CHANGE MANAGEMENT

WITH BUILDING INFORMATION MODELS: A CASE STUDY

by

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ABSTRACT

Successful management of design changes is critical for the efficient delivery of construction projects. Building Information Models (BIM) and the use of parametric modeling provide significant benefits in coordinating changes across different views in a model. However, coordinating changes across several discipline-specific models is significantly more challenging to manage.

In this thesis, I present a case study that used observation-based empirical research methods to investigate current practices and the requirements of practitioners in conducting change management during the design and construction of a building project. The case study examines change management in the context of a multi-disciplinary collaborative BIM environment during the design and construction of a fast-track project. I documented the design changes, analyzed the change management processes and evaluated existing BIM tools in support of this process. Using examples from the case study, I identified the characteristics of design changes required for tracking the history of changes and understanding the consequences of changes. I developed an ontology of changes based on the identified characteristics and patterns in the observed changes. The ontology characterizes design changes based on changed component attributes (the geometry, position, and specification), dependencies between components (analytical and spatial), level of changes (conceptual, primary and secondary), timing of changes (design, procurement or construction stages) and time and cost impacts of changes. Based on the developed ontology, I further categorized numerous examples of changes encountered throughout the design and construction of the building in a taxonomy of changes. I then proposed a computational approach for tracking the consequence of changes in an information model.

This research provides a common understanding of design change characteristics for practitioners who develop or utilize BIM tools for managing changes. The results of this study provide some possible directions for future developments in change management systems, particularly in reference to a BIM-based delivery process. Additional research is needed to implement and test these characteristics in a decision support system, and to analyze different types of changes across different types of projects.

PREFACE

An earlier version of Chapter 3 has been accepted for publication. Pilehchianlangroodi., B., and Staub-French, S., ASCE Construction Research Congress (CRC), 2012. I wrote the manuscript with the guidance of Dr. Staub-French. Subsequent editing and refinement was performed by Dr. Staub-French before the finalization.

Panoramic photos presented in Appendix 1 were taken by Amir Mohammad Tangestani Zadeh, my friend and my colleague at UBC.

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To my dear Nahid …

CHAPTER 1
THESIS OVERVIEW

1.1 Introduction

Change is an integral part of building design as the design process is iterative in nature and involves the exploration and analysis of many alternatives (Tory, Staub-French, Po, & Wu, 2008). Changes are not limited to the design phase, but often continue throughout the construction phase due to concurrency of design and construction, particularly on fast-track projects, or in order to remove inconsistencies and enhance quality. Studies have shown that 20-25% of the construction period is lost due to deficiencies in design (Undurraga, 1996) and 78% of quality problems are attributable to design (Koskela, 1992). Therefore, successful management of design changes is of vital importance for the efficient delivery of construction projects.

During such an iterative process, the content and structure of design information is not static but subject to continual changes. In this dynamic environment, information models that are developed to coordinate design changes must be as flexible and dynamic as the design process itself (Leeuwen, & de Vries, 2000). This is a significant challenge in the development of computer-based information models.

Building information models (BIM) are integrated databases that have the capacity to process dynamic data. They combine a design model (geometry and data) with a behavioral model (change management) to enable real-time coordination of the information in every view of the model (Autodesk, 2007). Thus, they have the potential to coordinate changes throughout the dynamic process of building design.

Although dynamic data are processed reasonably well in a single BIM with all the necessary parameters explicitly defined, changes across inter-related multi-disciplinary designs that reside in a federated environment are significantly more challenging to manage. Hence, many BIM projects still rely on paper-based printouts of 2D drawings, as it is difficult to determine what has changed in the model with existing tools. These demonstrate the need to improve BIM-based change management systems for effective coordination of multi-disciplinary models throughout the dynamic process of building design and construction.

In this thesis, I describe a case study that used observation-based empirical research methods to investigate current practices and the requirements of practitioners in conducting change management throughout the project delivery process. The project studied was the Pharmaceutical Building project, which is being constructed on the University of British Columbia (UBC) campus. This $150 million project provides 18,000 m^2 that includes a variety of teaching and learning spaces, a pharmacist clinic and three floors of research spaces. Building Information Modeling (BIM) was used throughout design and construction, which allowed us to evaluate the efficiency of BIM tools for management of changes in a multidisciplinary environment on a fast-track project.

I conducted the case study of the Pharmaceuticals project over a one-year period. Data was collected based on observations of BIM coordination meetings, extensive site visits, and communication with various design and construction professionals. During this period, I attended and recorded more than forty BIM coordination meetings and conducted more than eighty site visits and documented numerous examples of changes encountered throughout design and construction. I then analyzed this data to identify, categorize and generalize the different characteristics of the observed changes to develop an ontology of changes. The ontology focuses on facets that would be essential in establishing a BIM-based change management system that is capable of tracking the history of changes between revised models and the consequences of potential changes. Finally, I proposed a computational approach for tracking the consequence of changes in an information model. The results of this study provide some possible directions for future developments in change management systems, particularly in the context of a BIM-based delivery process.

This chapter describes the literature review, the research objectives, and the research methodology. It concludes with a summary of the manuscript.

1.2 Literature Review

Research on change management systems has tended to focus on best practice recommendations for managing changes, change management systems, evaluating the change effects on certain project elements, the role of IT in change management and modeling the change process in construction, which I summarize below.

Change management best practices, policy guidelines and procedures

Examples of such guides include best practice guides and recommendations for the effective management of changes (Construction Industry Institute [CII], 1994) and (Construction Industry Research and Information Association [CIRIA], 2001). Cox, Morris, Rogerson & Jared (1999) and Stocks & Singh (1999) provided procedures for issuing and analysing the rate of Change Orders.

Change management systems

Ibbs, Wong & Kwak (2001) presented an advance change management systems. Park & Peña-Mora (2003) adapted Dynamic Planning and control Methodology (DPM) to assist in the preparation of construction plans and to provide policy guidelines to manage changes.

Evaluating the change effects on certain project elements

Examples of studied project elements include the effect of the size of change and its impact time on a project (Ibbs, 1997); the impact of change orders on labor productivity (Hanna, Russell & Vandenberg, 1999); the risk of changes to safety regulations (Williams, 2000); productivity losses caused by change order impacts (Lee, Hanna & Loh, 2004).

The role of IT in change management

Ahmed, Sriram & Logcher (1992) presented an integrated environment for computer aided engineering to facilitate collaborative-engineering design using object-oriented databases. Mokhtar, Bedard & Fazio (1998) provided a model for handling design changes in a collaborative environment, which is capable of circulating design changes and tracking past changes. Soh & Wang (2000) proposed an approach constraint methodology based on a parametric technique that can facilitate the coordination of engineering design information through managing design changes with the help of a parametric coordinator. Charoenngam, Coquinco, & Hadikusumo (2003) presented a web-based change management system to support documentation practice, communication and integration between different team members in the change order workflow.

Developing Information Models for Managing Changes

A number of other research efforts, such as those carried out by Mokhtar, Bedard & Fazio, (1998) and Hegazy, Zaneldin & Grierson (2001) focused on developing information models intended for storing design information, recording design rationale, and managing design changes to help the coordination of design information through the management of design changes. Mokhtar et al. (1998) presented a central database, which carried building components data, to track past changes and assist in the planning and scheduling of the future ones. Hegazy et al. (2001) attempted to improve design coordination and control over changes by automating communication of changes to affected parties through preset communication paths. They built an information model around a central building components library (BCL) to create the building project hierarchy (BPH) and store related components performance criteria and design rationale so each building component in the model could have preset communication paths to automatically communicate changes.

BIM and Model Based Coordination and Change Management

BIM is taking an extended role in the construction industry that need to keep up with the increasing demand for improving productivity, efficiency, quality and sustainable development (Arayici et al, 2011). Considering this evolving role there is a need to improve understanding of change management systems in the context of a BIM environment. A few research efforts have attempted to address this need, such as Wang, Akinci & Garrett (2007) and Akcamete, Akinci & Garrett (2009). However, the issue of managing design changes using BIM has not received as much attention in the literature. Wang et al., (2007) presented a semi-automated approach for detecting the differences between versions of a data model (e.g., data exchange standards and task-specific data models) that can be utilized for rapid update of existing implementations of the model in AEC-related software. The presented approach incorporated a taxonomy for describing possible differences between two versions of a data model and provided a way to classify these differences. The provided taxonomy focus on the track of changes between revisions of the models and do not include characteristic that are important to identify time and cost impacts of changes. Akcamete et al., (2009) identified the types of changes that occur during the life cycle of a project, which had a particular emphasis on facility management and maintenance activities. They discussed some challenges associated with managing such changes and the relevant update of building information models. They also investigated how well commercially available systems address these challenges. I utilized similar approach in analyzing the changes that I documented during my data collections. I attempted to identify the common characteristics of the documented changes to classify them into a taxonomic ontology. However, the ontology that I developed in this study incorporates a broader range of facets and focuses on the characteristics that are essential to track history and consequence of changes.

In summary, considering the evolving role of BIM in design and construction of building projects, there is a need to better understand the requirements of change management systems in the context of a BIM environment and manage changes throughout design and construction of building projects, particularly as more projects are executed with a fast-track delivery method.

1.3 Research Objectives

The research objectives on this project were:

1) *Investigate current BIM-based change management practices using observation-based empirical research methods to develop an improved understanding of the practices, the needs of practitioners, bottlenecks and requirements.*

Throughout this research, I was in continuous communication with the project team and in particular people who were involved in Building Information Modeling. I attended BIM coordination meetings and observed the methods used for resolving design discrepancies and coordination of changes in information models. I also recorded numerous example of changes encountered in this process and investigated the challenges associated with the use of BIM for communication and implementation of these changes. I also conducted extensive site visits to explore the efficiency of BIM for communication of changes between design and construction teams and to explore the requirements and bottlenecks of this process.

2) *Identify the characteristics that are essential to track the history and the consequence of changes in an information model and develop conceptual approaches to assist with the automation of this process.*

I analysed the changes that were documented during the case study to identify the important characteristics and to recognize various spatial and analytical dependencies between the changed component attributes. I then attempted to categorize and generalize these facets based on the indentified patterns in the results in order to develop an ontology of changes. Based on the developed ontology, I then proposed a computational approach for tracking the consequence of changes in an information model.

3) *Assessment of state-of-the-art BIM tools in terms of successful management of changes in multi-disciplinary fast-track construction projects.*

During the course of my study, I attempted to used and evaluate the capabilities of existing BIM tools to manage the observed changes throughout the design and construction process. Specifically, I investigated the capabilities of Autodesk® Revit®, Navisworks®, Solibri Model Checker™ and Vico Doc Set Manager™. I examined these tools against the requirements of practitioners and explored their capabilities to overcome different barriers encountered in the course of the case study. An example of this effort was examining these tools for building a 4D dynamic as-built model, which contained the updated construction status of the model components within a specific period of construction. Another example was tracking the history of changes in a specific group of components, such as fire-rated walls, during the course of the project.

4) *Provide some possible directions for future developments in change management systems, particularly in reference to a BIM-based delivery process.*

Further research can be conducted based on the results of this study to improve BIM-based change management systems. The developed ontology of changes and the proposed computational approach for tracking consequences of changes can be an initiation into development of automated change management tools that are capable of tracking the history and consequence of changes in an information model. These possible directions for future developments and research are described in the conclusion of this study.

1.4 Methodology

Figure 1-1 shows a flow-chart diagram that presents the method that I used to achieve the research objectives discussed in the previous section. A brief description of each step is provided in this section.

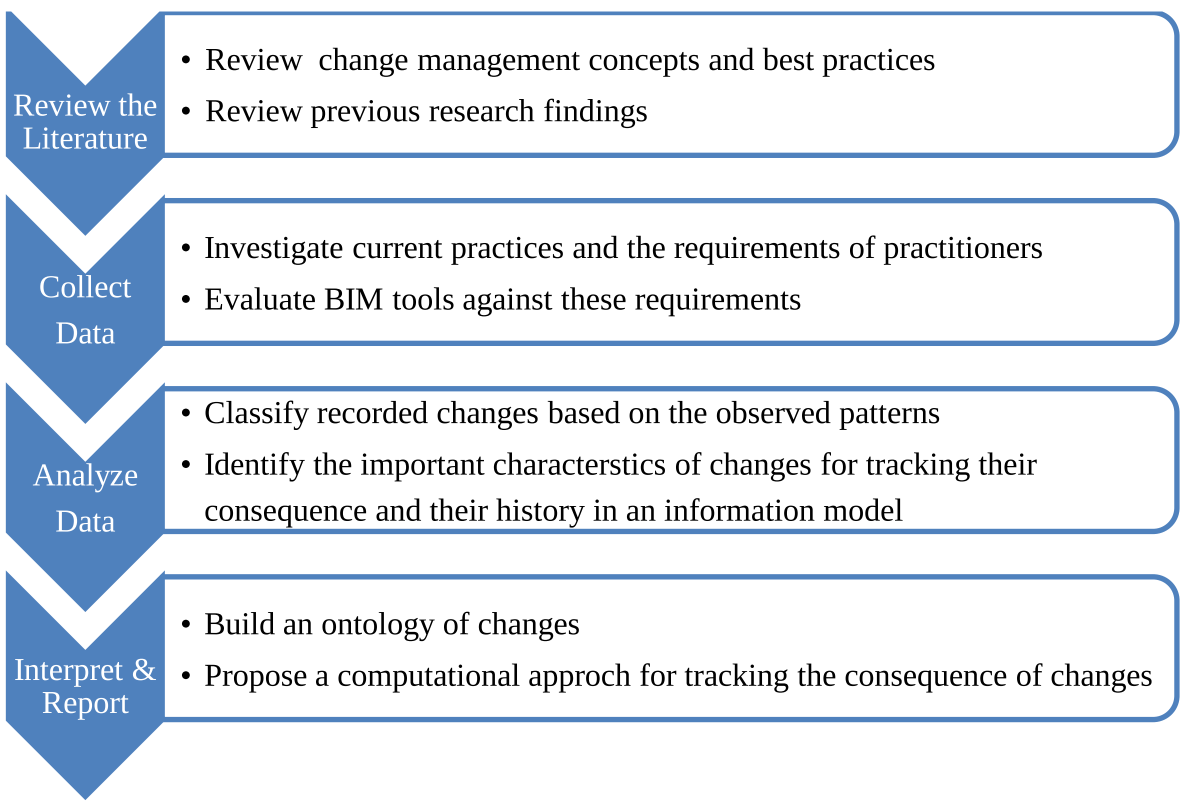


Figure 1-1 : Research methodology

1) Literature Review

I reviewed the available literature in the area of change management to identify the body of knowledge I required for the case study. In addition, the literature review provided me with an updated understanding of the current change management processes and the role that can be assumed for BIM in such processes. This formed a solid background for performing the case study, as well as the point of departure for my research. I also reviewed the literature related to BIM and model-based coordination to establish the basis for my data analysis and to recognize the requirements of change management systems in the context of a BIM environment. In particular, I initiated my data analysis based on the taxonomy presented by Wang et al., (2007) and the classification of version differences developed by Akcamete et al., (2009).

2) Data Collection

The data collection period took around one year. During this period, I used observation-based empirical research methods to investigate current practices and the requirements of practitioners in conducting change management during design and construction. I attended and recorded the BIM coordination meetings, conducted several site visits and documented numerous changes observed throughout the course of this project. I also evaluated the functionality and potential capabilities of BIM tools against the requirements of practitioners identified. I examined the capabilities of Autodesk® Revit® and Navisworks® for building a 4D dynamic as-built model to track the updated construction status of different components within a specific period of construction. Moreover, I tracked the history of changes in a specific group of components, such as fire-rated walls, both in the models (using Solibri Model Checker™) and in the drawings extracted from the models (using Vico Doc Set Manager™). I compared different barriers in each process, the clarity of the results, and the requirements and the limitations of each tool in this process.

3) *Data Analysis*

I further analyzed numerous examples of changes observed during the data collection period and attempted to categorize and generalize their different characteristics to develop an ontology of changes. The analysis of the recorded changes focused on facets that would be essential in establishing a BIM-based change management system that is capable of tracking the history and consequence of changes.

4) *Interpretation and Report*

Based on the results obtained from the analysis of collected data, I developed an ontology of changes. The developed ontology identifies various kinds of dependencies between changed component attributes and characterizes important facets of changes in a taxonomic hierarchy. I also proposed a computational approach for tracking the consequence of changes in an information model.

1.5 Overview of the Manuscript

In the next chapter, I introduce the project and provide the background information about the case study including the project details, design and construction teams and the project coordination and change management procedures.

In the third chapter, I categorize design changes, analyze the change management processes and evaluate existing BIM tools in support of this process. I describe five examples from the case study in detail to identify the characteristics of design changes required for tracking the history of changes and understanding the consequences of them. I later develop an ontology of changes based on the identified characteristics and patterns in the observed changes and investigate the relationships between these characteristics and their impacts on the project cost and schedule. Based on the developed ontology, I then categorized the other documented changes under a taxonomy of changes. At the end, I explain about the dynamic as-built model I developed during the course of this study. An earlier revision of Chapter Three will be published in the ASCE Construction Research Congress 2012 conference.

The fourth chapter presents a computational approach for the tracking consequence of changes in an information model in order to control the time and cost impacts of changes.

Next, in the concluding chapter, I summarize the results of this research and discuss my conclusions. I then provide suggestions for future research.

CHAPTER 2

THE CASE STUDY- BACKGROUND

2.1 Introduction

The presented case study focuses on the Pharmaceutical Building project, which is being constructed on the University of British Columbia (UBC) campus. The project budget is approximately $150 million. The 18,000 m^2 facility provides a variety of teaching and learning spaces range from lecture halls to classrooms and seminar rooms, as well as study spaces for students. The building also includes a pharmacist clinic and three floors of research spaces. Construction of the project started in mid 2010 and completion will be in late summer 2012. Coordination and constructability were key concerns in this fast-track project because of the overlapped design and construction in addition to the complex MEP systems.

Figure 2-1 shows the 3D rendered view of the building extracted from the architectural model and Figure 2-2 depicts the construction site and some general information about the project.

Figure 2-1 : Rendered 3D view of the building

(Source: Saucier + Perrotte Architects | Hughes Condon Marler Architects)

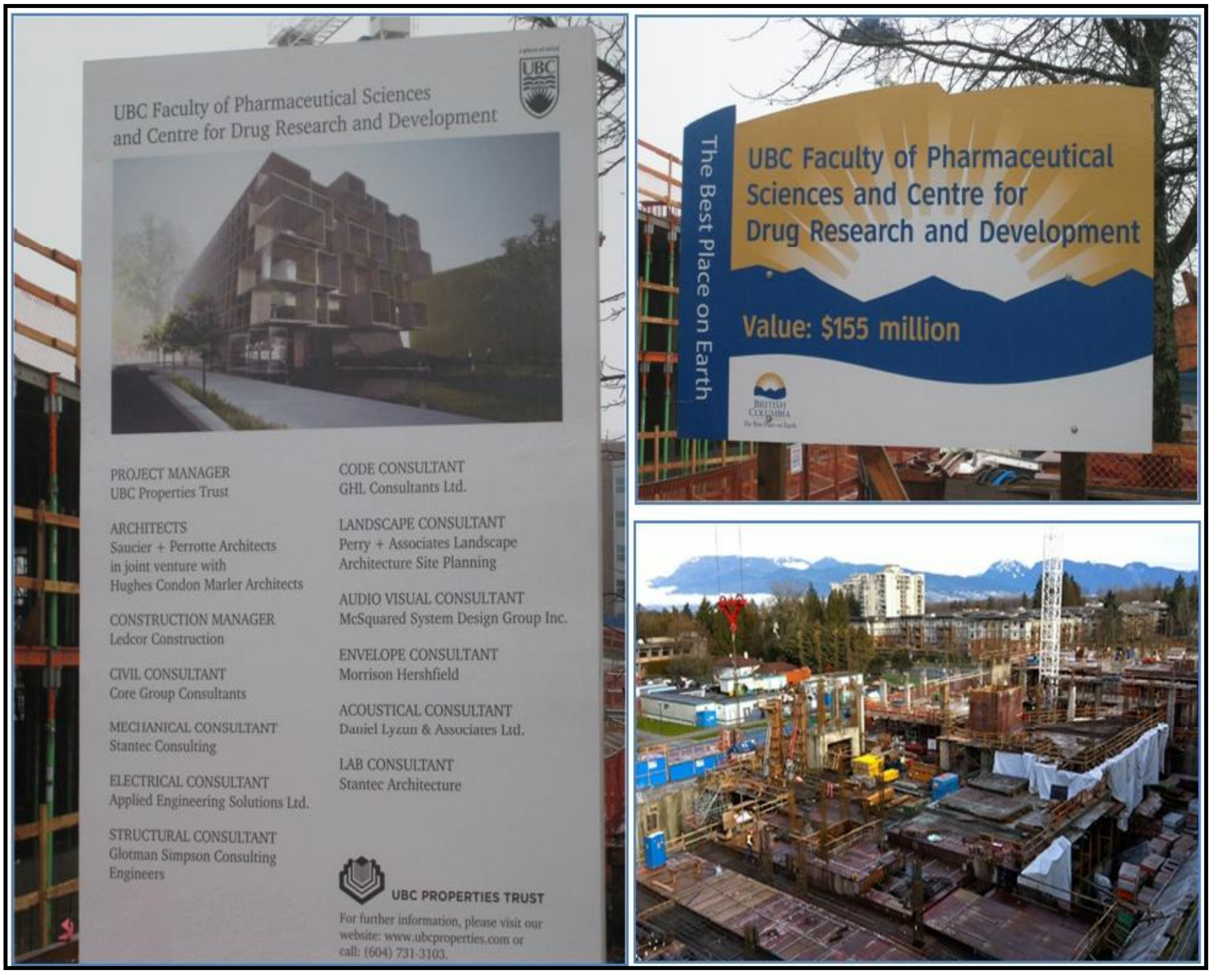


Figure 2-2 : UBC pharmaceutical building- project overview

In this project, BIM was used during design and construction. I participated in the design coordination process, which gave me the opportunity to evaluate the efficiency of BIM for managing design changes. The project team consists of the representatives from different companies involved in the project including the owner, the construction manager, architects, engineering consultants and construction sub-trades as listed in Table 2-1.

