REQUIREMENTS FOR BIM-BASED BUILDING DESIGN COORDINATION PROCESSES

by

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Abstract

Building design coordination is a critical and challenging task to ensure that the design meets the functional, aesthetic, and economic requirements of project stakeholders. The cost of design coordination can be significant, with some estimating as high as two percent of the total cost on projects. It is therefore imperative that coordination issues get resolved as efficiently as possible, particularly given that thousands of conflicts may be identified during design coordination.

Even with implementation of Building Information Modelling (BIM) project participants still face significant challenges that disrupt and hinder the coordination process. I have identified three critical issues that impact the successful implementation of BIM in design coordination processes: (1) the extent of BIM-based design coordination processes and protocols implemented, (2) the efficiency and ease in which practitioners interact with state of the art of BIM tools, and (3) the effectiveness in which design coordination issues are captured, represented and documented. Very little research has specifically looked at the BIM-based building design coordination with such focus.

This dissertation investigates BIM-based building design coordination through the lens of two state of the art public sector projects. The research involved embedded case study analyses and a mixed-method contextualist research approach that included iterative grounded theory and co-production of knowledge.

The investigation of BIM-based design coordination resulted in the formalization of design coordination processes, identification of bottlenecks faced by practitioners, and development of design considerations for BIM tools. The exploration of design coordination meetings resulted in taxonomy of interactions with design artifacts, outlining the relationships between goals, artifacts, interactions and transitions. The research on design coordination issue representation resulted in a

classification taxonomy that explicitly represents process-based, model-based, and physical design issues.

This research has many practical implications to the construction industry, as well as the BIM software development community. The research enables practitioners and researchers to better understand the challenges of BIM-based design coordination processes, helps the software development community to design state of the art BIM tools to better support practitioner interactions and navigations with BIM, and better manage and represent design coordination issues encountered throughout the coordination process.

Lay Summary

This dissertation investigated two state of the art public sector projects in Canada to better understand practitioner requirements in BIM (Building Information Modelling)-based building design coordination. Although the implementation of BIM has resulted in numerous benefits and efficiencies in the design coordination process, project participants still face significant challenges that disrupt and hinder the coordination process, even when BIM tools are readily available. I investigated current BIM-based design coordination practices and processes, the bottlenecks encountered, and the required functionality of BIM coordination tools. Next, explored how and why participants interact with different types of design artifacts when analyzing and resolving design coordination issues, and identified necessary functionality for a BIM-enabled coordination environments. Finally, I developed a formal classification to support issue representation, resolution and documentation. The contributions of this dissertation will inform the construction industry, as well as the software development community, to better understand and manage BIM-based building design coordination processes.

Preface

The core focus of this research work is understanding the requirements for BIM-based building design coordination processes. The research included analysis on three levels: (1) formalization of the design coordination processes: (2) characterization of interactions with and transitions between design artifacts, and (3) representation of design coordination issues. The author of this research work is solely responsible for all the content presented in this manuscript-based thesis that relates to the literature review, case studies, interviews, model and document analyses, video analysis, development of the process, interaction and design issue frameworks, and the detailed methodology to support the research questions.

Much of the content of this dissertation is in the form of manuscripts prepared for publication. For each of these, the dissertation author (Mehrbod) was the primary manuscript author, while the other co-authors provided guidance on the development and application of various aspects of the research as well as manuscript review and editing. The research has been carried out under the certificate obtained and renewed from the University of British Columbia, Behavioral Research Ethics Board, with the certificate number H12-03693.

