hardhats in the test video frames could be detected by
the proposed method. However not all the detections are correct. The strategy for the hardhat detection is
to reduce the detection miss rate. The low detection miss rate is more important than the correct hardhat
detection rate in terms of monitoring whether a person is wearing a hardhat or not on the construction site.
In other words, most false hardhat detections do not significantly affect the performance of issuing the
final safety alerts, when persons are not wearing hardhats. The reason is mainly due to difficulty in
establishing the links of the incorrect hardhat detection results to the detection of any human bodies.

5.2 Performance of Safety Alerts for not Wearing Hardhats

When there is no hard detected in a human body detection region, it indicated that the individual person
in the human body detection region is not wearing a hardhat. Therefore, a safety alert should be issued o
highlight the person for the onsite safety inspector’s attention. In order to measure the performance of the
safety alerts issued by the proposed method, the issued safety alerts are manually classified as true
positive (TP) alerts, false positive (FP) alerts, and false negative (FN) alerts. The TP alerts are the alerts
that should be issued in reality. The FP alerts are the alerts that do not have to be issued in reality. The
FN alerts are the alerts that should be issued in reality but the alert is not issued by the method. Their
definitions have been illustrated in Table 1. Based on the number of TP, FP, and FN safety alerts, the
precision and recall for issuing the safety alerts could be calculated using the following equations.

[1] Precision = TP / (TP + FP)

[2] Recall = TP / (TP + FN)
Table 1: Definition of TP, FP, and FN safety alerts

<table>
<thead>
<tr>
<th>Category</th>
<th>Issuing the alert based on the method</th>
<th>Issuing the alert based on the safety regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>FP</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>FN</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

According to the test results, it was found that the precision for issuing the safety alerts reached 94.3%, while the recall for issuing the safety alerts was 89.4%. The 94.3% precision means that 5.7% of the alerts issued by the proposed method are false. The 89.4% recall indicates that nine out of ten individual persons without wearing hardhats could be successfully monitored when applying the proposed method on construction sites. Both high alert precision and recall show the effectiveness of the proposed method on monitoring whether individual persons on the construction site are wearing hardhats as required by existing safety regulations, such as the Safety Code for the Construction Industry and the Safety and Health Regulations for Construction.

6 LIMITATIONS AND DISCUSSION

There are several limitations found from the tests. Most limitations are more or less associated with the detection of human bodies on a construction site. First, the human body detection is limited to the detection of the persons with standing or walking postures on the construction sites. So far, it is difficult to detect the persons with other postures. For example, when the workers are crouching down, bending, or sitting, it is difficult for the method to detect them. Therefore, the detection template used by the method should be extended to include more training samples of the workers with different postures.

Second, the occlusion is one of the major obstacles that could affect the performance of the proposed method on monitoring the wearing of the hardhats. If the persons are partially or fully occluded on the construction site, the monitoring with the proposed method will fail. The proposed method could only monitor the workers when they are visible in the camera view. Therefore, it is important to install an appropriate number of construction cameras and select the appropriate positions for installing the cameras on a construction site.

In addition, the proposed method relied on the background subtraction to speed up the detection of human bodies. The purpose of the background subtraction is to limit the detection of human bodies only in the foreground blobs in motion. This means only moving persons on the construction site could be detected. If they are static without any motions, the workers are filtered out through the background subtraction, since they are considered as the background. Considering the workers could always be detected when they just enter into the camera view, the integration of the detection and tracking of onsite persons might provide one possible solution to continuously monitor the persons even if they are static.

7 CONCLUSIONS AND FUTURE WORK

Existing safety policies and regulations could enhance construction site safety; however, these policies and regulations might not be strictly followed on the construction site. For example, construction workers might slip up and not exactly keep the requirements in the policies and regulations due to fatigue, distractions, carelessness, etc. Therefore, it is necessary to monitor any violations of the safety policies and regulations on construction sites. Currently, this safety monitoring job is manually performed by onsite safety inspectors (e.g. construction site health and safety management guarantors in Quebec). It might be difficult for the inspectors to monitor all safety policy and regulation violations on the construction site at any time through manual monitoring.

In order to facilitate the safety inspectors’ monitoring work, this paper proposed a novel, vision-based method for automatically monitoring whether any individual persons wear hardhats on the construction site as required by existing construction site safety polices and regulations. The method includes three
main steps: 1) human body detection, 2) hardhat detection, and 3) human body and hardhat pair-wise matching. If there is a human body detection area without the corresponding hardhat detection matched, it means that the person in the area is not wearing the hardhat. Therefore, a safety alert will be issued.

The method has been tested with the video frames captured at a real site. According to the test results, it was found that the overall precision and recall for issuing the safety alerts with the proposed method could reach 94.3% and 89.4%. The high precision and recall indicate the effectiveness of the proposed method on monitoring whether individual persons are wearing hardhats on the construction site. Future work will focus on the following two areas. First, the monitoring of wearing other types of personal protective equipment (safety vests, boots, etc.) on the construction sites will be investigated using vision technologies. Also, more investigations regarding the detection of human bodies with different postures will be performed in the future.

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