Table 2-1 : Project participants

Participant's Role	Participant's Name
Owner	UBC Properties Trust
Construction Manager	Ledcor Construction Ltd
Architect	Hughes Condon Marler Architects
Mechanical Consultant	Stantec Consulting Ltd
Structural Consultant	Glotman Simpson Consulting Engs
Electrical Consultant	Applied Engineering Solutions Ltd
Plumbing/ HVAC Subcontractor	Kith Plumbing and Heating Co Ltd
Electrical Subcontractor	Western Pacific Enterprises Ltd
Sheet Metal/Duct Work	Viaduct Sheet Metal Ltd
Dust control System	Dust Control Canada Inc
Steel Framing	CRS Construction Ltd
Fire Fighting System/ Sprinklers	Troy Life & Fire Safety Ltd

The data collection period took around one year. During this period, I observed the design and construction coordination process and evaluated the efficiency of BIM for managing design changes. The collected data was mainly based on observations in BIM coordination meetings, extensive site visits, and communication with design and construction groups. I attended and video recorded more than forty BIM coordination meetings and conducted more than eighty site visits. Figure 2-3 shows a number of photos taken during the site visits, which present the progress in the construction of the building during data collection period. More information and photos about the construction site are provided in Appendix 1.

Figure 2-3 : Different stages of the construction

The construction process could also be observed using an on-line access to a security camera, which had been setup on the roof of the adjacent building. The camera provided snapshots from the construction process 24 hrs a day and 7 days a week. Figure 2-4 shows a screenshot of the camera control panel. I used this camera to monitor construction activities while I was updating my dynamic as-built model. I prepared this model to record the latest status of construction in order to identify new design constraint imposed by the progress in construction. In general, such dynamic as-built models can be useful to track consequence of changes in fast-track projects where architects and engineers need to consider whether the component that would be affected by a change in design have been already constructed or not. More information about this model and its potential benefits in terms of controlling timing of changes is elaborated in Chapter 3.

Figure 2-4 : Screenshot from the control panel of the roof mounted security camera

Early BIM coordination meetings were held in the architect's office almost every other week. These meetings mainly focused on the coordination between the architect, the construction management team, and different engineering disciplines in terms of meeting various design requirements and resolving inconsistencies in design (Figure 2-5). An integrated BIM model was reviewed during each meeting and major clashes and design discrepancies were discussed. Based on the proposed solutions, each design group was responsible for incorporating the required changes in their design and updating their BIM prior to the next meeting. The updated models were uploaded on the project FTP servers (later changed to a secure online portal called TR-Trade) a couple of days prior to the next meeting. Further, the BIM coordinator, who was with the Construction Management team, combined the different models, performed clash detection, and prepared a clash report to be discussed during the next meeting. A sample of such report is presented in Appendix 2. The construction progress was also reviewed and design tasks were prioritized based on in progress activities.

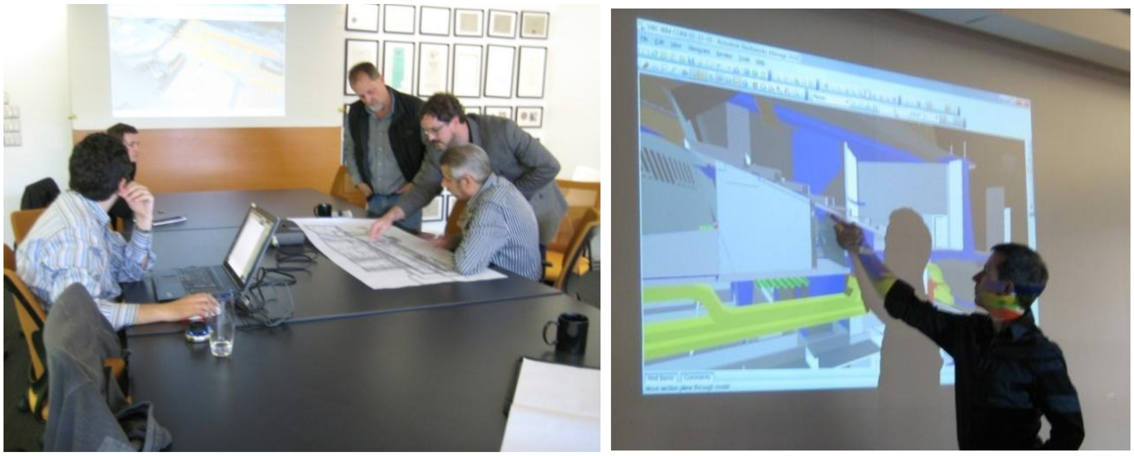


Figure 2-5 : BIM meetings in architect's office at design stage

After the design had sufficiently progressed and construction of the foundation had started, various subcontractors were also hired and engaged in the modeling process. In particular, the main Mechanical, Electrical, and Plumbing (MEP) subcontractors became extensively involved in the modeling process to increase the level of detail of the mechanical and electrical BIMs that were initially developed by the consultants. The main MEP subcontractors who were engaged in this process were piping, plumbing, HVAC, electrical cabling and lighting subcontractors. Due to the involvement of the construction subcontractors at this stage, the location of the BIM meetings also changed to the construction site. The meetings were held in our research-based BIM trailer. The trailer was equipped with two large LCD screens and smart annotation tools to write and mark on the screens. These tools provided an effective method of visualization and communication Figure 2-6 shows the outside and inside view of the trailer.

Figure 2-6 : BIM trailer at the construction site

The BIM meetings at this stage intended to enhance the constructability of the design by increasing the level of detail of the models and resolving conflicts and clashes (Figure 2-7). Moreover, some secondary systems and missing components, which were not included in the model during the detailed design (e.g. dust controls system and sprinklers), were added to the model at this stage.

Figure 2-7 : BIM coordination meetings in the BIM trailer at the construction site

2.2 Current Practices of Change Management

In this section, I explain my observations in terms of current practices in conducting change management throughout design and construction of the project.

Information Model and Document Control System

As discussed, during the early BIM coordination meetings, the updated models were uploaded on the project FTP server. However, only the initiator of each model often kept various revisions of them, as models were not included in the regular document control system. Thus, although there were several copies of models on the FTP server, there were no specific file naming procedure to keep different versions of uploaded models, and the initiators of the model sometimes overrode the older revisions when they uploaded the new version. Therefore, at this stage, tracking the history and timing of changes in different engineering models were mainly performed by the separate engineering firms engaged in the design. However, the filing system was improved when the construction manager team adopted a secure online portal, TR-Trades plan room, which provided different project participants with secure online access to the projects documents. Consultants and trades were able to upload their models and had access to other models from the different locations via the internet. The system maintained all uploaded files and was able to track who, why and when users uploaded a new file in the system. The integrated model prepared for the purpose of clash detection and the clash detection reports were uploaded into the system after each BIM coordination meeting. Figure 5 shows a screenshot from the project filing hierarchy made in the TR-Trade system.

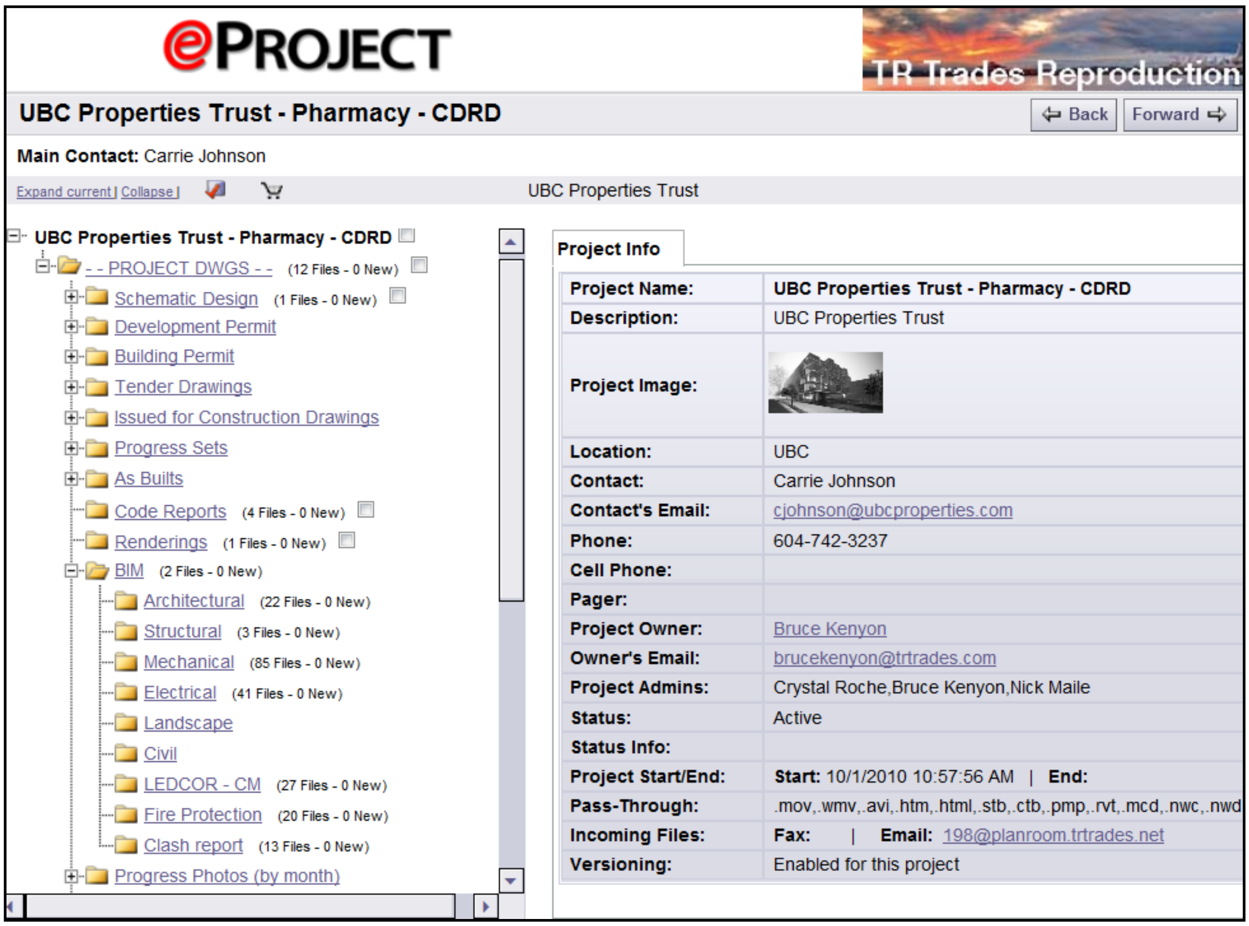


Figure 2-8 : Project filing system portal (TR-Trades)

Linkage between Information Models and Extracted Drawings

Most of the engineering drawings, including plan views, elevations and sections, were extracted from the model and stored in the information model. These different views were automatically consistent - in the sense that the objects were all of a consistent size, location, specification - since each object instance was defined only once and views were automatically updated while a change was made in any component. This drawing consistency eliminated many possible errors while a change happened.

Furthermore, considering that changes in the drawings were often marked by revision clouds in each information model, which also contained the latest revision of the drawings, indirectly contained some history of changes too. Thus, the comparison of the models corresponding to each revision could provide a way to track changes during the evolution of the design. However, this kind of tracking was only possible when information models corresponding to every official issue of the drawings were collected and tracked systematically. However, only a limited number of changes that were marked in the extracted drawings could be tracked by this method. Tracking unmark changes was difficult and time consuming and was another challenge for the project participants. I tried to address this challenge by tracking the history of changes in a specific group of components, such as fire-rated walls, both in models (using Solibri Model Checker™) and in the drawings extracted from the models (using Vico Doc Set Manager™). The benefits of each method and the barriers in each process will be elaborated in the next chapter.

Communication of Changes with Construction Team

During the course of the project, I recognized the different methods that were employed to communicate changes between design and construction groups. This communication was partly by the means of typical method such as official revision of drawings, Supplementary Instructions (SIs), and coordination meetings. Another common way to update construction team on the latest design changes was the use of Progress Sets. Progress sets were informal sets of drawings extracted from the relevant engineering models at weekly or biweekly intervals to make the construction parties aware of latest design changes and reduce the lag in transition of design changes to construction subcontractors and trades. BIM meetings and the solutions discussed in those meeting for resolving detected clashes were another kind of communication between design and construction groups. In some cases, execution was carried out simply based on the solutions proposed in the BIM meetings without any further official change notice. However, such clashes and proposed solutions were recorded in the clash reports prepared during each meeting.

Evaluated Software and BIM Tools

During the course of this study, I used and evaluated four start-of-the art software tools. These software tools and their usage or evaluation objectives were illustrated in Table 2-2.

Table 2-2: Evaluated software and BIM tools

Software Name	Application/ Evaluation Objectives
Autodesk® Revit®	Architectural / MEP Modeling; Developing the 4D as-built model
Navisworks®	Clash detection; Developing the 4D dynamic as-built model
Solibri Model Checker™	Tracking the history of changes in BIM
Vico Doc Set Manager™	Tracking the history of changes in 2D documents (drawings)

Managing Interdisciplinary Changes

The review of different design alternatives and making decision about multi-disciplinary changes were conducted during BIM meetings. The study of these meetings can also be a base for examining BIM as a means of effective visualization and communication to enhance the quality of coordination meetings.

2.3 Conclusion

In this chapter, I introduced and explained the background information about the project we studied, Pharmaceutical Building Project. In particular, I provided information about the project details, design and construction team, the project coordination and change management procedures, and the BIM tools I utilized and evaluated during this study.

In the next chapter, I will focus on examples of changes I documented during the case study and will analyze their important characteristics.

CHAPTER 3
DEVELOPING THE ONTOLOGY OF CHANGES

An earlier version of this chapter has been accepted for publication: Pilehchianlangroodi., B., and Staub-French, S., ASCE Construction Research Congress (CRC), 2012

3.1 Introduction

In the previous chapter, I explained the background information and details about the project. As it was discussed, numerous examples of changes were documented during the case study. In this chapter, I discuss five examples of these changes to illustrate the typical requirements of practitioners and to evaluate the functionality, efficiency and potential capabilities of BIM tools against these requirements. I then analyze the different characteristics of these changes, and present them in an ontology of changes. Next, I discuss the evolution of an information model by progress in design and construction and highlight the main characteristics that are significant in controlling the impacts of changes.

3.2 Example Design Changes

This section examines five design change examples from the project by describing the reasons for each change, the consequences or impacts of the change, and the challenges of managing these changes using existing tools. The analysis of these examples aims to specify the characteristics that are required for tracking the history or consequence of changes in an information model. I have highlighted these key characteristics in **bold** letters throughout the analysis sections. These highlighted characteristics will be summarized later as a part of our BIM-based ontology of changes, which will be presented later.

<u>Example #1: Relocation of Fire-rated Walls</u> *<u>(Tracking the History of Changes)</u>*

Due to architectural requirements, the arrangement of two-hour fire-rated walls changed slightly. The construction manager noticed the effect of this change on the wall openings, and consequently on the arrangement of their internal framing. Thus, he wanted to know which walls would be affected to modify their assembly prior to installation. To address this issue, I investigated a range of possible methods for tracking such changes in an information model. I also evaluated the capability of a state-of- the-art BIM tool to detect such changes.

It is usually difficult to determine where and what changes have been made in the models. A basic solution is exporting the model outputs into spreadsheets and track changes by components ID number which is time consuming and almost impossible for large models. There are also some indirect ways of extracting history of changes from the model. For example, considering that changes in the drawings are often marked by revision clouds, each information model, which also contains latest revision of the drawings, indirectly includes some history of changes too. Thus, the comparison of the models corresponding to each revision can provide a way for tracking changes during the evolution of the design. However, this kind of tracking is only possible when information models corresponded to every official issue of the drawings are collected and kept systematically. Moreover, only those changes that are marked in the extracted drawings can be tracked by this method.

A number of BIM software packages have recently introduced specific tools for comparing versioned building models. I evaluated one of the most advanced commercially available BIM tools to examine its capability, Solibri Model Checker™. I first used this tool to detect changes that occurred in the location of wall openings between two versions of the model. The results of our first attempt indicated that 322 openings were **added**, 242 openings were **deleted** and 61 openings were **modified** (Figure 3-1).

Further investigation showed that many of the detected additions or deletions were incorrect as the added or deleted openings were identical. This might have occurred, for example, because of modifications in some adjacent components, the wall and its openings were simply removed and again recreated at the same location. A number of detected changes were also due to negligible adjustments in the openings location or geometry, which were not relevant to the contractor. Moreover, components were reported as modified when a change was detected in any of their attributes, including **position**, **geometry** or **specifications**. However, we were only concerned about changes in a specific attribute, i.e. position. Thus, many of the detected changes were not intended targets of our analysis.

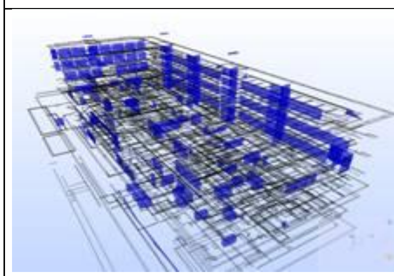
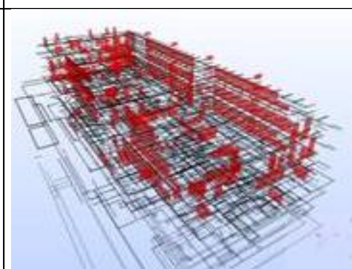
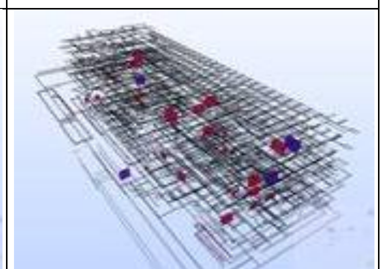
Added Openings	Deleted Openings	Modified Openings
322	242	61
		

Figure 3-1 : Track of changes in openings - Solibri Model Checker™

In another attempt, I used the same BIM tool to detect changes in the location of two-hour fire-rated walls, instead of their openings only. To obtain clearer results, I narrowed down our comparison to the east side of the first level of the building. I also focused just on a specific attribute, the **position** of the walls, and excluded changes in any other attributes such as **geometry** or **specifications** of the walls. Figure 3-2 shows the results from this analysis. As can be observed, the results of such a customized comparison are much clearer and can be better communicated. However, this result also included some irrelevant changes. These inaccuracies increased the number of detected changes, which affected the traceability and reliability of the results. Moreover, the capability of this BIM tool to present the footprint of walls in the results enables the user to find the approximate location of the highlighted components with reference to the walls. However, it is not an effective and accurate method for identifying the changed component especially when the results are printed. Due to this ineffective method of presentation, I eventually decided to highlight the detected changes on drawings manually. This method of presentation was more acceptable to construction professionals who were the end users of such information.