The following three journal papers have been submitted for publication:

> A version of Chapter 2 has been submitted to a journal on May 2018, and a minor revision was submitted September 2018. The full paper reference is: Mehrbod, S., Staub-French, S., and Tory, M. (2018). *BIM-based Building Design Coordination: Processes, Bottlenecks, and Tools.*

A version of Chapter 3 was submitted to a journal on December 2016, and after several major revisions and a minor revision, was submitted September 2018. The full paper reference is: Mehrbod, S., Staub-French, S., Mahyar, N., and Tory, M. (2018). *Characterizing Interactions with BIM Tools and Artifacts in Building Design Coordination Meetings.*

A version of Chapter 4 was submitted to a journal on August 2018, and a minor revision was submitted October 2017. The full paper reference is: Mehrbod, S., Staub-French, S., Mahyar, N., and Tory, M. (2018). *Beyond The Clash: Investigating BIM-Based Building Design Coordination Issue Representation and Resolution.*

The following peer-reviewed conference papers have been published in conference proceedings:

Mehrbod, S., Staub-French, S., and Bai, Y. (2017). Analysis of Bottlenecks in BIM - based Building Design Coordination Process and Benchmarking State of the Art BIM Tools. *Canadian Society for Civil Engineering Annual Conference*, Vancouver, BC, pp. 55.1– 55.10.

Mehrbod, S., Staub-French, S., Tory, M., and Mahyar, N. (2015). A Framework for Classifying BIM Design Coordination Issues. *Canadian Society for Civil Engineering Construction Specialty Conference*, Vancouver, BC, pp. 329.1 – 329.10.

Mehrbod, S., Staub-French, S., and Tory, M. (2013). Interactions with BIM tools in design coordination meetings. *Canadian Society of Civil Engineering 4th Construction Specialty Conference*, Montreal, Quebec, pp. 197.1– 197.10.

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Glossary

Artifacts researchers commonly use the term ‘artifact’ to describe an object of any medium (e.g. paper) that supports access to design information (Schmidt and Wagner, 2004). including the project’s records set (drawings, manuals and specifications), and any digital project information such as CAD files and building information models.

Axial Coding is an approach which reassembles fractured data, and group code labels produced during coding, core categories by constant comparison (Glaser and Strauss, 2009).

BIM the term BIM is used in a broader sense of ‘BIG BIM’ (Redmond, Hore, Alshawi, and West, 2012) that is seen as a key component to efficient design coordination and review processes, and has been used within two different contexts of Building Information Model from a “product” view (NBIMS, 2007), and from the “process” view (CIC, 2009).

BIM Coordinator is the person(s) who is in charge of model integration, examination of clashes, and documentation of design coordination issues.

Clash is a conflict that is detected through an automated clash detection function of BIM tools when two or more building elements occupy the same space (Eastman, Eastman, Teicholz, and Sacks, 2011).

Design Coordination Issues are the more complex conflicts between systems that are either not detected through automated clash detection or require further examination.

Ethnographic Research is a qualitative method where researchers observe and/or interact with a study's participants in their real-life environment.

IDEF0 is Integration Definition Function Modeling Technique type 0, which is used as structured representation of the functions, activities or processes within the modeled system or subject area (DOD 2001).

Interactivity is defined as "the extent to which users can participate in modifying the form and content of a mediated environment in real-time" (Steuer, 1992).

Inter-coder reliability is the extent to which independent coders evaluate a characteristic of a message or artifact and reach the same conclusion (Tinsley and Weiss, 2000).

LOD is the Level of Development based on the American Institute of Architects (AIA) (2008) report.

Meeting is a type of interaction process and as such, is analyzable relative to its inputs and outputs (Bostrom, Anson, and Clawson, 1993).

MEP Coordinator is the person(s) who is in charge of overall design coordination.

Ontology is a collection of various taxonomies that can be used to describe a domain of knowledge along with the relationships among them (Green et al. 2010)

Project Team is a multi-disciplinary group of three or more individuals who are interdependent in their tasks, interact intensively for a time-limited period, and are committed to providing a 'built' product, plan, or service (Cohen and Bailey, 1997; Tannenbaum, Beard, and Salas, 1992).

SMART Board® is the software and hardware on the interactive displays, which enables the participants to draw on top of design information, in multiple colors, erase, save screenshots, and use panning techniques to navigate through what is being displayed.