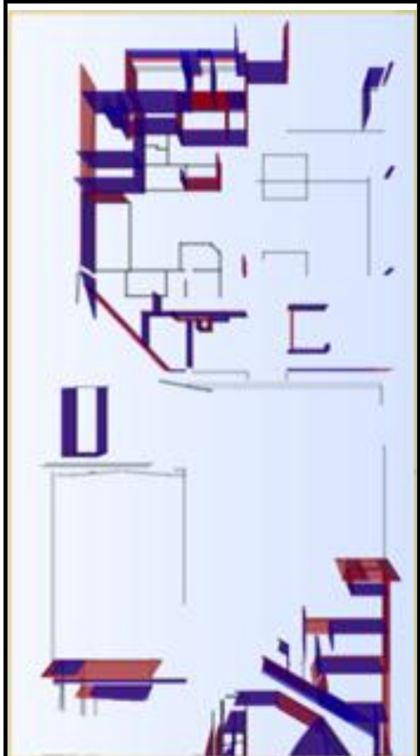
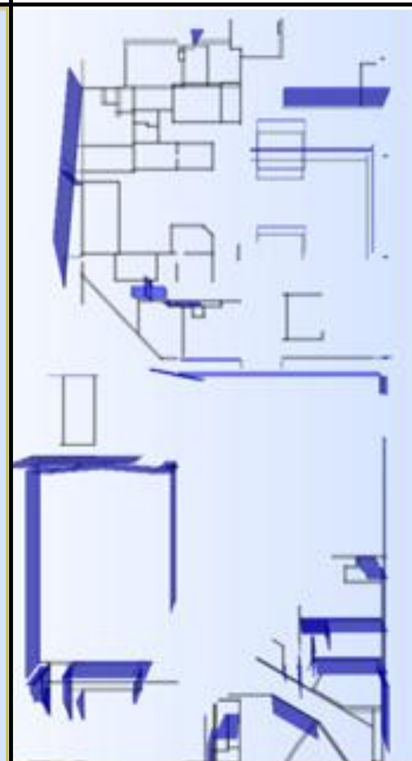
Modified Walls	Deleted Walls	Added Walls
		

Figure 3-2 : Tracking changes in the location of first-level walls - Solibri Model Checker™

To address the need to clear presentation of the results in 2D, I also examined another tool, Vico Doc Set Manager™, to track changes in drawings. This tool provides a quick comparison and mapping between multiple sets of drawing (DWG or PDF format) to identify the changed drawings. It then generates a color-coded document registry table, which includes the list of drawings, their versions, and their changes. Figure 3-3 shows the table prepared for the architectural drawings of the first level of the building. In this figure, a red cell in each revision column indicates that the corresponding drawing has changed and a green cell shows new or unchanged drawings.

Document Name	File Name	Sheet Number	Current	IFC 2010-09-01	IFC-2010-11-12	Prog Set-2011-04-13
Project Documents						
Data Centre- Conc Outline	A2.20a.pdf	-	A2.20a.pdf			
Lev -1 West, Conc Outline	A2.20b.pdf	-	A2.20b.pdf			
Lev 1 East, Conc Outline	A2.21b.pdf	-	A2.21b.pdf			
Lev -1 Interst., Conc Outline	A2.20c.pdf	-	A2.20c.pdf			
Level 1 West, Conc Outline	A2.21a.pdf	-	A2.21a.pdf			
Unassigned						

Figure 3-3 : The color-coded document registry table - Vico Doc Set Manager™

Moreover, every two revisions of drawings can be overlaid to investigate the changes. The results of this comparison can be reviewed in three modes: side by side, highlight with color-coding, and slider mode (a slider bar can be dragged across the screen to reveal each of the two overlay drawings). Then, the identified changes can be marked with cloud marks and an RFI document can be generated for each identified change (Figure 3-4). Clouds with pending RFIs are transferred to the new versions so user can keep track of those changes and retrieve their historical data.

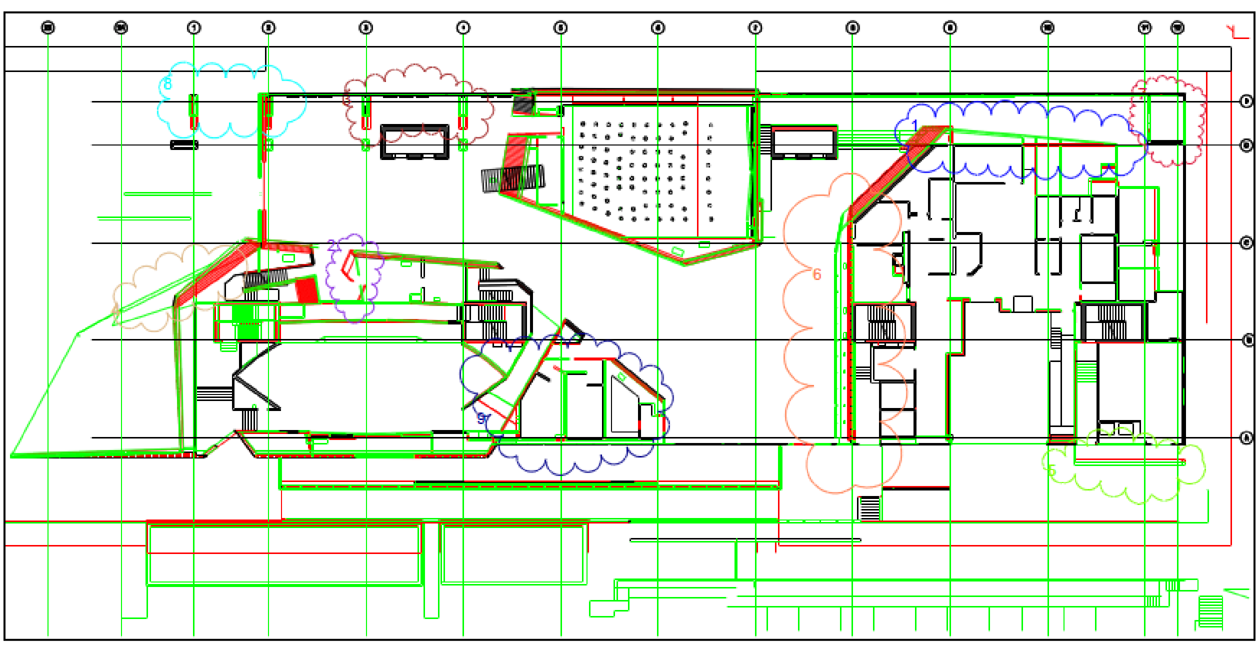


Figure 3-4 : Track of changes in 2D (drawings) - Vico Doc Set Manager™

The main problem in the comparison process was that if a part or the whole drawing moved slightly relative to its borderlines, which happens frequently due to realignment of the drawing, all those moved parts would be considered as changed. This problem also happened when the scale of a drawing changed. This was a major problem since this type of modification, which is quite probable, should not be considered as a change too. In this specific example, almost 70% of the reviewed documents were affected by such changes so the changed that were identified automatically could not be considered as the real targets of our change detection. Due to this problem, I reviewed most drawings in the slider mode only and detected major changes by visual comparison.

Table 3-1 compares the advantages and the disadvantages of these two tools with respect to their capabilities to automatic detection of changes in BIM and 2D.

Table 3-1 : Comparison between Solibri Model Checker™ and Vico Doc Set Manager™

	Solibri Model Checker™	**Vico Doc Set Manager™**
Advantages	• Works with IFC files • Comparison is customizable • Results can be filtered. • Effective presentation tools	• Easy and quick comparison • Works with both CAD and PDF files • User-friendly review tools • Results are clear and easy to read
Disadvantages	• Hundreds of changes in each report • Need manual process for marking changes on 2D drawings • Historical records of deleted components are not retrievable. • Specific modeling strategy is required to reach better comparison results.	• Comparison is not possible if the whole drawing moves slightly or the drawing scale changes • Each sheet of documents needs to be saved as a separate file. • File names of all revisions should be identical

Example #2: Changes in HVAC Routing *(Tracking the consequences of changes)*

The route of air supply ducts in the small lecture hall needed to be changed because of the limitations in available space and architectural design restrictions on exposed ducts. At the time of this change, the piping and electrical design were at the final stages, the structural design was almost complete and construction of the basement structure was in progress. Several alternatives were discussed in the BIM meetings. The final solution was passing the main air supply duct through the space between the lecture hall sloped floor slab and the steel deck of the lower floor ceiling. The impact was that they now needed to provide 80 openings with a diameter of 12” in the floor slab to allow sufficient airflow between the HVAC plenum and the lecture hall (Figure 3-5). This solution eliminated the need for secondary ducts and minimized the effect on piping and the electrical design. The size of the openings was determined based on the maximum size recommended by the structural engineer to eliminate the effect of openings on the structural integrity of the floor slab. Coping with the different constraints imposed by requirements of other engineering disciplines and progress in construction along with congestion and geometric complexity were the primary challenges in developing the final solution.

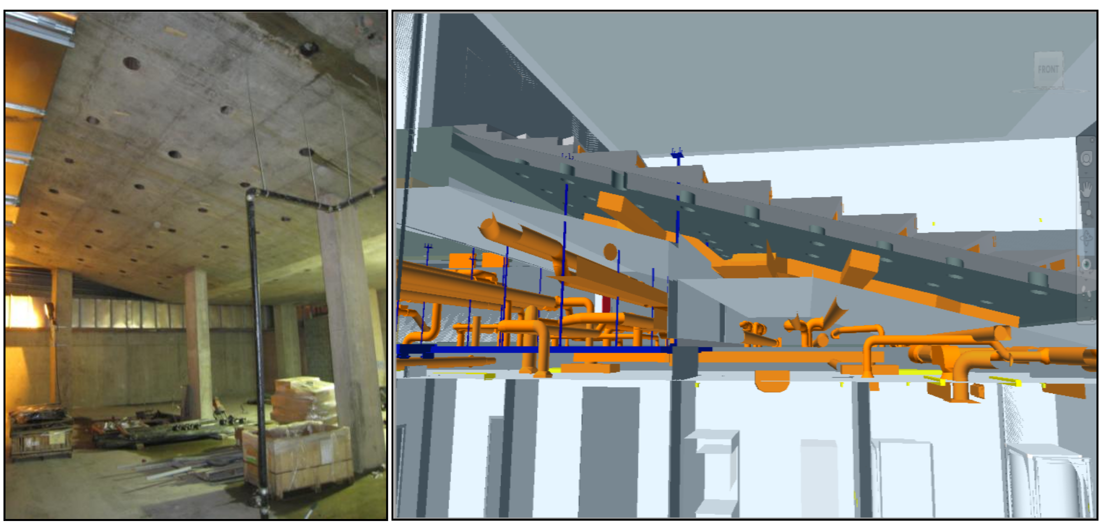


Figure 3-5 : Opening in the lecture hall slab
Site photo (left); 3D view (right)

To overcome these challenges, the consequence of each alternative solution needed to be examined thoroughly. These consequences were generally explored in the BIM meetings by examining different **spatial** or **analytical dependencies** between changed components and other components that might be affected.

Spatial dependencies between components are usually easy to track as they are related to the geometry or position of components. For instance, relocation of the main air supply duct affected secondary ducts **connected** to it and the steel hangers that **supported** it. It also influenced a number of **adjacent** components such as piping and electrical cable trays. Moreover, as the duct were **surrounded** in the small space between the sloped floor slab and steel deck of the lower floor, a large change in the location of the duct could affect the surrounding structural components.

Investigation of **analytical dependencies**, on the other hand, is much more difficult as they need specific technical information and expertise. For instance, although an opening with diameter of 12" did not influence the **structural integrity**, a slight increase in the opening size would change the structural design significantly because in case of such an increase, the opening size would exceed the available clear distance between reinforcing bars and consequently would interrupt rebar arrangement in several locations. Similarly, other analytical relationships, such as **architectural consistency**, **operational** and **maintenance requirements**, and **mechanical** and **electrical interactions,** also needed to be examined that necessitated engagement of different engineering disciplines and sub-trades.

Commercially available BIM tools are able to detect a number of **spatial dependencies**. For example, many of them can recognize that the length of columns is linked to the elevations of floors. Thus, if a change happens in a floor elevation, they will automatically update columns length. These tools also have limited capability of detecting and tracking analytical relations. For example, due to operation and maintenance requirements, there should be a minimum clear space around mechanical components, such as ducts and pipes. BIM tools are usually able to check the clear distance between different components and detect components that do not comply with a minimum preset clearance requirement. The BIM tool we investigated throughout this study, Solibri Model Checker™, uses a rule-based reasoning approach to interpret typical relationships between components and analyze their interferences. For example, a specific rule checks for the components that are not attached or supported bellow (e.g. hanging in the air). This tool provides more than 50 rules to check similar logical dependencies, such as whether spaces are enclosed with walls, if components are within a space, if components interfere with each other, etc. However, these rule sets still cannot effectively recognize a wide range of logical relations, especially analytical dependencies.

Example #3: Change in Basement Level *(Controlling Effects of Conceptual Changes)*

Due to the extensive and massive MEP system and limitation of space in the basement and the interstitial level (the half storey between basement and ground level), these areas were extremely congested and, therefore, subject of a vast number of clashes between MEP components and frequent changes (Figure 3-6). During the early BIM meetings, the design team noticed that they might need to increase the height of these levels to provide more space and resolve clashes in these areas. However, because the change in the level of basement would affect the early stages of construction (excavation, shoring and foundation), it was the critical for the design team to develop their design to the extent that they can finalize the required basement height. In fact, no further changes were possible after completion of excavation and start of construction of foundations.

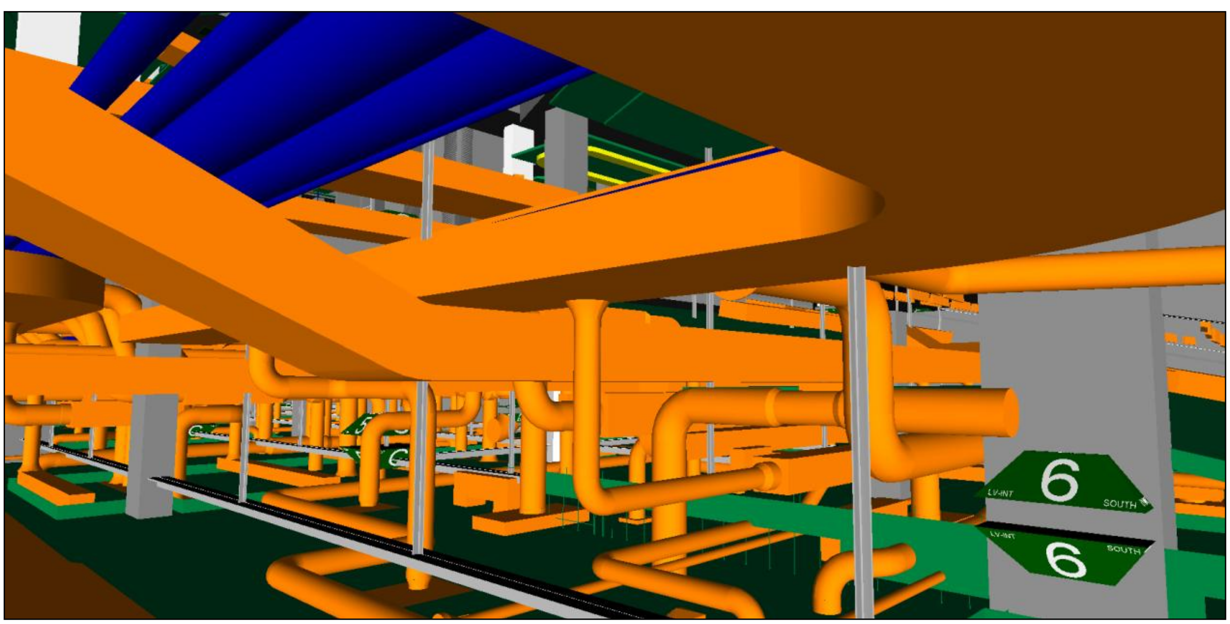


Figure 3-6 : Congested MEP system in the basement and the interstitial levels

Parameters such as the elevation of the basement floor are among fundamental design parameters that need to be set in the very early stage of the design process (**basic design** or **early detail design**) as changes in these parameters can affect the design of almost all other components. However, complexity of the design may cause uncertainty in such parameters and further changes might be required as the design evolves. For the purpose of this study, such changes in basic documents, design, and specifications that have fundamental effects on many components are categorized as **conceptual changes**. Acceptable **timing** of these **conceptual** changes is limited to specific milestones that can be determined based on the **design or construction status** of the changed component and the other component that are affected by the change component attribute. In the **design phase**, **cost and time impacts** of the change depend on the progress in design of other affected components and systems and can be calculated based on the amount of rework required for such modifications. In the **construction phase**, however, by the progress in construction of each affected component, the **cost and time impacts** associated with the change would increase significantly and sometimes to the degree that the change would no longer be feasible. In this example, the change in the basement elevation would affect the basement and all other components that have a **spatial** or **analytical dependency** with the basement components, which affects almost all building components including the foundation and base slab. However, since none of the building components had been constructed at the time of the change, the critical milestone, which determines the acceptable timing of the change, would be the start of the construction of the first component in the construction schedule (foundation/ base slab). This example demonstrates that the information model should include the **construction schedule** and **actual construction status** of the affected components to be able to determine the acceptable timing of such changes.

Example #4: Change in the Height of Ceilings *(Controlling Effects of Primary Changes)*

The majority of MEP components in each storey of the building pass through the available spaces above the ceiling and based on the route of each system, the components of the different systems need to pass on top of each other at their crossing locations (Figure 3-7). The available space above the ceiling at these crossing locations is critical and the ceiling height needed to be changed in some cases when there is not enough space for passing all MEP components.

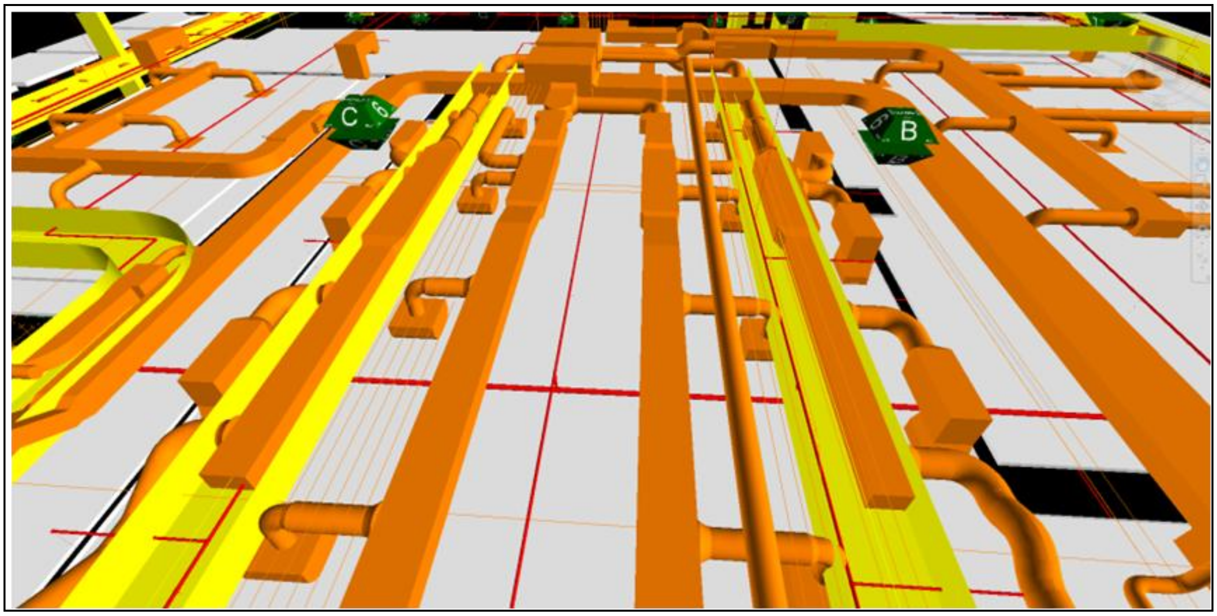


Figure 3-7 : Route of different MEP systems passing above the ceiling - 3rd Level

This lack of space and the need for local changes in the ceiling height were discussed in several BIM meetings while the clashes between different MEP systems at each storey were reviewed. Figure 3-8 shows one of these congested locations at the 3rd level of the building.

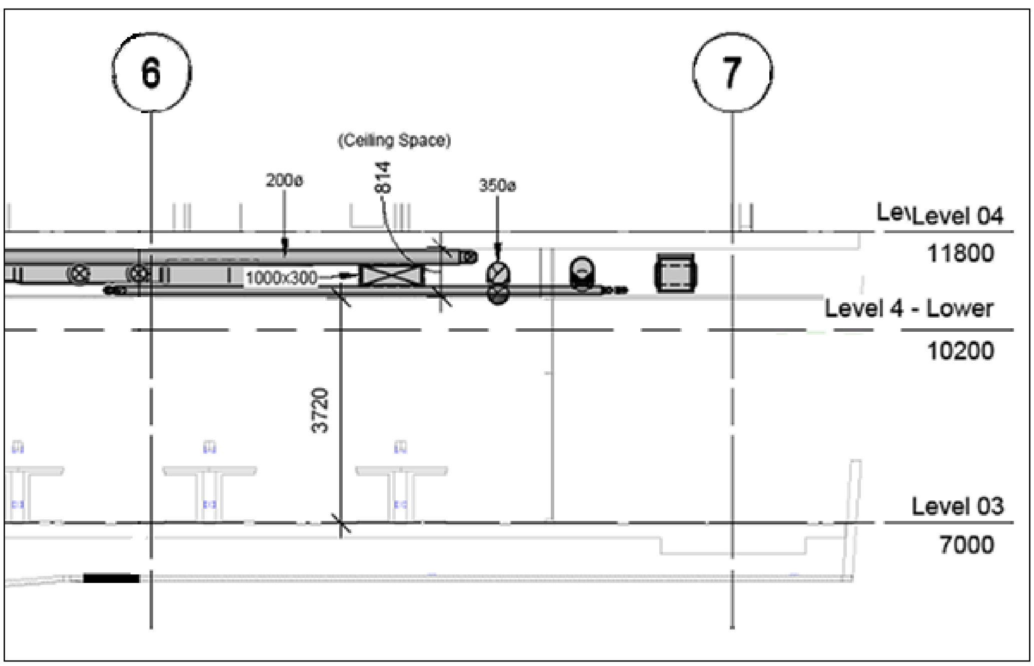


Figure 3-8 : Route of different MEP systems passing above the ceiling - 3rd Level

Compared to the change in basement elevation, the effect of the change in the ceiling height is local and only affects its **adjacent** components. However, this change still influences a wide number of components, such as adjacent partition walls, lightings and MEP systems. Although this change is not a **conceptual change** (as defined in the previous example), it still affects several components. For the purpose of this stud, such changes in the attributes of a main component that have major effects on several other components are categorized as **primary changes**. Therefore, although this change is not a **conceptual change** (as defined in the previous example), we can consider it as a **primary change,** change in main components position, geometry, etc, which affect several other components). Moreover, minimum clear headroom is a critical **analytical dependency** between the elevations of the storey ceiling and floor slab. This clear headroom is defined by architectural requirements and as long as the changed ceiling height remains greater then this minimum amount, the change is acceptable. Here, this acceptability criterion is based on the fact that the building structure and its floor slabs have already been **constructed** so the change in total storey height is not feasible anymore. Another decisive factor is derived by the construction status of the adjacent partition walls. As the height of these walls would be affected by the ceiling height, the change impacts would increase by progress in **procurement** and **construction** process. Thus, the information model should also include the **procurement**, **fabrication** and **installation** status of the affected components to be able to determine the impacts of such changes.

Example #5: Change in the Loading Dock Slope *(Controlling Effects of Secondary Changes)*

Figure 3-9 depicts a change in concrete sloped slab at the first level and southeast side of the building within loading dock area. The slope of the slab in the last IFC revision of drawings was around 8%. Then based on a change in architectural design, this slope has increased to around 10%. This change was communicated to the construction team via the unofficial architectural drawings (progress sets) around one month after submission of the IFC drawings.

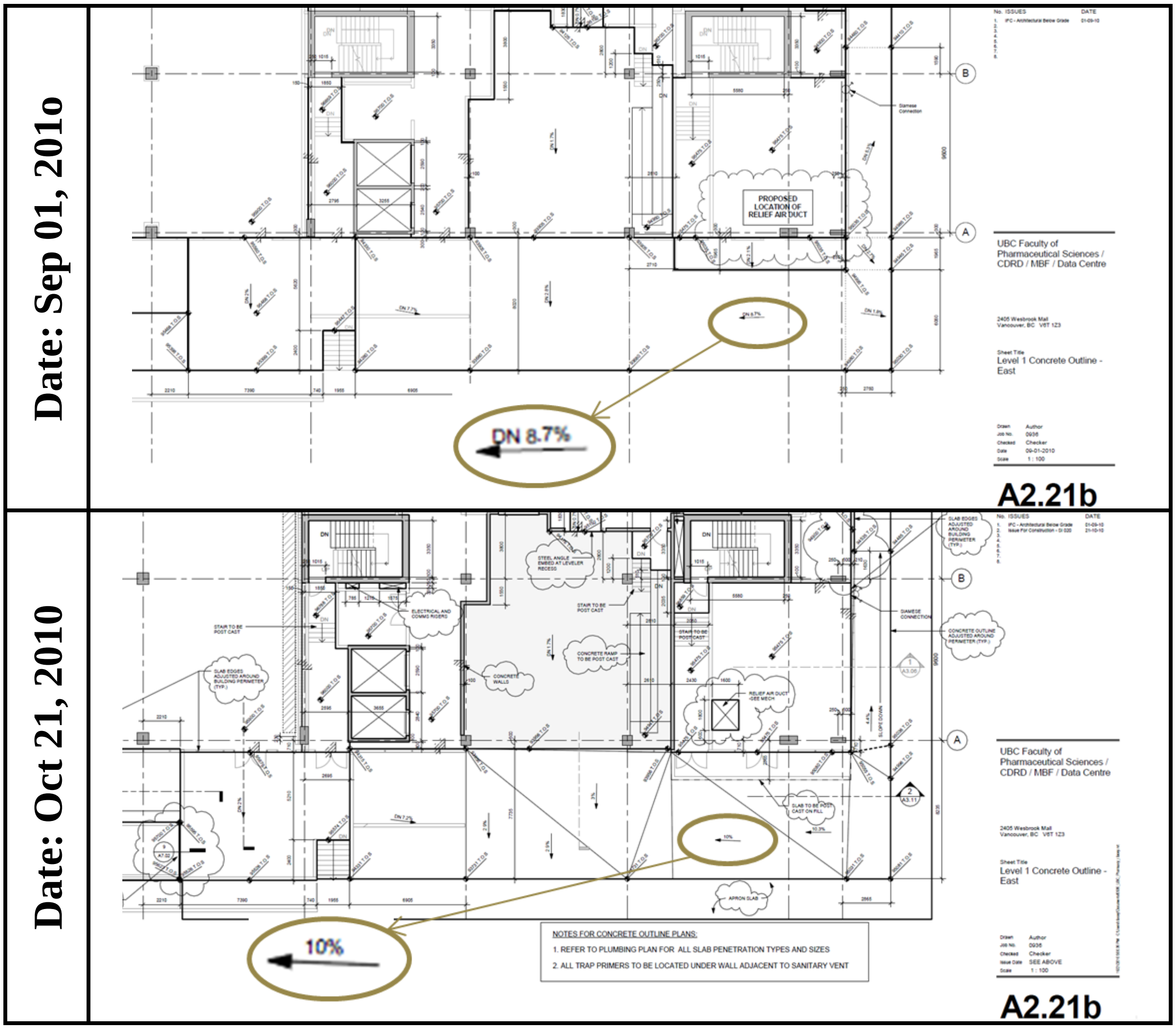


Figure 3-9 : Change in the slope of concrete floor slab- Loading dock area

Compared to the changes in the basement or ceiling heights, which was defined as a primary change in the previous example, the change in the slope of the slab can be considered **secondary change** as it only affects the elements of the changed components and has minor or no effects on the other components of the building. Because of the limited effects of this secondary change, the control of its effects might be easier. However, as discussed, the timing of the change is another critical factor that should be considered too. In this example, **fabrication** of the slab reinforcing bars was almost completed based on the latest IFC issue (slope of 8%). Therefore, the time and cost associated with this change could be significant. However, as the increase in slope was small, it was implemented by an equal increase in the thickness of the rebar cover so the **fabricated** reinforcing bars did not affected by this change. This example shows that despite limited effects of **secondary changes**, **timing of** such **changes** still plays a crucial role in controlling the effect of such changes.

Another point that is worth mentioning is the limited capability of BIM tools in visualizing such changes. Figure 3-10 shows an attempt that was made during the BIM meeting to visualize this change by comparing the corresponding models in Navisworks®. In this figure, the old model (IFC) is shown in gray and the new model (progress set) is presented in green. As it can be observed, such small changes in the geometry of components cannot be recognized by simple methods such as overlaying two revisions of the model. This emphasizes that BIM tools require some specific features to be able to track changes between two revisions of BIM.

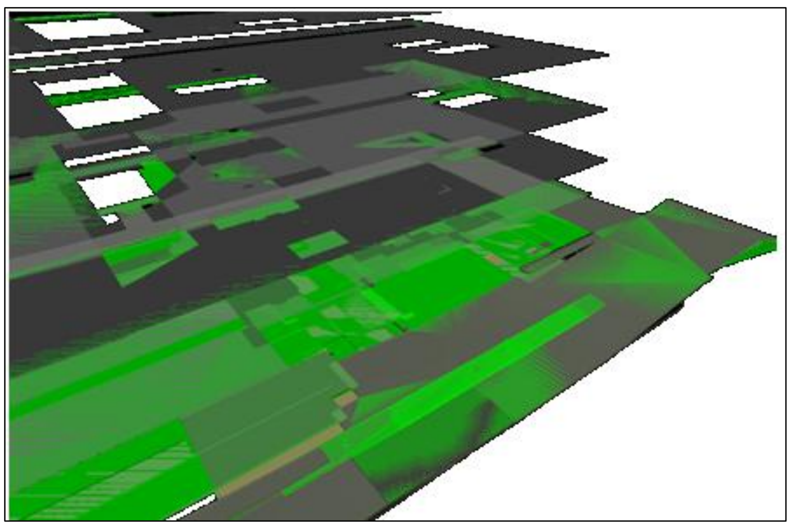


Figure 3-10 : An attempt to visualize the change in the slab slope using Navisworks®

The provided examples highlight a number of key characteristics that are significant for controlling **impacts** (**cost** and **time**) of changes via an information model. As illustrated, the **level of a change** (conceptual, primary or secondary) and its **timing** (whether the affected components have been designed, procured, purchased, fabricated or constructed or not) are the important characteristics that need to be considered in controlling the change impacts. The **level of changes** is a qualitative scale for the number of affected components and the timing of the changes indicates the **design**, **procurement** or **construction status** of the affected components. These characteristics were also classified in the last three classes of the ontology of changes, which was provided in the previous chapter.

3.3 Conceptual Characterization of Design Changes

The provided examples highlight a number of key characteristics that are significant for tracking history and consequence of changes in an information model. The first example illustrated important characteristics for tracking the history of changes, which included attributes specific to a component's **geometry**, **position** and **specifications.** The second example illustrated the important characteristics required for tracking the chain or sequence of changes that are a consequence of **spatial** or **analytical dependencies.** The analysis of the next three examples aimed to identify **conceptual**, **primary** and **secondary levels of changes** and investigated the effect of different change characteristics (especially the **timing of changes**) on its **time and cost impacts**.

I analyzed and classified these conceptual characteristics and arranged them in a taxonomic (subclass–super class) hierarchy to develop a BIM-based ontology of changes. Table 3-2 presents this ontology. This ontology explicitly defines a BIM-based structure to organize these changes. It also shares a common understanding of the key attributes of changes for practitioners who develop or use BIM tools for managing changes.

The developed ontology is comprised of 6 classes and 19 sub-classes that cover conceptual characteristics of design changes. Table 3-2 depicts theses classes and their relevant subclasses and briefly explains their important facets. The first and second classes of the ontology (change Type and Changed Component Attributes) were discussed in the first example and the third class (Dependencies between Components) was explained in the second example that we provided in the previous sections. The next three classes (Level of Change, Change Timing and Change Impact) were the focus of the next three examples. The relationship between these classified characteristics will be elaborated in the next section.

Table 3-2 : Conceptual characteristics of changes

Classes	Sub-classes	Facets: *Description/ Example*
Change Type	Addition	*Adding a new component*
	Modification	*Modification in one or several attributes of a component*
	Deletion	*Deleting an existing component*
Changed Component Attributes	Geometry	Shape: *cubic, cylindrical, rectangular, plate*
		Dimensions: *length, width, thickness, diameter, slope*
	Position	Coordinates: *X ,Y ,Z*
		Orientation: *Rx, Ry, Rz*
	Specification	Material: *concrete, mild steel, galvanized steel*
		Elements: *Stud, Rebar: size, shape, arrangement*
		Semantic Properties: *Fire-rating, acoustic, water proof*
Dependencies between Components	Spatial	Connected To : *column and floors, main and secondary ducts*
		Adjacent To: *duct and adjacent pipes, duct and ceiling*
		Supported By: *duct and steel hangers*
		Surrounded By: *duct and false ceiling/ plenum area*
	Analytical	Structural Integrity: *size of sleeves and arrangement of rebar*
		Architectural Consistency: *functionality of room and exposed duct*
		Mechanical Interaction: *location of air supply duct*
		Electrical Relationship: *size of cable tray and motor power*
		Operational Requirement: *clearance around a pipe*
Level of Change	Conceptual	*Change in basic documents, design, specification with fundamental effect on many components*
	Primary	*Major change in main components position, geometry, etc, which affect several other components*
	Secondary	*Minor change in component elements or properties with minimal effect on other components*
Change Timing	Conceptual design	*During early decision making about the primary aspects of the design*
	Basic design	*During early stages of the design but prior to the full extended design*
	Detail design	*During the extended design but prior to any procurement /construction*
	Procurement	*After Purchase Order but prior to fabrication*
	Fabrication	*After Fabrication but prior to erection*
	Construction	*After commence of construction*
Change Impacts	Cost impacts	Major: *considerable effects on costs*
		Minor: *insignificant effects on costs*
	Time impacts	Major: *considerable effects on schedule*
		Minor: *insignificant effects on schedule*

3.4 The Relationships between Different Change Characteristics

In the previous section, we explored primary characteristics of changes that are important for tracking their history and controlling their consequences. These characteristics and their important facets were summarized and briefly explained in Table 3-2. In this section, I focus on these characteristics and their facets, which are again highlighted in **bold**, and attempt to identify their relationships and their impacts on the project cost and schedule.

Figure 3-11 illustrates the evolution of an information model by progress in design and construction in a typical BIM-based project and highlights the main characteristics that are significant in controlling the impacts of changes. As this diagram depicts, the information model evolves throughout the design and construction process. In very early stages of the project (**feasibility study** and **conceptual design**) the information model, if it exists, only includes very basic design aspects. The **conceptual model** may include basic components such as volumes, areas, levels and main components of structural system and building envelop. In this stage, incorporation of changes in design needs minimum effort and the majority of available BIM tools are able to implement them automatically since the number of components and their spatial and analytical dependencies are extremely limited at this stage. During **basic design**, models include the majority of main components such as column, beams, floor slabs, doors and windows. However, models include only **basic attributes** of these components (**geometry**, **position** and probably **material** type) and models do not include most **detailed attributes** of these components (**elements**, **Semantic properties** and **Material specifications**). During basic and detailed design phases (**component-based modeling process**) the increase in the number of components and component attributes cause exponential increase in the number of **spatial** and **analytical dependencies**. This reduces the capability of BIM tools in automatic tracking of the consequence of changes significantly as the commercially available BIM tools only identify a limited range of **spatial dependencies** and do not recognize most **analytical dependencies.** The limitation increases when the Level of Development/ Detail (LOD) increases during the design process. [The standardized definition of LOD has been provided by AIA (2008), Document E202]. By the increase in LOD, more components and component attributes are created and the **dependencies** between these component attributes become more and more complicated. This increases the **time and cost** of incorporating changes in the model and in the design.

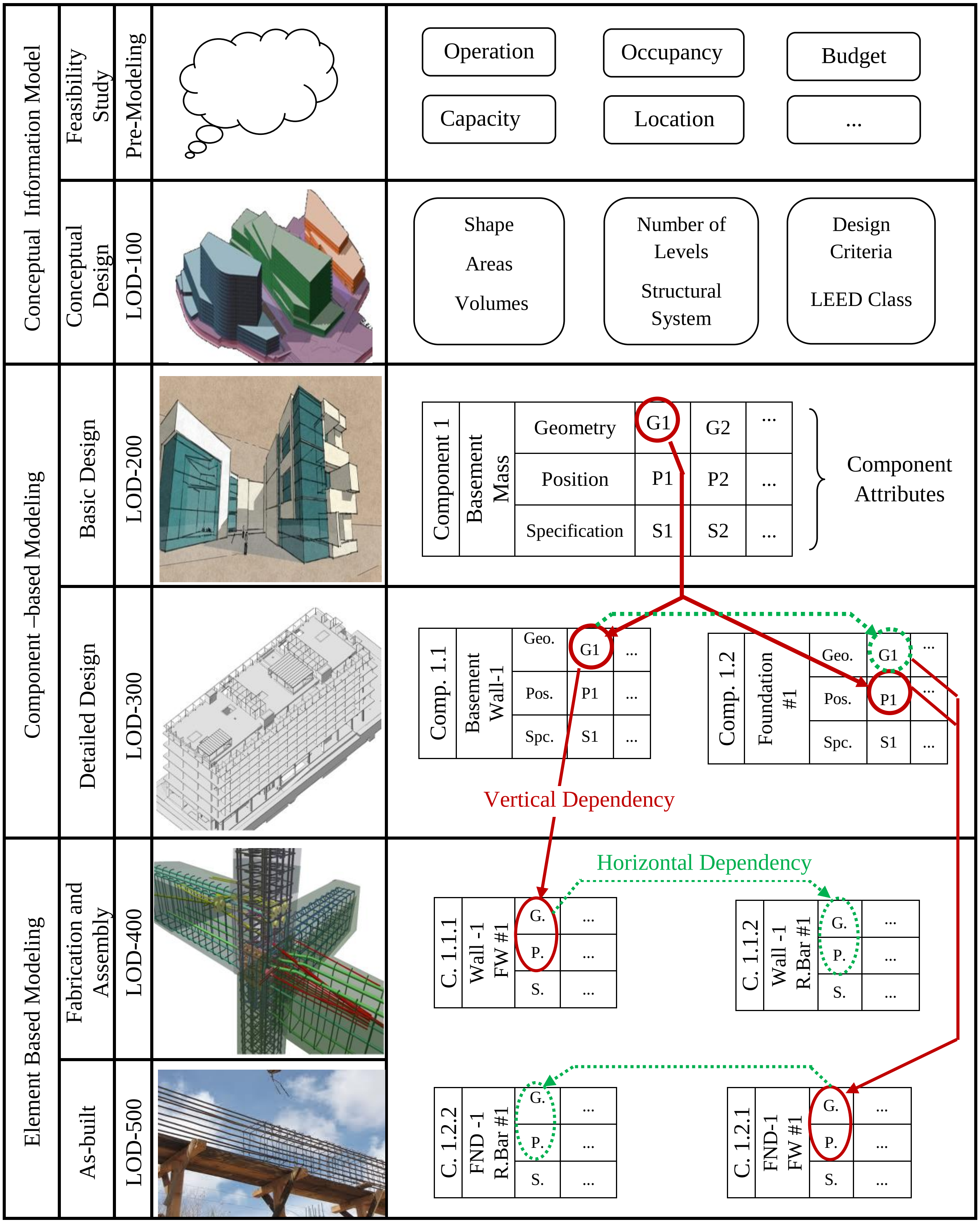


Figure 3-11 : Formation of vertical and horizontal dependencies throughout BIM evolution

[For the definition of LOD refer to AIA (2008), Document E202]

Another issue that increases this complexity is the creation of another type of **dependency** when components progress from one LOD to the next. Compared to the earlier type of **dependency,** which exist between attributes with a similar LOD, this type of **dependency** is more influential in expanding the effects of a change throughout other model components. To distinguish between these two types of dependency, I call the former **Horizontal Dependency** and the latter **Vertical Dependency**. As an example, we can consider the change in the basement height that was discussed in Example #3 in this chapter. In fact, the elevations of floors and basement height are among basic parameters that are supposed to be finalized in the **basic design** phase since a considerable change in one of these elevations will cause extensive successive changes in a wide range of the model components in the **detailed design** phase. The diagram presented in Figure 3-11 shows a small part of the chain of successive changes made by the initial change in the basement height. This dependency diagram presents the vertical and horizontal dependencies (shown by solid and dashed lines respectively) that creates the chain of changes. Overall, compared to the effect of **horizontal dependencies** changes in an attribute that is in **vertical dependencies** with components in the next LOD is much more extensive. Thus, identifying such **vertical dependencies** is crucial in controlling **impacts of changes** by managing the **timing** of such changes.