Taxonomy is the practice and science of classification of things or concepts, including the principles that underlie such classification (Green et al. 2010).

List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
AR	Augmented Reality
AEC	Architecture, Engineering, Construction
BIM	Building Information Modeling
FM	Facilities Management
HCI	Human Computer Interaction
IFC	Industry Foundation Class
MEP	Mechanical, Electrical, Plumbing
RFI	Request For Information
VR	Virtual Reality

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This long and interesting journey could not come to an end without the help, guidance, and support of many people. I am very much grateful to my supervisor, Dr. Sheryl Staub-French, for her persistent support, guidance, encouragement and trust. Her patience and enthusiasm has motivated me to overcome many obstacles throughout my PhD study and I will be always thankful for that.

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I would like to express my warmest and deepest thanks to my parents and sisters; who have supported me morally along this journey as they have always done throughout my entire life. Last but surely not least, I could not have done any of this without my wife, Neshat. Her unflinching and unconditional love and support played a great role in ensuring the success of this journey.

To my parents and wife

Who taught me the meaning of love, patience and support

Chapter 1: Introduction

Building design coordination is a critical and challenging task that is necessary to ensure the design meets the functional, aesthetic, and economic requirements of project stakeholders. During the coordination process, the components of building systems are defined and routed to avoid interferences and to comply with diverse design and operations criteria (Barton, Fryer, and Highfield, 1983). The systems typically include architectural, structural, mechanical, electrical and plumbing (MEP) designs and require extensive knowledge of building systems. The level of difficulty of the design coordination process correlates with the complexity and number of building systems in a facility (Tatum and Korman, 2000).

The cost of design coordination can be significant, with some estimating as high as six percent of the MEP cost or two percent of the total cost on light industrial construction projects (Tatum and Korman, 1999). In fact, 57% of design coordination errors potentially have a direct impact on construction costs, with some costing over $26,000 USD per design error (Lee, Park, and Won, 2012). In a traditional setting, building design coordination is conducted through visual inspection, where 2D drawings are compared and potential conflicts are identified. This process is inefficient and error-prone, and as a result, numerous conflicts often remain undetected and must be addressed in the field where it is costly and inefficient (Liston, Fischer, and Winograd, 2001). Design coordination meetings are also costly, particularly in fast track projects with significant sustainability goals (Alwan, Jones, and Holgate, 2017). It is therefore imperative that coordination issues get resolved as efficiently as possible, particularly given that thousands of conflicts may be identified during design coordination (Wang and Leite, 2016).

BIM is having a significant impact on the efficacy and efficiency of the design coordination process. Studies have shown that design coordination and conflict detection are the most frequent and valued uses of BIM in the construction sector (Bernstein and Jones, 2012). Teams using BIM tools for MEP coordination are more satisfied (Liston et al., 2001), and spend less time arguing over issues (Fischer, 2006). BIM-based design coordination improves schedule performance, cost control and productivity (Khanzode, Fisher, and Reed, 2007), reduces deficiencies on site (Rankin, Fayek, Meade, Haas, and Manseau, 2008), minimizes change orders and RFIs (Barlish and Sullivan, 2012), and improves labor productivity (Khanzode and Reed, 2009). A growing number of governmental bodies are mandating BIM as part of their contractual requirements because of the many cited benefits (Shafiq, Matthews, and Lockley, 2013).

The transition to BIM, however, constitutes a departure from traditional practice (Dossick and Neff, 2011). Figure 1 shows the current BIM-based design coordination process based on our observations of numerous projects. The design coordination process consists of a cycle of three interconnected steps: (1) Issue Identification, (2) Issue Resolution, and (3) Issue Documentation.

(1) Issue Identification: In a typical coordination process, the BIM Coordinator receives 2D and 3D digital information, project requirements, and design specifications (e.g. the minimum ceiling height, clearances required to access and service equipment) to initiate the coordination process. They then integrate the models in Navisworks Clash Detective and the system automatically identifies physical 'clashes' between components. Then the BIM Coordinator reviews the automatically detected conflicts and identifies the design coordination issues that would be analyzed in the next coordination meeting.