By the start of **construction** (including **fabrication** and **erection**), a new phase in the development of information model begins. In this phase, the information model includes almost every components required by design and the focus of the modeling is on increasing the level of detail. It happens by including required component elements in the model (**element-based modeling**). **Fabrication model** is an example of such element-based modeling. A unique aspect of this phase is the transfer of responsibility, or even the ownership of the model, from the design group to different construction trades or the general contractor. This increases the **process time** associated with changes that are dependent on one, or more, **primary attributes** through a **vertical dependency.** Change in ceiling height, which was discussed in Example #4 in this chapter, is an example of such a change. Another important characteristic of this phase is the significant increase in the **cost of changes** that affect **constructed** or under construction components. This cost can be so high that it significantly influences the feasibility of the change. Therefore, **constructed components** usually are assumed unchangeable and any change in a component attribute that impose a change (through any kinds of spatial or analytical dependencies) in one of the constructed component will be unattainable.

In the next chapter, I present the discussed **vertical and horizontal dependencies** in the form of "dependency diagrams" and provide a computational approach to track the consequence of changes in an information model.

3.5 Taxonomy of Changes

During my data collection period, I documented numerous examples of changes encountered throughout the design and construction of the building. I analyzed these examples to identify their different characteristics that are significant in tracking their history or controlling their impact. The five examples provided in the previous sections aimed to highlight these common characteristics, which were categorized and generalized in the presented ontology of changes. Based on different classes and sub-classes of the developed ontology, I categorized all other documented changes under a taxonomy of changes. Table 3-4 shows a part of this taxonomy that only includes twenty changes. In this table, the following abbreviations are used:

Table 3-3 : List of abbreviations

Type	ADD	Addition
	MOD	Modification
	DEL	Deletion
Spatial Dependency	CT	Connected To
	AT	Adjacent To
	SPB	Supported By
	SRB	Surrounded By
Analytical Dependency	SI	Structural Integrity
	AC	Architectural Consistency
	MI	Mechanical Interaction
	ER	Electrical Relationship
	OR	Operational Requirement

Table 3-4 : Taxonomy of changes (including the first twenty recorded changes)

NO	Description of Changes	Date	Department	Reference Documents	Component Type	Modeled?	Changed Attributes	Spatial Relationship	Analytical Relationship	Change Type	Level of Change
1	Plumbing specification	2010-09-08	Mechanical	PSI-01	Document	No	Specification	None	MI, AC	MOD	Conceptual
2	Plumbing Penetrations	2010-09-14	Mechanical	SI-006, A2.20	Piping/ Penetration	Yes	Position: CRD	AT	MI, AC	MOD	Secondary
3	Elevator shaft	2010-09-17	Structural	SI-004, S201.05	Opening/ Floor slab	Yes	Geometry: SHP, DIM	CT, AT	SI, MI	ADD	Secondary
4	Column at gridline 1	2010-09-17	Structural	SI-004, S201.01	Column	Yes	Position: CRD	CT, AT	SI, AC, MI, ER, OR	MOD	Primary
5	Pull Pit	2010-09-17	Structural	SI-004, S501	Pit: Wall, Floor	Yes	None	CT, AT,LT	SI, AC, ER, OR	ADD	Primary
6	Structural IFC revision	2010-10-01	Structural	All Structural drawings	Many	NA	None	NA	NA	MOD	Secondary
7	Column size	2010-11-01	Structural	SI-021,S301,S303, SKS005-9	Column	Yes	Geometry: DIM	AT, CT	SI	MOD	Primary
8	Column orientation	2010-11-01	Structural	SI-021,S301,S303, SKS005-9	Column	Yes	Position: ORN	AT, CT	SI	MOD	Primary
9	Column rebar	2010-11-01	Structural	SI-021,S301,S303, SKS005-19	Column	No	Specification: ELM	None	SI	MOD	Secondary
10	Top of wall	2010-11-02	Architectural	SI-023, ASK016	Wall	Yes	Geometry: DIM	AT	AC, MI, ER	MOD	Secondary
11	Elevator #5 rough opening	2010-11-08	Architectural	SI-026, ASK018, Conc. outline	Wall	Yes	Geometry: SHP, DIM	CT	AC, SI	MOD	Secondary
12	Slab Acoustic Isolation joint	2010-11-09	Architectural	SI-027, ASK019, Conc. Outline	Joint	No	Geometry, Position	None	MI, AC	MOD	Secondary
13	Slab opening at A.IS. Joint	2010-11-09	Architectural	SI-027, ASK019, Conc. Outline	Slab	Yes	Geometry: SHP, DIM	None	MI, AC	MOD	Secondary
14	Location of plumbing wall	2010-11-10	Architectural	SI-027, ASK019, Conc. Outline	Wall	Yes	Position: CRD	AT	MI, AC	MOD	Secondary
15	Slab Openings-Lecture hall	2010-11-16	Mechanical	SI-030, A2.21b, HVAC Plan	Opening/ Floor slab	Yes	Geometry: SHP, DIM	CT, LT	MI, SI, AC	ADD	Secondary
16	Slope of Floor Slab	2010-11-21	Structural	A2.21b, S203.2, S203.3	Floor slab	Yes	Geometry: DIM	SRB	AC	MOD	Secondary
17	Louver Block-out	2010-12-13	Mechanical	SI-039, ASK 030	Wall/ openings	Yes	Geometry: SHP, DIM	CT, LT	SI, MI,AC	ADD	Secondary
18	Partition Layout	2010-12-14	Architectural	SI-041, ASK 029	Partitions	Yes	Geometry, Position	AT	AC, MI	MOD	Secondary
19	Ceiling Height	2011-04-21	Architectural	CL. R #2, A2.13, E4.04, M2-8,P2.05	Ceiling	Yes	Position	CT, AT	AC, MI, ER, OP	MOD	Primary
20	Cable Tray Relocation	2011-04-21	Electrical	CL. R #3, A2.13, E4.04, M2-8,P2.06	Cable tray	Yes	Position	CT, AT	EI, AC	MOD	Secondary

3.6 Dynamic As-built Model

As discussed in the provided example, acceptable timing of changes is limited to specific milestones that can be determined based on the design or construction status of the changed component and the other component that are affected by the change component attribute. When construction of affected components start, the cost and time impacts associated with the change would increase significantly and, in most cases, to the degree that the change would no longer be feasible. Thus, identifying the components that are already constructed or are under construction is crucial to decide about the acceptable time of design changes.

To address this requirement, I developed a 4D as-built model that only included components that were under construction or already constructed. I gathered the latest construction status of the components during my site visit or through the online picture of the security camera mounted on the roof of an adjacent building. I examined different capabilities of Autodesk® Revit® and Navisworks® for development of such models and utilized different modeling approaches such as phase-based modeling, definition of groups based on timing of construction, and the use of section boxes to prepare this model. These methods and the challenges associated with each method are elaborated in this section.

In my first attempt to develop the model, I utilized the capability of Autodesk® Revit® in defining project phases and categorized different groups of structural components in several construction phases. Each time I was updating the model, I was defining a new phase and then I was selecting individual components, which were recently constructed or were under construction, to categorize them under the new phase. In this method, the developed phases should follow the sequence of the model updates and differ from the construction phases that were defined during the project scheduling. Figure 3-12 presents different phases developed in Autodesk® Revit® during the construction of the first floor slab. As it can be observed in this figure, the name of the last phase is "New Construction". This name was identical in all other revisions of the model and presented components that were recently constructed. In fact, prior to each update, I was renaming this phase and then was creating a new phase under the name of "New Construction" to include the recent constructed components into the model.

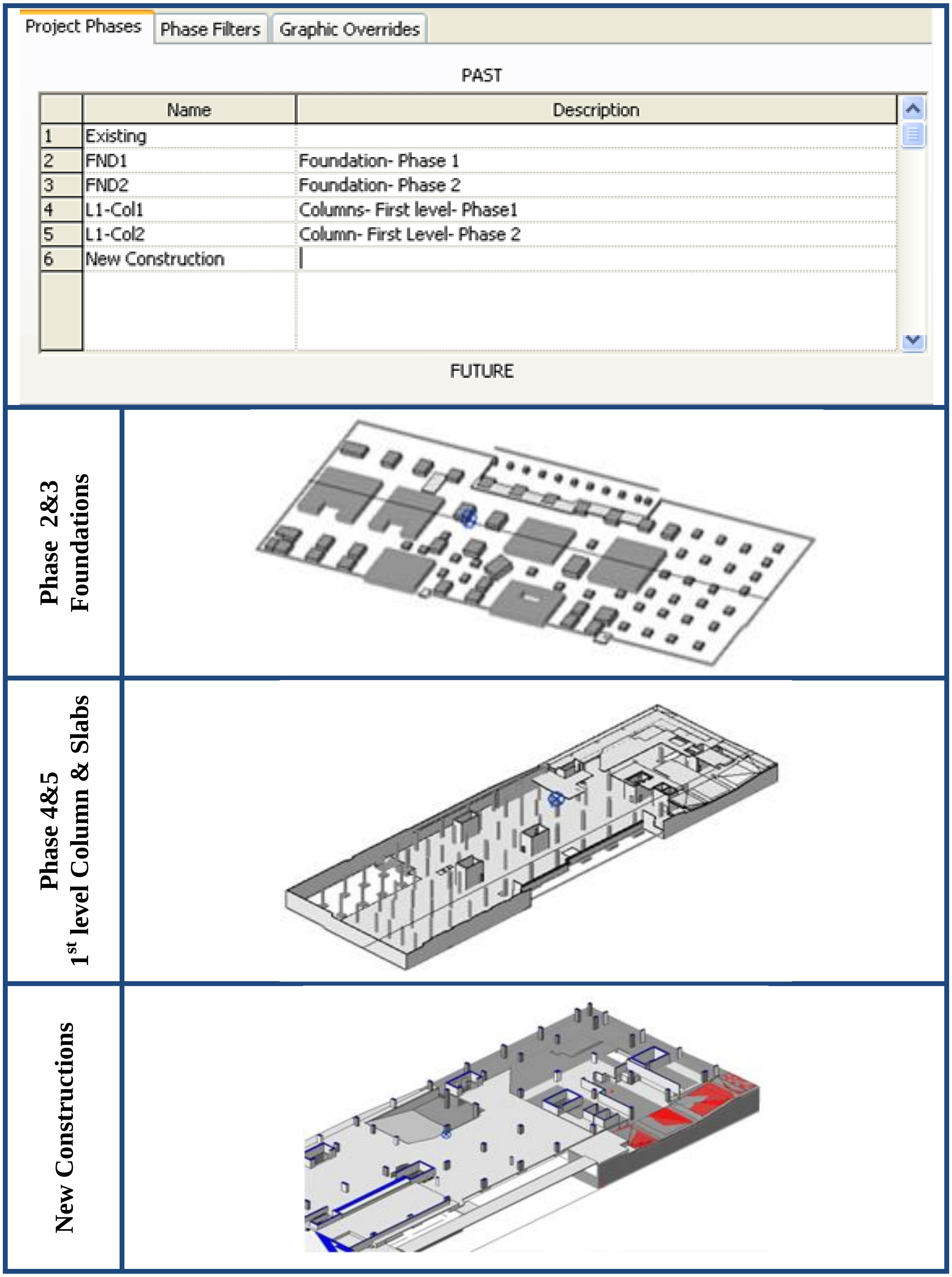


Figure 3-12 : Development of phases for preparation of dynamic as-built model

Moreover, the performed phasing could provide an efficient and simple way of 4D modeling based on the actual construction progress (versus planed construction process) since it would enable the user to filter and select all components classified in each specific phase and easily map them onto the different timing milestones in actual construction schedule. Figure 3-13 depicts this phased-base filtering process in Navisworks®.

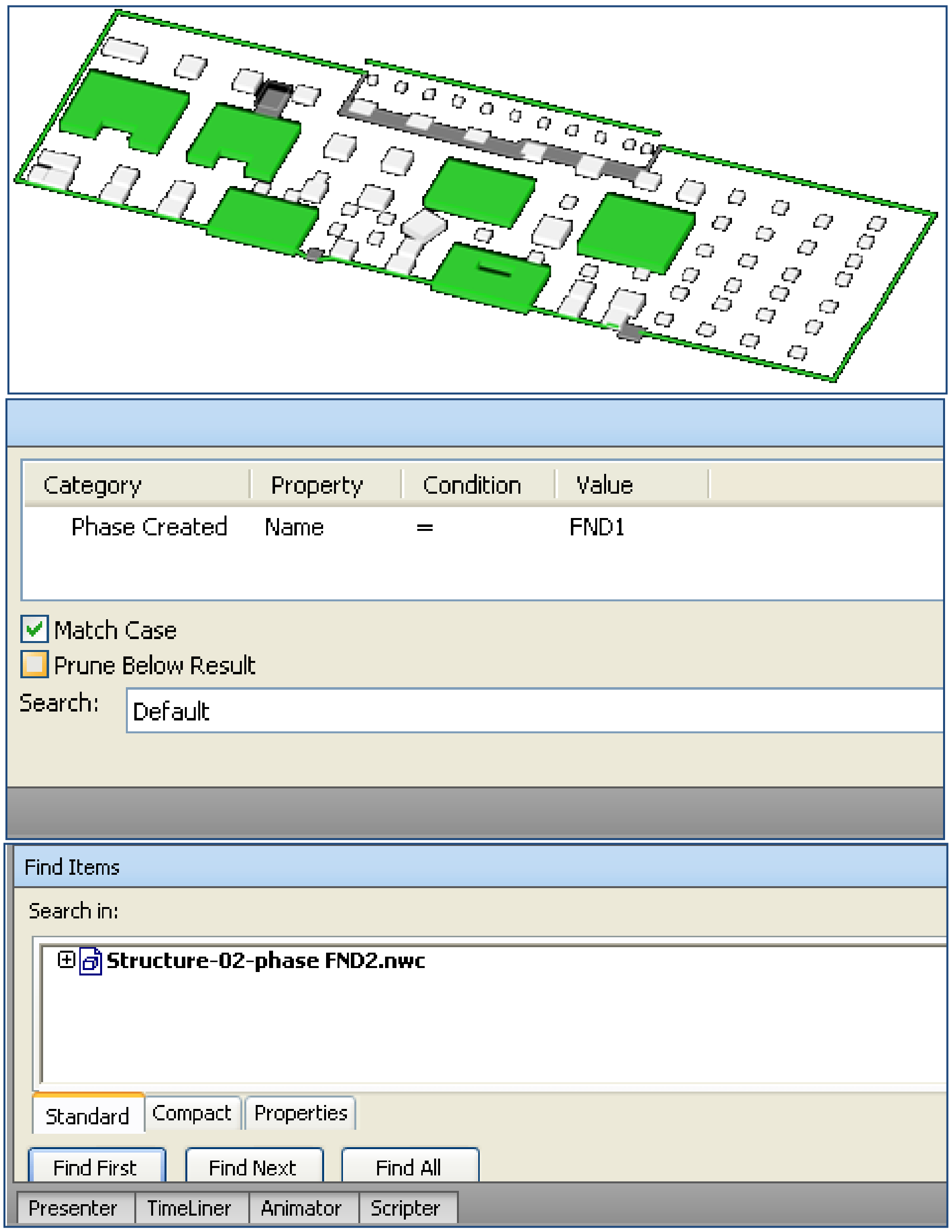


Figure 3-13 : Development of 4D model based on created phases

The main challenges in this process were:

- The extensive time required for filtering and separating new constructed components from the other components of the model
- A wide range of tiny components created due to the geometric complexity and irregularity of the structure
- The necessity of splitting model components at "Construction Joints"
- Revising the as-built model due to revision in the design model

To address the first two challenges I used section boxes to split different levels of the model and used various filtering techniques to separate my target components from the rest of the model. I also grouped the small components that were constructed together to facilitate this process. (Figure 3-14)

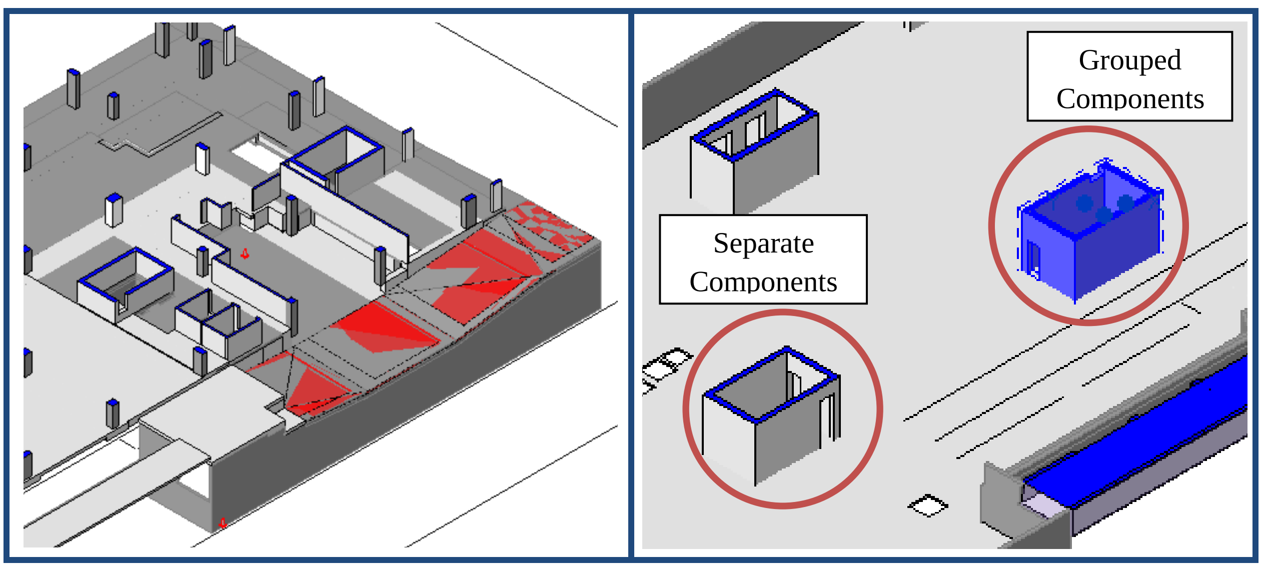


Figure 3-14 : Modeling challenges during development of the dynamic as-built model Geometry complexity (left); Grouping solution (right)

The other challenge was splitting components at construction joints. The model included large and long slabs that were constructed in two or several stages. However, these components were modeled either as a large component or were divided into smaller segments that differ from their real splits in construction. Therefore, I needed to split all those members at the construction joints and it was not straightforward in Revit. For this purpose, I required to duplicate such components, split each duplicated part, and then cut the unrequited segments of each part to finally reach to two separated segments with a minimum clear distance (Figure 3-15).

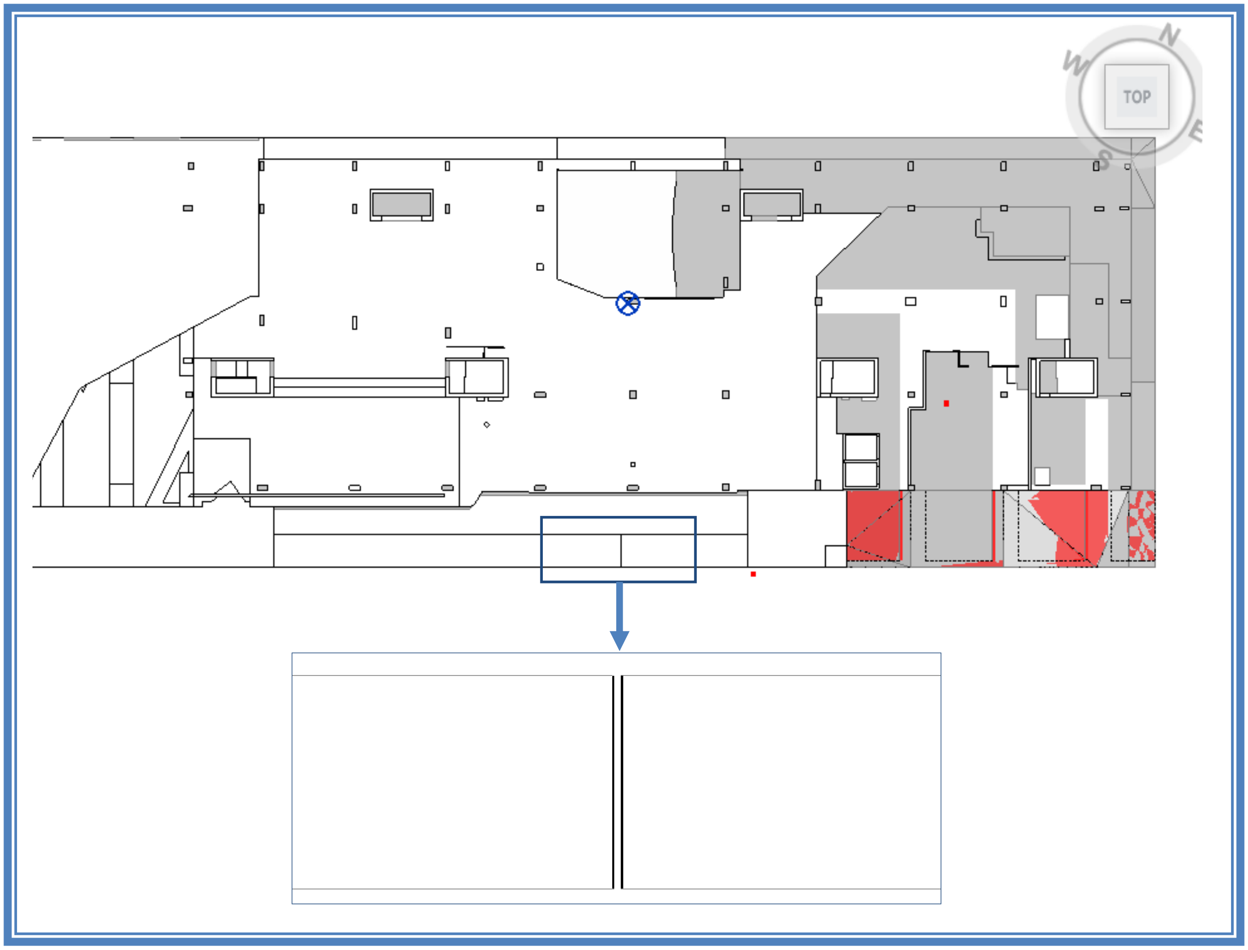


Figure 3-15 : Creation of construction for the development of dynamic as-built model

The update of the as-built model due to the revision in the design model was another challenge, and in fact the most significant one. It is obvious that the new model could not contain previously defined phases as it was prepared by the design group. Thus, after each revision in BIM, a complete iteration of almost the whole process was required. To address this challenge, I changed my modeling approach. I used a number of section boxes to split the model into different segments that approximately correspond to different construction phases. Although this method was rough and inaccurate at component level, it could provide an overall overview of the construction status and its update was significantly quicker than the previous method.

This dynamic model was shared with the project team and I kept it updated until the construction of the concrete structure of the second floor of the building. This period was important for the project team because of the concurrency of design and construction of the lower part of the structure.

As discussed, to evaluate the impact of a change, the construction status of different components at the time of the change should be taken into account. The 4D as-built model we talked about in this section was an attempt to record such information in the model. In this particular case, we only developed the 4D model to update designers on the new design constrains, which were imposed by the construction progress. However, the incorporation of this information into the BIM is a necessary for a BIM-based change management system. The importance of including such data into the information model will be discussed in the next chapter when we talk about automatic track of the consequence of changes in BIM.

3.7 Conclusion

In this chapter, I investigated five examples of design changes and analyzed their important characteristics. I classified these characteristics to develop an ontology of changes and identified their relationships and their impact on the project costs and schedule. I also discussed the 4D as-built model that I developed during the construction of the building and highlighted the necessity of incorporating the construction statue of different components into the model in order to identify impacts of changes. This issue will be discussed in the following chapter while we set up our computational approach to track the consequence of changes in BIM.

CHAPTER 4

TRACKING THE CONSEQUENCE OF CHANGES

4.1 Introduction

In the previous chapter, we discussed fundamental characteristics of changes and arranged them in a taxonomic (subclass–super class) hierarchy to develop a BIM-based ontology of changes. In general, the first two classes of the developed ontology specify characteristics that should be considered for tracking the history of a change and the last four classes of the provided ontology focus on aspects that are essential for controlling impacts of a change. This chapter focuses on tracking on the consequence of changes. Based on the analysis provided in the previous chapter, to control the impacts of changes we need to:

1- Track the chains of all successive changes caused by a specific change (i.e., all components that have at least one of their attributes affected by the change).
2- Identify the design, procurement or construction status of the affected components.
3- Evaluate the severity of the change based on the status of the affected components.

The first step can be considered as the most challenging part of this process and we found none of the state-of-the-art BIM tools are able to identify the chains of such successive changes in an information model. This step is the primary focus of this chapter.

The second step can be an objective of 4D modeling. However, 4D models are usually developed according to the planned schedule so they need to be updated in the course of the project to include the actual construction status of different components. The dynamic 4D as-built model that was discussed in the previous chapter was an attempt to record and retain such data in an information model.

The third step is a component-based evaluation of the change impacts. This evaluation is based on the construction status of the affected components and can be either quantitative or qualitative. The quantitative evaluation needs a component-based cost estimate for different design alternatives (5D modeling) as well as the cost associated with any required alterations to the constructed or procured components. The qualitative evaluation of the change impacts, on the other hand, specifies the severity of the change impact based on a number of predefined levels of severity. This evaluation process is conducted based on the number of affected components and the construction or procurement status of each affected component. In this chapter, we only discuss the qualitative evaluation of changes but the same approach can be applied to perform quantitative evaluations if the information model contains the required cost estimates.

In the following sections, I first explain the necessity of recognizing different spatial and analytical dependencies in order to track chains of successive changes in BIM and examine the capability of the state-of-the-art BIM tools in automatic recognition of these dependencies. I then present a computational approach to identify and track the chains of successive changes in an information model. This approach can further be incorporated into the BIM tools, which are capable of recognizing spatial and analytical dependencies, to automate identification of such successive changes. I later discuss briefly about recording the construction status of different components in BIM and the qualitative analysis of change impacts based on the construction status of the affected components.

4.2 Identification of Spatial and Analytical Dependencies

In the previous chapter, we examined different types of dependencies that exist between a changed component and the affected components in an information model and classified them as a part of the developed ontology of changes (Table 3-2). These dependencies were categorized in two main subclasses of Spatial Dependencies (supported by, surrounded by, connected to, etc) and Analytical Dependencies (Structural Integrity, Architectural Consistencies, Mechanical Interaction, etc). Identification of these dependencies is the first step in recognizing the components affected by a change and the corresponding chains of successive changes. However, the variation of these dependencies and the analytical or technical logic behind them make this process complicated and challenging. In comparison with Analytical Dependencies, Spatial Dependencies are easier to be tracked as they can be formulated based on the geometry and the position of different components. In the previous chapter, we briefly discussed the capability of

Navisworks® and Solibri Model Checker™ to recognize these dependencies. As it was indicated, Navisworks® can detect a number of basic spatial dependencies such as the required clear distance between different components but it still cannot recognize most analytical dependencies. Solibri Model Checker™, on the other hand, follows a rule-based reasoning approach that interprets typical relationships between components and analyzes their interferences. This tool provides more than 50 rules that check various logical dependencies, such as whether components touch other components, if components are connected to spaces, if components are within a space, etc. Figure 4-1 depicts some examples of predefined rules in this software tool.

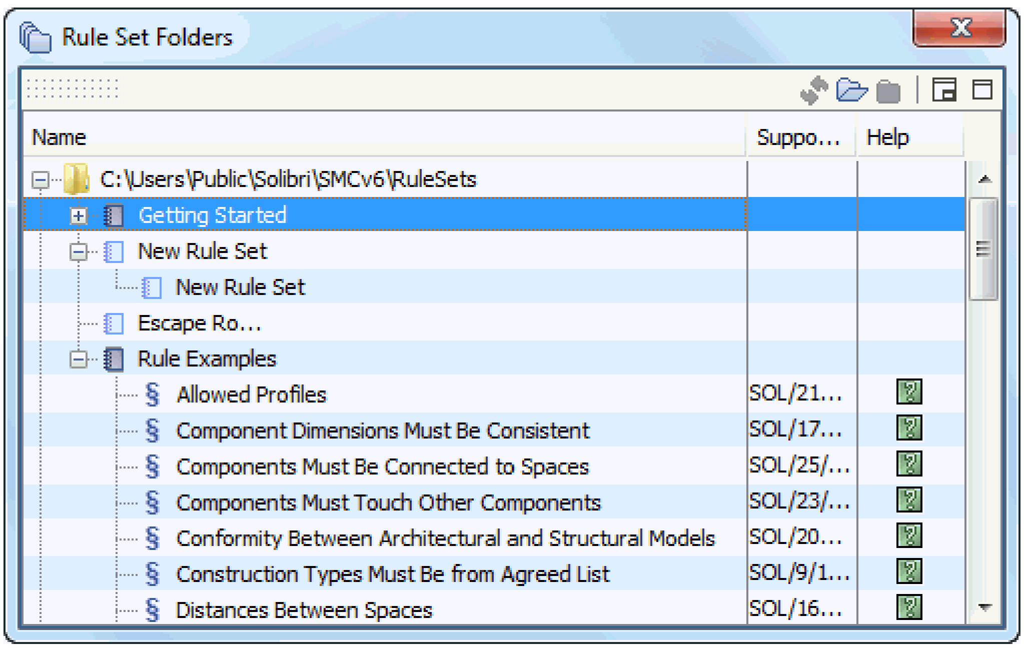


Figure 4-1 : Examples of predefined rules in *Solibri Model Checker™*

In Solibri Model Checker™, rules can have parameters, which are used to configure and customize them to fit project specific needs. Rules can also be grouped into a rule set to be used as a predefined functional unit. A rule set contains information about the rules in the set, order of the rules and possible sub rule sets, and parameter values used for the rules. Figure 4-2 illustrates the structure of different rules within a rule set (Escape Route Analysis) and depicts the parameters of one of its rules.

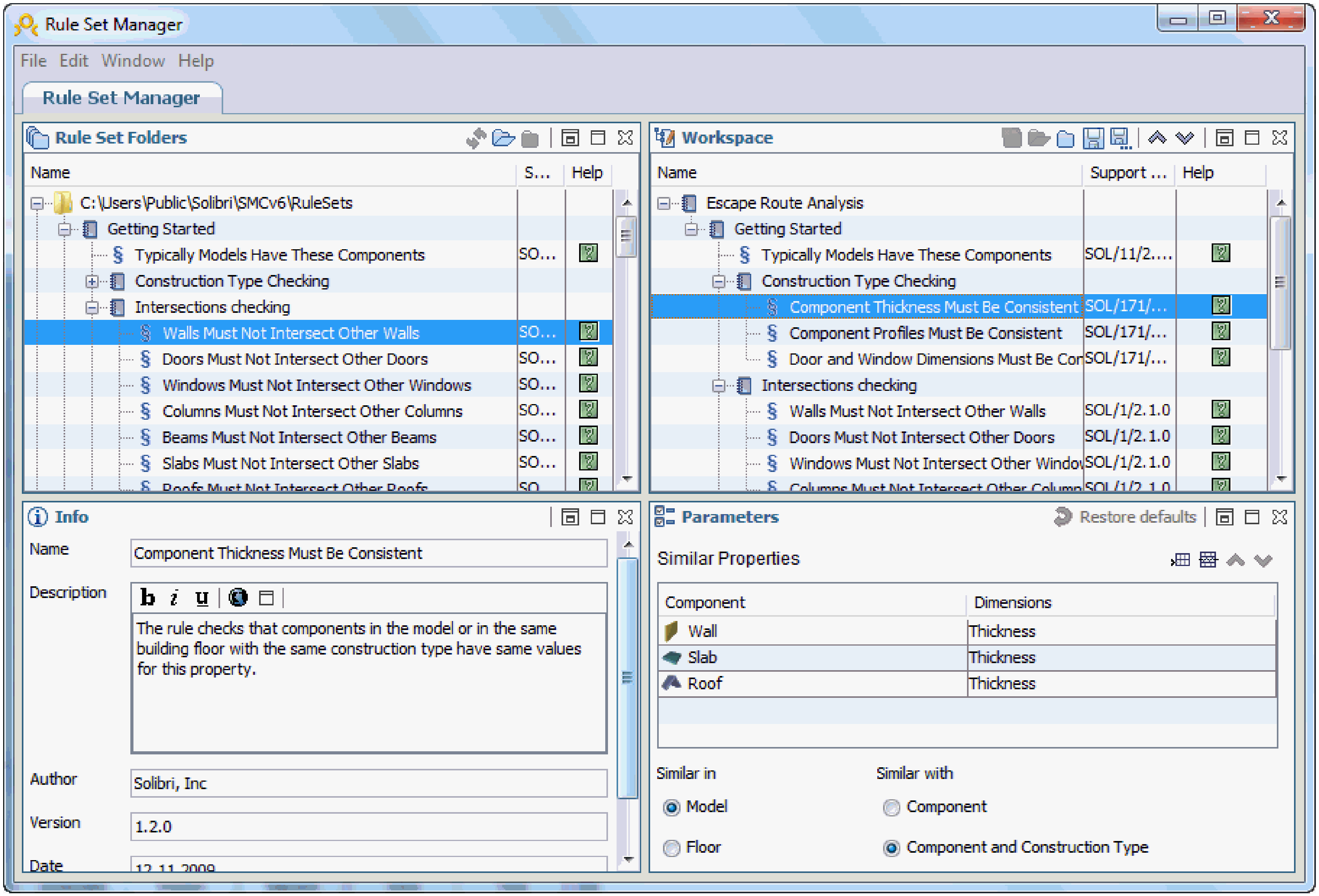


Figure 4-2 : Structure of rule sets and rule parameters in *Solibri Model Checker*™

Although the predefined rules in Solibri Model Checker^{TM} still cannot effectively recognize a wide range of logical relations, it does have the potential to automatically identify some dependencies. Specifically, the parametric logical rules can be customized into rule sets to automatically identify different dependencies between a changed component and the other components in an information model. This capability is crucial in automatic tracking of the chains of successive changes in BIM and can be subject of further researches.

In this study, however, we assume we are using an ideal BIM tool that is able to recognize all significant dependencies between components. Although this assumption seems unrealistic at first glance, it is necessary in order to separate underlying problems with automatic recognition of different types of dependencies from the challenge of tracking the chains of the successive changes, which is the main objective of this chapter. Moreover, considering the rapid improvement of BIM tools in recognizing various component dependencies, reaching such level of automation is not far away. In the next section, I present a computational approach that enables us to track the chains of successive changes with such an ideal BIM tool.

4.3 Tracking the Chains of Successive Changes

In the previous section, I examined the capability of BIM tools in automatic recognition of different types of dependencies between the model components. As discussed, the commercially available BIM tools cannot still recognize a wide range of these dependencies. However, for the purpose of this study, we assume we are using an ideal BIM tool that is able to recognize all significant dependencies between components. Based on this assumption, I attempt to develop a computational approach for such BIM tools to enable them to track the chains of all successive changes caused by a change in a single component attribute.

In this section, I first use an example to present the concept of a Dependency Network. I then introduce Dependency Matrix, which is a numerical representation of the Dependency Network. The Dependency Matrix later is used to calculate the Vector of Changes, which defines whether each component attribute has changed or not.

4.3.1 Dependency Network and Dependency Matrix

In this subsection, I use the Example #5 from Chapter 3 to present the concept of a Dependency Network and Dependency Matrix. This example is suitable for the purpose of this section since it is simple and only considers the dependencies between two main components, i.e., the loading dock sloped slab formwork and reinforcing steel. However, the concept of this example is generic and can be extended to more complex situations as well. In this example, I explained the change in the loading dock slope and its consequential effects on the slab reinforcing steel. Here I elaborate different dependencies between the attributes of the slab formwork (component #1) and the slab reinforcing bars (component #2) and attempt to represent these dependencies in the form of a diagram, which we call a Dependency Diagram.

To examine the effects of the change in the formwork of the concrete slab on its reinforcing bars we need to understand different dependencies between the attributes of these two components. Figure 4-3 summarizes these dependencies in the form of a Dependency Diagram. In this diagram, each arrow shows a type of dependency between two component attributes. The arrow tail specifies the changed component attribute and its head points to the affected component attribute. The tree-letter abbreviation beside each arrow indicates the type of dependency between two attributes. These abbreviations were already defined in Table 3-3. If the arrow presents more than one type of dependency, the abbreviations of each type of dependency are indicated beside the arrow and are separated by semicolon.

As it can be observed in Figure 4-3, any changes in the formwork position will affect the reinforcing bars positions too. This is because the reinforcing bars are surrounded by the formwork (SRB spatial dependency). Likewise, any changes in the formwork geometry will affect the geometry of the reinforcing bars. Moreover, changes in the formwork geometry, for example the height of the slab, may also affect the size and the arrangement of the reinforcing bars to fulfill structural design requirements such as the minimum amount of steel per cross-sectional area of the slab (SI analytical dependency). However, changes in the formwork specifications (such as material) usually will not affect reinforcing bars.

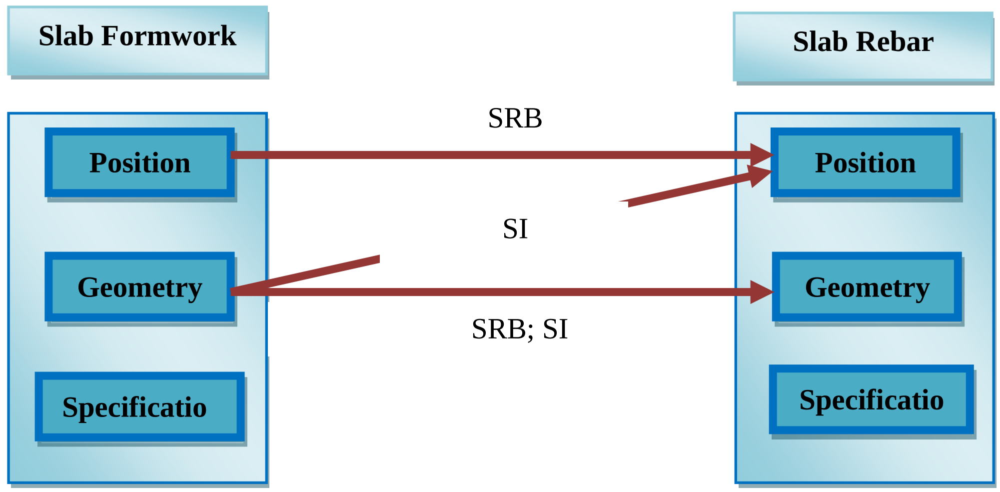


Figure 4-3 : Dependence of the rebar attributes on the formwork attributes

Likewise, we can consider the effects of changes in the slab reinforcing bars on its formwork as presented in Figure 4-4. In this case, changes in the reinforcing bars position or geometry does not affect the formwork since the geometry and the position of formwork should be consistent with architectural requirements. In fact, any changes in the reinforcing bars shape or arrangements should be made so that they remain inside the formwork space and in a proper distance to the formwork surfaces to maintain minimum cover. However, changes in reinforcing bars specifications (such as their strength) may cause change to the slab thickness (formwork geometry) to fulfill structural requirements (SI analytical dependency). In such cases, however, the position of slab, for example the top of slab elevation, does not change.

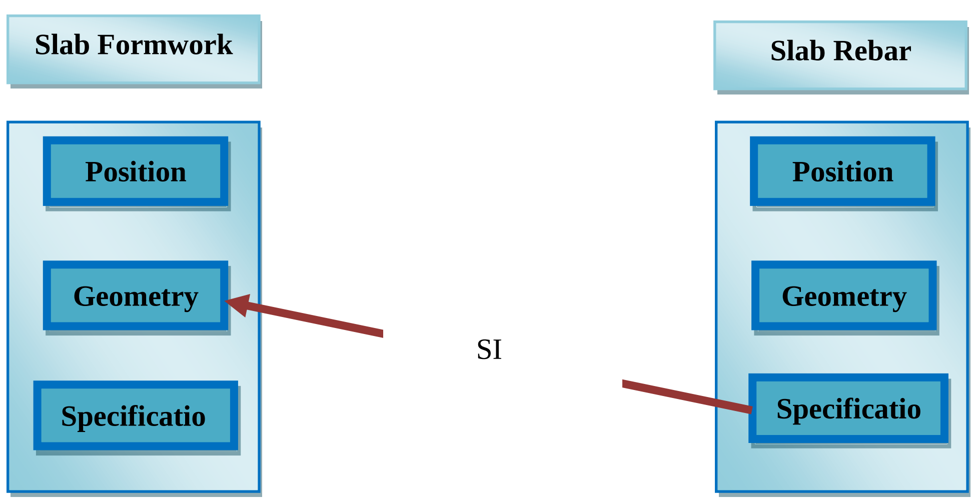


Figure 4-4 : Dependence of the formwork attributes on the rebar attributes

Moreover, we can consider the effects of changes in an attribute of each individual component on the other attributes of the same component. Figure 4-5 depicts a diagrammatic presentation of this situation. As this diagram represents the dependence between attributes of individual components, we call it Internal Dependency Diagram. Now we review each component separately. In terms of slab reinforcing steel, a change in the rebar strength (specification) usually affects the number and the arrangement of the reinforcing bars (position). It also affects the overlap length (geometry) of them. However, changes in the reinforcing bars position usually does not affect their geometry or specification. Finally, changes in the reinforcing bar geometry do not affect their specification but usually change their position. With respect to slab formwork, changes in the formwork specification or position do not affect the other attributes but a change in the formwork geometry, for example its slope, may require adjustments in its position.