(2) Issue Resolution: In the second step, project stakeholders meet to review, discuss and develop solutions to resolve the identified coordination issues. Participants interact with three major design information representations, primarily 2D digital pdf's, 3D Digital

Models, and 2D physical drawings. They then make decisions about how to resolve each design coordination issue, given the time constraints and available information. The time and effort to resolve each issue can vary considerably and some issues require multiple meetings to resolve.

(3) Issue Documentation: Finally, once the discussion on the design coordination issue has reached an end, the BIM Coordinator documents the issues. At this point, based on their understanding and documentation strategy, they filter the necessary information as to which issue to capture, what details to record, and who to hold accountable. They also track each design issue separately and prepare them for the subsequent issue identification stage.

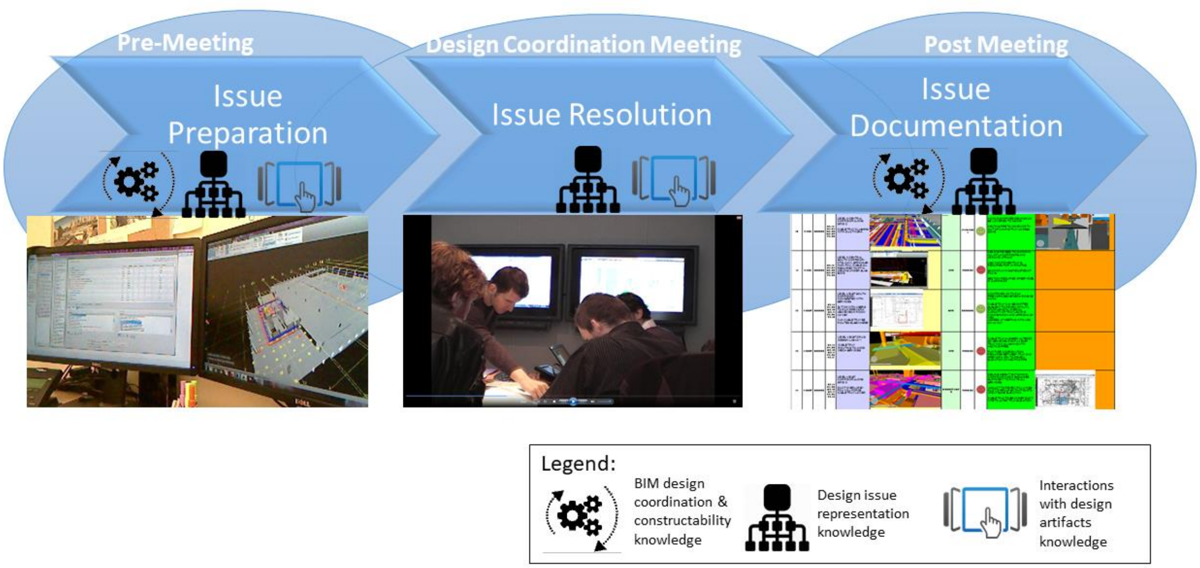


Figure 1: A typical BIM-based design coordination process is executed in three steps: (1) issue preparation, (2) issue resolution, and (3) issue documentation.

Although the implementation of BIM has resulted in numerous benefits and efficiencies in the design coordination process, project participants still face significant challenges that disrupt and hinder the coordination process, even when BIM tools are readily available (Park, Le, Pedro, and Lim, 2016). While there are many factors influencing BIM-based building design coordination, I have identified three critical issues that impact the successful implementation of BIM in design coordination processes: (1) the extent of BIM-based design coordination processes and protocols implemented, (2) the efficiency and ease in which practitioners interact with state of the art of BIM tools, and (3) the effectiveness in which design coordination issues are captured, represented and documented. Figure 2 illustrates the three challenges that are the focus of this research and the respective Chapters in which these challenges are described and addressed in this thesis.