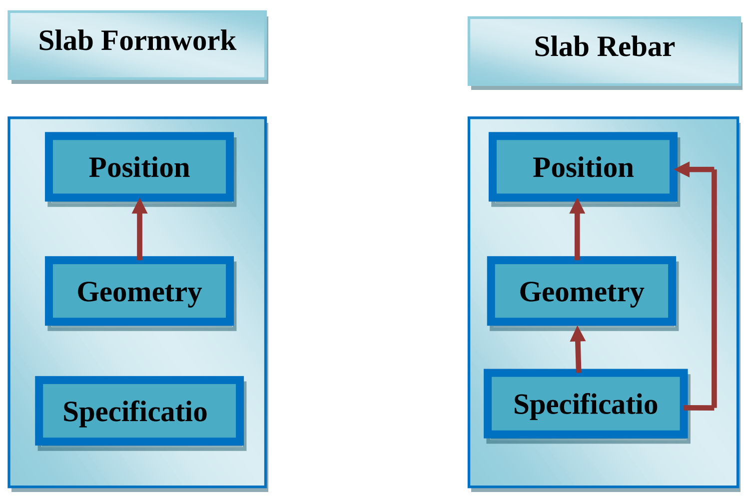


Figure 4-5 : Internal dependencies between the attributes of each component

In summary, we can combine the previous diagrams and provide a single Dependency Diagram that represents different spatial and analytical dependencies between the attributes of the slab formwork and reinforcing bars. Figure 4-6 shows this Dependency Diagram.

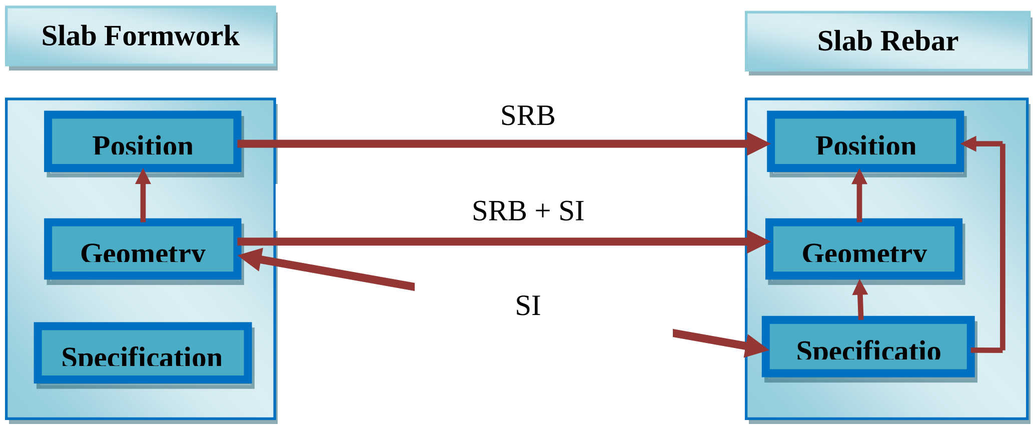


Figure 4-6 : Dependency diagram between the slab formwork and rebar

The approach that we used to develop a Dependency Diagram for this example can be extended to other situations too. To generalize this approach, I number the components, the component attributes, and the dependencies between these attributes. Figure 4-7 provides this numeric representation of the Dependency Diagram we developed earlier. In this figure, the slab formwork is “component #1” and the slab rebar is “component 2”, and their position, geometry and specification are attributes #1, #2 and #3. Based on this type of representation, for example, we can say a change in attribute #1 (position) of the component #1 (formwork) will cause change in attribute #1 (position) of component #2 (rebar) because of the dependency type of R1 (spatial dependency- Surrounded By) between them.

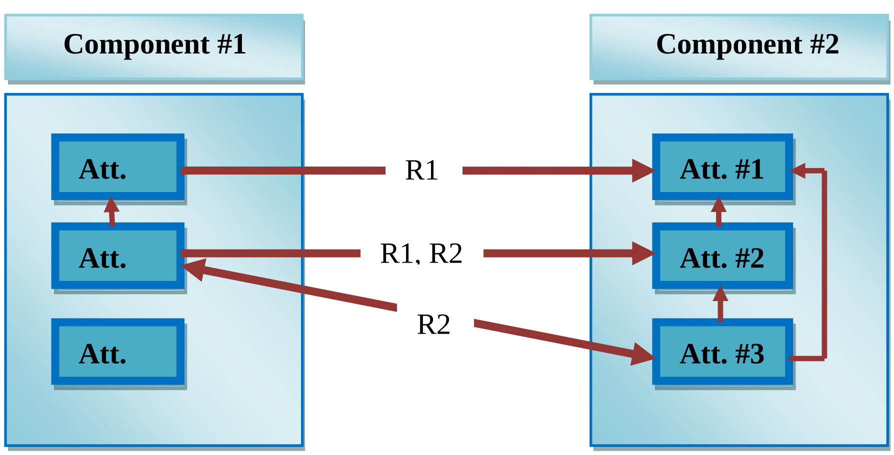


Figure 4-7 : Typical dependency diagram between two components (Corresponds to the provided example of the slab formwork and rebar)

According to the graph theory, we can represent this diagram in the form of a logical matrix (i.e., a matrix that contain just two different values of 1 and 0 meaning "Yes" and "No") . This matrix, which is the basis of our computational approach, shows whether two component attributes are connected by a dependency arrow or not and simply save this information in a numerical format that can be used for the programming purpose. As this matrix includes the information that is related to the component dependencies, we call it a Dependency Matrix. The Dependency Matrix is produced by the integration of component-based logical matrices that represent the dependency of each component attributes with the other attributes of the same components or the attributes of another component. Figure 4-8 illustrates the development of Dependency Matrix for the provided example. This figure depicts four component-based logical matrices (i.e., D11, D22, D12, and D21) that respectively correspond to the internal dependency diagrams of Component #1 and #2, the dependency diagram of Component #1 to #2, and the dependency diagram of Component #2 to #1. As it can be observed, logical values of the entry in the *p*-th row and the *q*-th column of a each matrix (d*pq*) illustrates whether there is a dependency between *p*-th attribute of the first component and *q*-th attribute of the second component or not. It should be noted that when we consider internal dependencies (D11 and D22), the first and second components are identical.

Accordingly, a generic illustration of Dependency matrix is provided as follows:

$$\text{D= Dependency Matrix} = \begin{bmatrix} |D11| & \cdots & |D1n| \\ \vdots & Dij & \vdots \\ |Dn1| & \cdots & |Dnn| \end{bmatrix},$$

$$D_{ij} = \text{Dependency Matrix between component i and j} = \begin{bmatrix} d11 & \cdots & d1m \\ \vdots & \mathrm{dpq} & \vdots \\ dm1 & \cdots & dmm \end{bmatrix}$$

$$d_{pq} = \begin{cases} 1: & if\ change\ in\ the\ attribute\ p\ of\ the\ component\ i \\ & affects\ the\ attribute\ q\ of\ the\ component\ j \\ & \\ 0: & if\ change\ in\ the\ attribute\ p\ of\ the\ component\ i \\ & does\ not\ affect\ the\ attribute\ q\ of\ the\ component\ j \end{cases}$$

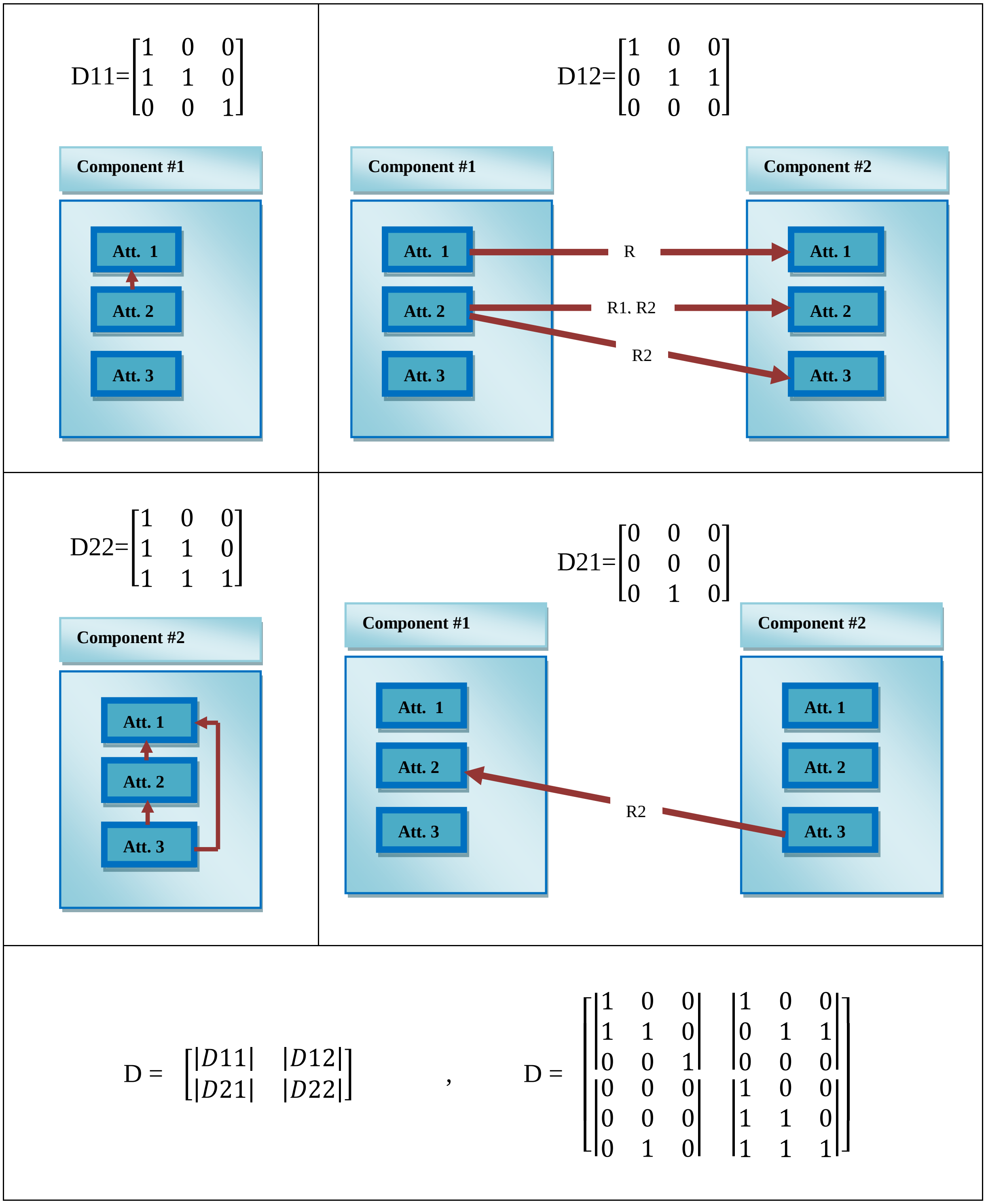
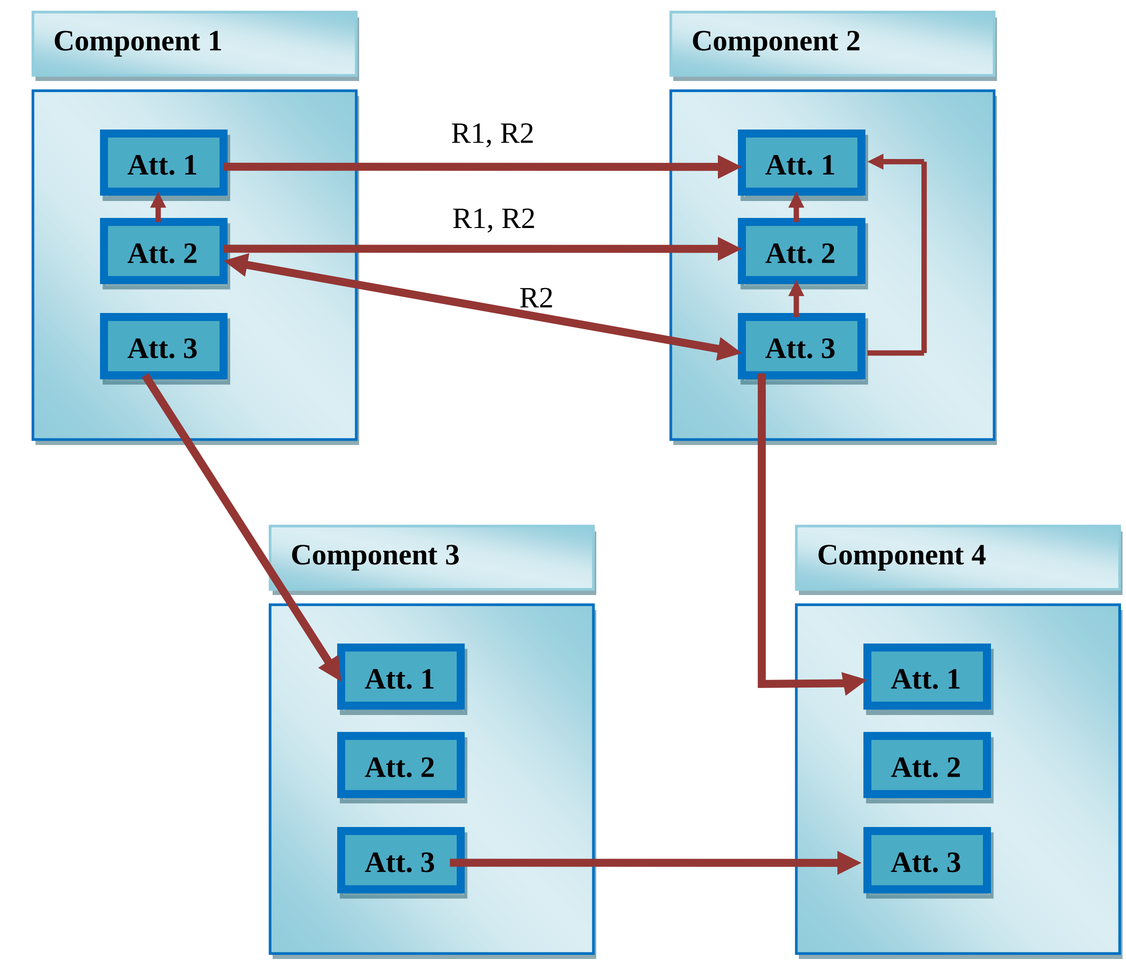


Figure 4-8 : Integration of component-based logical matrices to form a dependency matrix (Corresponds to the provided example of the slab formwork and rebar)

Likewise, we can integrate all component-based Dependency Diagrams and develop a Dependency Network (See Figure 4-9). Accordingly, the Dependency Matrix corresponds to this network presents all relationships between attributes in the network as explained above.



$$D = \begin{bmatrix} |D11| & \cdots & |D14| \\ \vdots & \ddots & \vdots \\ |D41| & \cdots & |D44| \end{bmatrix}$$

Figure 4-9 : Typical dependency network and matrix for a model with four components

4.3.2 Vector of Changes

Vector of changes is a matrix with one row only (row vector). Each entry of this vector has a logical value (0 or 1) that defines whether each component attribute has changed or not. A generic definition of this vector is provided as follows:

C = Change Vector = {[C1], …., [Cn]}

[Ci] = Change vector for component i = { $c_1, \ldots, c_j, \ldots, c_m$ }

$$c_j = \begin{cases} 1: & \textit{if attribute j of the component i has changed} \\ 0: & \textit{if attribute j of the component i has not changed} \end{cases}$$

For instance, in the provided example of concrete slab if the geometry of the formwork (second attribute of the first component) changes the Change Vector will be:

C_0 = {[0 , 1 , 0] , [0 , 0 , 0]}

This initial change vector only determines the initial change and not the changes that happen as the consequence of this initial change. Therefore, we call it C_0. The effect of this change on the other component attributes can be determined by the product of multiplying this vector and the Dependency Matrix:

$C_1 = C_0 * D$

Since the value of each entry should be a logical value (i.e., cannot be greater than 1), we assume 1 + 1 = 1. Thus:

$$C_1 = \{[\,0 , 1 , 0\,] , [\,0 , 0 , 0\,]\} * \begin{bmatrix} \begin{vmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} & \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{vmatrix} \\ \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{vmatrix} & \begin{vmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{vmatrix} \end{bmatrix} = \{[\,\underline{\mathbf{1}} , 1 , 0\,] , [\,0 , \underline{\mathbf{1}} , \underline{\mathbf{1}}\,]\}$$

The calculated change vector (C_1) indicates the direct effect of the initial change vector (C_0) that are changes in the first attribute of the first component and the second and the third attributes of the second components (bolded and underlined in C_1 vector). This vector shows the first group of affected component attributes in the series of successive changes caused by the initial change. These component attributes were affected because they had a direct dependency with the changed component attribute (second attribute of the first component). These direct dependencies are shown by solid line in Figure 4-10. These new changes also generate a second group of successive changes. The attributes affected by these successive changes can also be determined by the product of C1and the Dependency Matrix as follows:

$$C_2 = C_1 * D$$

$$C_2 = \{[\,1\,,1\,,0\,]\,,[\,0\,,1\,,1\,]\} * \begin{bmatrix} \begin{vmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} & \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{vmatrix} \\ \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{vmatrix} & \begin{vmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{vmatrix} \end{bmatrix} = \{[\,1\,,1\,,0\,]\,,[\,\underline{\mathbf{1}}\,,1\,,1\,]\}$$

As the result shows, the first attribute of the second component (bolded and underlined in C_2 vector) will be affected by these successive changes, which are the result of dependencies between the new changed component attributes and the other attributes. These dependencies are shown by dotted line in Figure 4-10.

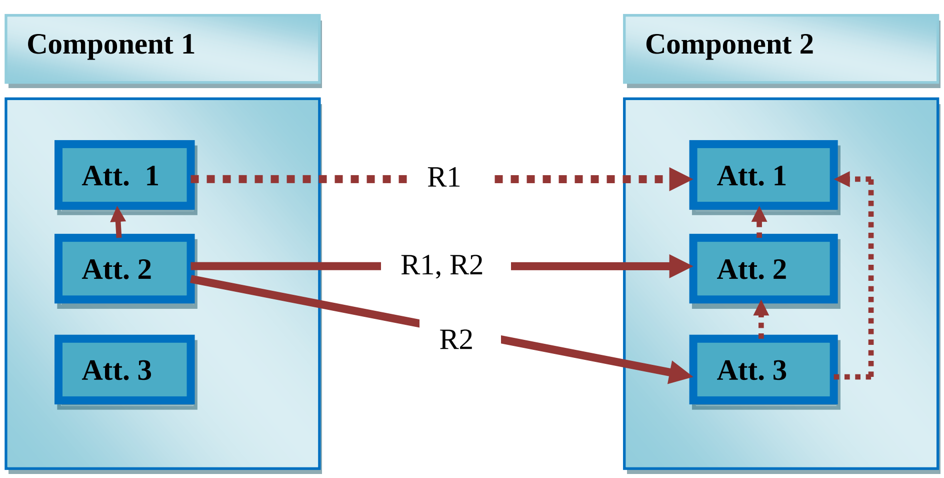


Figure 4-10 : Direct and indirect dependencies

This chain of successive changes (C1, C2,…, Ci) continuous until no new attribute is affected by the last group of effected attributes (Ci = C i-1). The equality between two successive change vectors demonstrates that no further attributes will be affected by the initial change or other successor changes. This means we reach to the end of the chain of changes and denotes the stop of the calculation. In this example, by performing the third iteration we will reach to this point. The relevant calculation is provided below:

$$C_3 = \{[\,1\,,1\,,0\,]\,,[\,1\,,1\,,1\,]\} * \begin{bmatrix} \begin{vmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} & \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{vmatrix} \\ \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{vmatrix} & \begin{vmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{vmatrix} \end{bmatrix} = \{[\,1\,,1\,,0\,]\,,[\,1\,,1\,,1\,]\}$$

$$C_3 = C_2$$

As it can be observed, C3=C2 that means no further attribute will be affected by this chain of changes.

In summary, this calculation shows that by a change in the second attribute of the first component (geometry of the formwork), all other attributes except the third attributes of the first component (specification of the formwork) might be affected either directly or indirectly. This result was obvious from the beginning since our focus was on two components only and we clearly knew the dependencies between the attributes of these components. However, this process becomes more complicated when the number of components increases. In this situation, identifying the effects of different types of dependencies and manually tracking the chain of successive changes caused by these dependencies becomes highly complex and almost impossible. Presenting this process in a numerical format that can be used for the programming purpose develops a potential for automating this process. This provides BIM tools with the capability of tracking the chain of successive changes in an information model.

4.4 Qualitative Analysis of Change Impacts

The focus of the previous section was on identification of the components that are affected by a change in BIM. In this section, we assume we have already identified all affected components and now we aim to evaluate the severity of the change based on the number of affected components and the design, procurement, and construction status (DPC status) of each affected component.

As discussed previously, with the progress in design and construction the cost and time impacts associated with changes will increase significantly. Therefore, for evaluation of theses impacts, the information model should also contain the DPC status of every component. The 4D as-built model discussed in the previous chapter was an attempt to record this information in the model. In general, the linkage between the model components and the schedule in 4D modeling is a potential for incorporating the DPC status of individual components into the information model. However, commercially available BIM tools still are not able to record this data effectively.

Table 4-1 provide a sample qualitative scale for the effects of a change in a specific component that is based on the DPC status of the component. To evaluate the effect of a change we first need to know which components were affected by that change. After we identified all affected components, we then evaluate the level of severity of the change corresponds to each affected component. This component-based evaluation is based on the DPC status of each affected component. The level of severity is determined based on a number of predefined levels (e.g., low, medium, and high). Finally, the number of changed components corresponds to each level can serve as an overall indicator for the severity of the change.

Table 4-1 : Levels of severity of changes based on the DPC status

DPC Status	Design completed	Procurement Completed	Construction Completed
Level of Severity	Low	Medium	High

4.5 Conclusion

In this chapter, I investigated the capability of the state-of-the-art BIM tools in automatic identification of different types of spatial and analytical dependencies between the component attributes. This investigation showed that although commercially available BIM tools still cannot effectively recognize a wide range of such logical relations, they have the potential to identify them automatically. I then presented a computational approach to identify and track the chains of successive changes in an information model. I presented the tracking process in a numerical format that can be used for the programming purpose and can be incorporated into the BIM tools, which are capable of recognizing spatial and analytical dependencies, to automate identification of such successive changes. I also discussed about recording the construction status of different components in BIM and the qualitative analysis of change impacts based on the construction status of the affected components.

CHAPTER 5
SUMMARY AND CONCLUSION

This chapter summarizes the obtained results from the analysis of the case study. In the following sections, I briefly discuss the content of each chapter and review their outcomes. According to the results obtained through this study, I then provide some possible directions for further researches on development of BIM-based change management systems.

5.1 Summary and Conclusion

In this research, I conducted a case study to examine change management in the context of a multi-disciplinary collaborative BIM environment during the design and construction of a fast-track project. In the course of the project, I attended and recorded more than forty BIM coordination meetings and conducted more than eighty site visits and documented numerous examples of changes encountered throughout the design and construction of the building. I analysed five examples of these changes in Chapter 3 and attempted to identify different facets that are essential in establishing a BIM-based change management system. I explored the relationship between these conceptual characteristics throughout the evolution of BIMs and categorized them in a taxonomic hierarchy to develop an ontology of changes as presented in Table 3-2. This ontology provides common understanding of changes characteristics for practitioners who develop or utilize BIM tools for managing changes. I also explained my attempt to develop a 4D dynamic as-built model with the aim of recording the construction status of the individual model components and elaborated the challenges I faced in this process.

During the course of this study, I also examined the capability of three state-of-the-art BIM tools, i.e., Autodesk® Revit® , Navisworks® , Solibri Model Checker™, in the context of BIM-based delivery of a fast-track project and investigated their potential benefits and problems in comparison with 2D change management tools such as Vico Doc Set Manager™.

Finally, in the fourth chapter, I examine the capability of the state-of-the-art BIM tools in automatic recognition of different types of spatial and analytical dependencies, which were already defined as a part of the ontology presented in the third chapter. I then proposed a computational approach that develops the potential for automatic track of successive chains of changes in BIMs. This provides BIM tools with capability of analyzing the consequence of changes based on the construction status of each individual component.

5.2 Suggestions for Further Research

Further research is required to investigate different spatial and analytical dependencies and to identify various facets that are important for automatic recognition of these dependencies in an information model. These facets further can be added to the ontology that I developed during this study. These new facets may fit into the provided classes or sub-classes or need to be considered as a new class or sub-class. Additional research also is required to implement and test these characteristics, and to analyze different types of changes across different types of projects based on the developed ontology.

Research should also be conducted to explore logical rules behind each type of dependency to formulate them based on the relevant parameters in a way that it can be adopted by BIM tools such as Solibri Model Checker™ in the form of dependency rule sets. Moreover, effort should be made to implement the presented computational approach into the commercially available BIM tools in order to track the chain of successive changes in information models and predict the impact of changes subsequently.

As another research area, a similar computational approach can be developed for tracking the history of changes in BIMs. For this purpose, as a proposal , a diagrammatic representation can be developed that identifies if a new component is the result of a split in an older component, combination of older components, modification in the attributes of an older component, or just a new independent component. The component-based diagrams then can be integrated into a network diagram that present the history of all changes in the information model. Based on the graph theory, the network diagram can be presented in numerical format that is readable by computer programs.

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APPENDIX 1: CONSTRUCTION PHOTOS

July 2010

August 2010

September 2010

October 2010

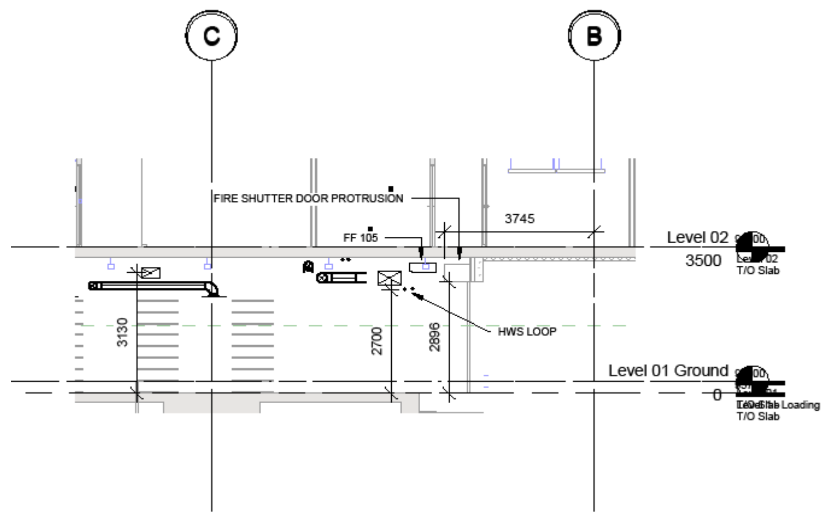
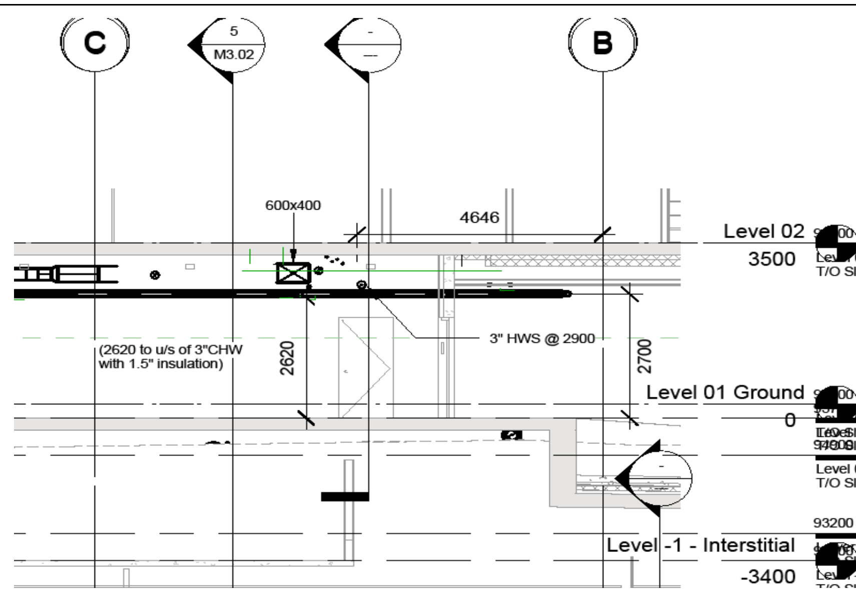
November 2010

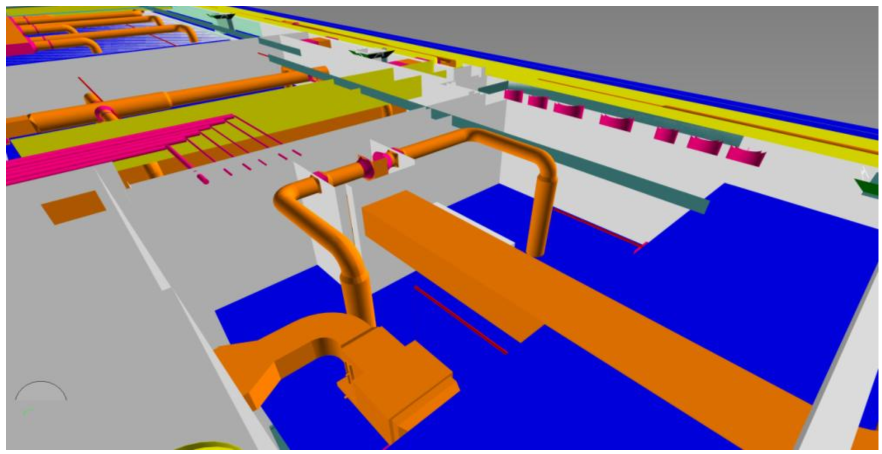
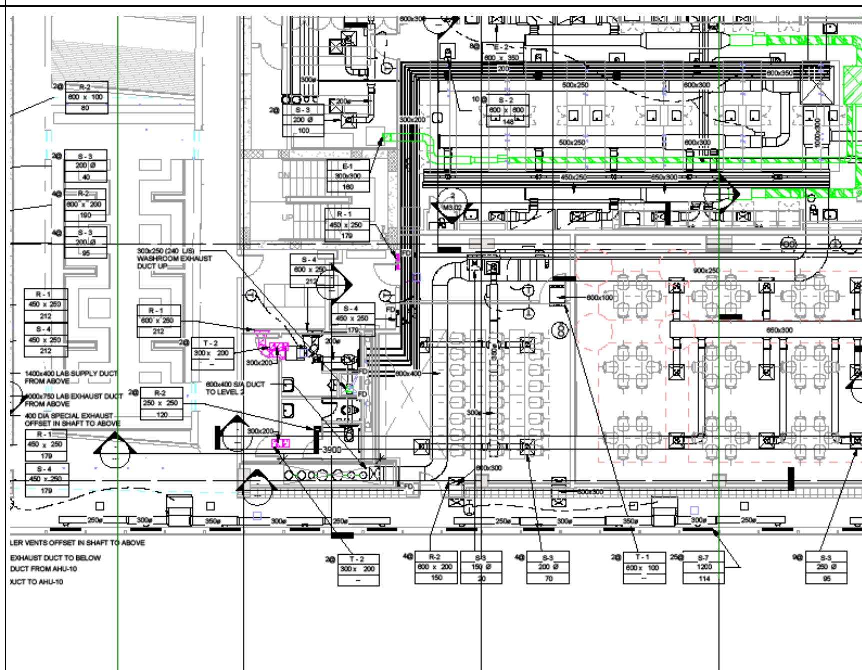
December 2010 to January 2011

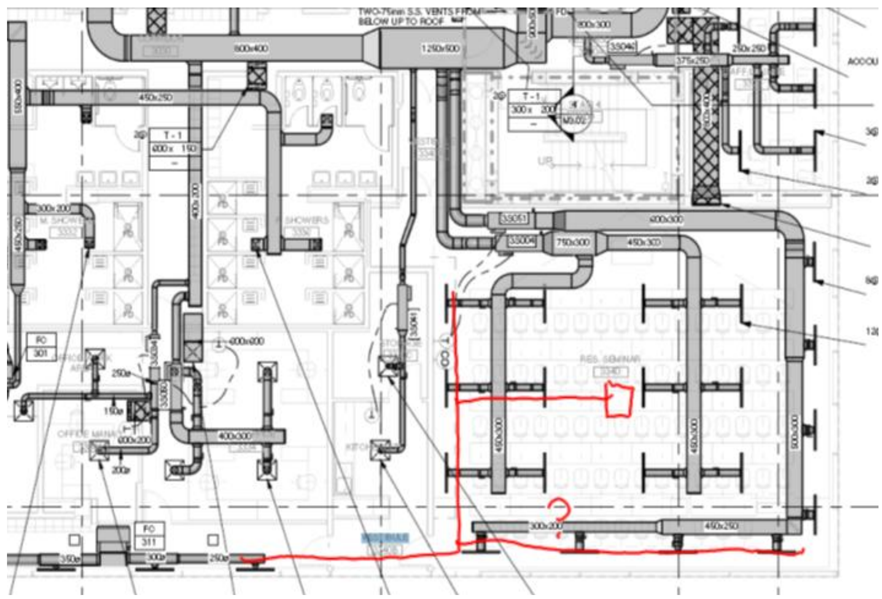
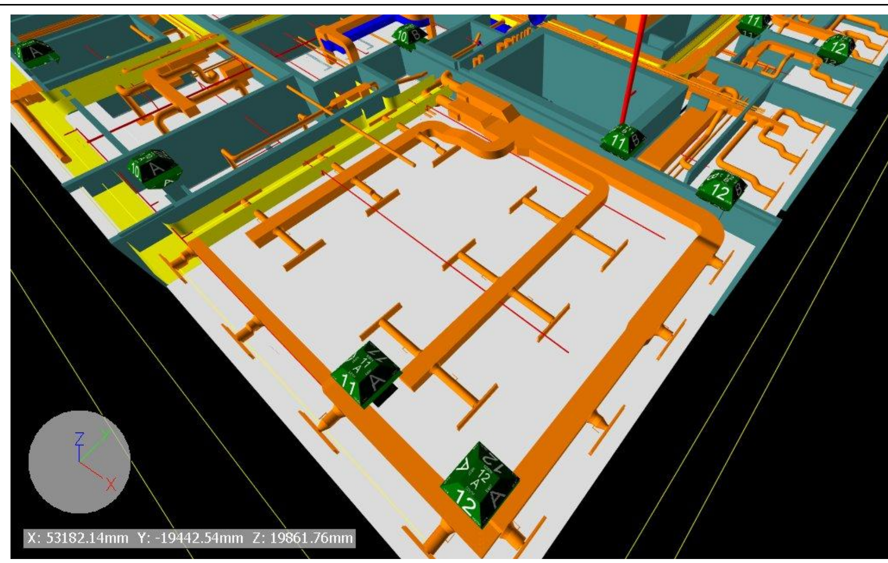
February to May 2011

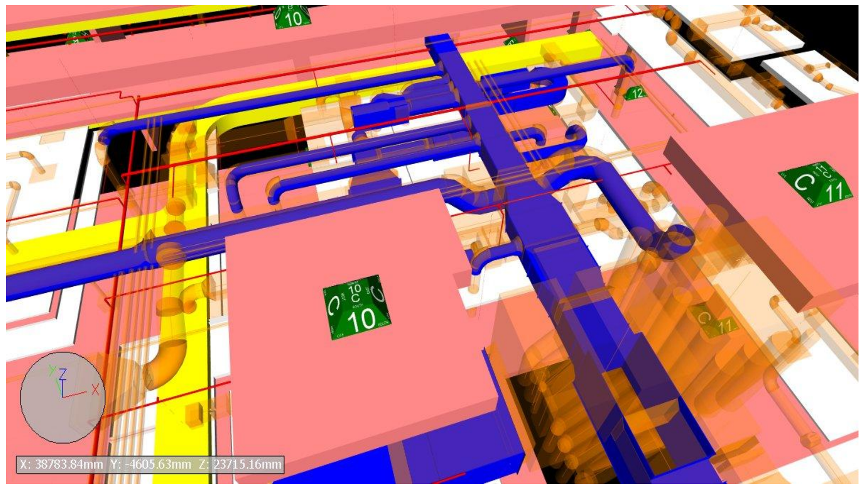
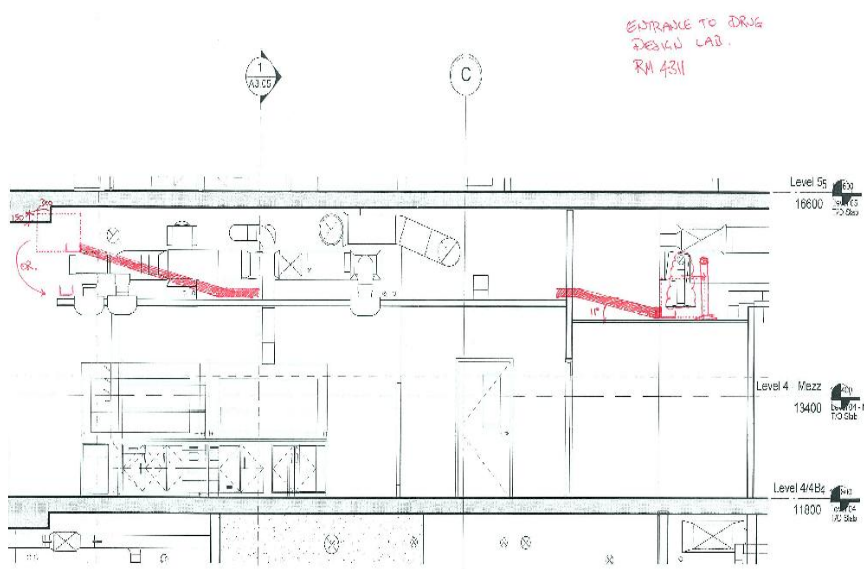
Jun to July 2011

APPENDIX 2: SAMPLE CLASH REPORTS

<table>
<tr><td>Clash ID</td><td>Status</td><td>Action Required By</td><td>Received Date</td><td>Resolved Date</td></tr>
<tr><td>Level 1East</td><td></td><td>KPH</td><td>19 April, 2011</td><td>Pending</td></tr>
<tr><td colspan="2">Design Drawing References</td><td colspan="3">-</td></tr>
<tr><td colspan="2">Issue Description</td><td colspan="3">Adequate clearance required at loading bay doors</td></tr>
<tr><td colspan="2">Sketch Plan/ Section/ 3D</td><td colspan="3">
</td></tr>
<tr><td colspan="2">Solution Description</td><td colspan="3">Heating & Chilled Pipe work to move up as high as possible- Heating running E-W will be 2900 to centre of pipe. Chilled running N-S will be 2620 to underside of insulation. HCMA to check this issue with UBC.</td></tr>
<tr><td colspan="2">Sketch Plan/ Section/ 3D</td><td colspan="3">
</td></tr>
</table>

Clash ID	Status	Action Required By	Received Date	Resolved Date
Level 3 CEN-B			26 April, 2011	26 April, 2011
Design Drawing References		A2.13 E4.04 M2.08 M2.09 P2.05		
Issue Description		Level 3 Central along South Corridor by washrooms. Duct connecting to level 2 runs in corridor along same route as cable tray.		
Sketch Plan/ Section/ 3D				
Solution Description		Duct to drop within pipe work riser rather than within washroom.		
Sketch Plan/ Section/ 3D				

Clash ID	Status	Action Required By	Received Date	Resolved Date
Level 3 CEN-D			21 April, 2011	26 April, 2011
Design Drawing References		A2.13 E4.04 M2.08 M2.09 P2.05		
Issue Description		Level 3 East room 3340. Is cable tray required along Sought side of the room?		
Sketch Plan/ Section/ 3D				
Solution Description		Confirmed as not required along this side. AV can be routed in conduit from tray along west side of the room.		
Sketch Plan/ Section/ 3D				

<table>
<tr><td>Clash ID</td><td>Status</td><td>Action Required By</td><td>Received Date</td><td>Resolved Date</td></tr>
<tr><td>Level 4East-B</td><td></td><td>WPE</td><td>3 May, 2011</td><td>Pending</td></tr>
<tr><td colspan="2">Design Drawing References</td><td colspan="3">A2.14 E4.05 M2.10 M2.11 P2.06 P2.11</td></tr>
<tr><td colspan="2">Issue Description</td><td colspan="3">LEVEL 4 EAST DRUG DESIGN LAB 4311
CABLE TRAY ROUTING TO AVOID MECH SERVICES</td></tr>
<tr><td colspan="2">Sketch Plan/ Section/ 3D</td><td colspan="3">
</td></tr>
<tr><td colspan="2">Solution Description</td><td colspan="3">Cable tray to be run at high level close to underside of slab or above end of ceiling fingers. To be as unobtrusive as possible in open ceiling area.
WPE to alert tray elevation to be just above lighting zone.</td></tr>
<tr><td colspan="2">Sketch Plan/ Section/ 3D</td><td colspan="3">
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