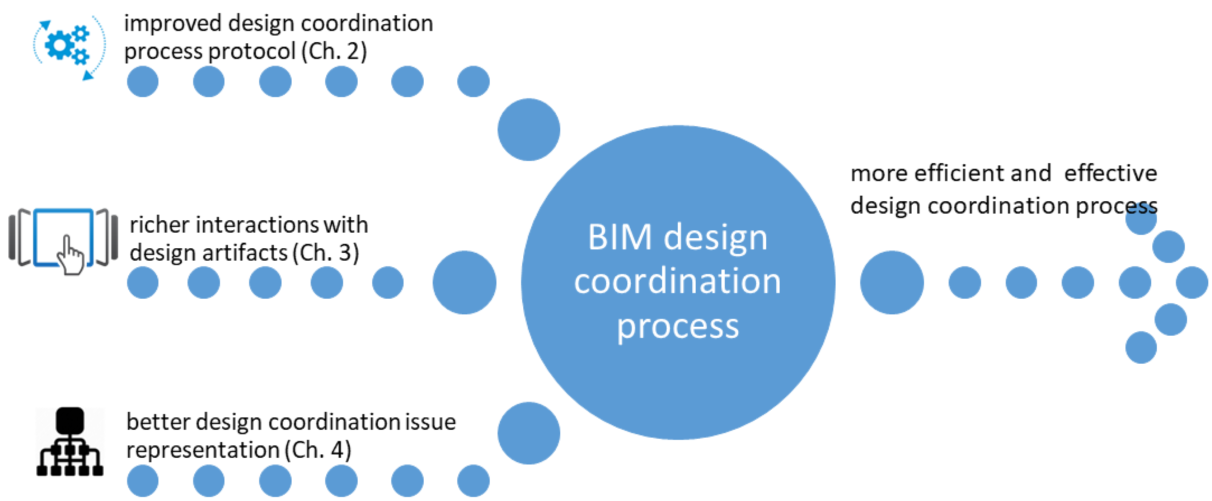


Figure 2: The impact of interactions, design issue representations, and processes on efficiency and cost of BIM design coordination

1.1 Research Questions

In this section, I describe the three research questions that are the focus of this research, which are informed by our analysis of current practices and challenges:

(1) What are the processes, bottlenecks, and requirements for implementing BIM in building design coordination practices?

(2) **How do participants interact with design artifacts to resolve design coordination issues in co-located meetings?**

(3) **How can design coordination issues be characterized in a representation schema to support future BIM-based design coordination processes?**

The following sections describe each research question in detail.

Research Question 1

What are the processes, bottlenecks, and requirements when implementing BIM in building design coordination practices?

Although the benefits of BIM in design coordination are well established, project participants still face significant challenges that disrupt and hinder the coordination process, even when BIM tools are readily available (Mehrbod, Staub-French, and Bai, 2017; Park et al., 2016). Practitioners often revert to 2D paper-based technical drawings as their first choice for technical data exchange between project members (Fiorentino, Uva, Monno, and Radkowski, 2012). Consequently, 3D design information is still underutilized (Leicht, Messner, and Poerschke, 2014). Many have recognized that the most critical issue of BIM-based design coordination remains not from the absence of enabling technologies or methodologies but from the lack of efficient coordination process strategies for integrating fragmented work processes (Dossick and Neff, 2010; Lee and Kim, 2014).

This research question investigates BIM-based design coordination practices and processes, the bottlenecks encountered, and the required functionality of BIM coordination tools. Relevant literature in the field has investigated findings related to characterization of issues in design coordination (e.g. Wang and Leite (2016a); Lee et al. (2012)), knowledge capture strategies in design coordination (e.g. Awad and Ghaziri (2007)), design coordination process (e.g. Yung et al. (2014); Saram and Ahmed (2001)), interactions with design artifacts (e.g. Tory et al. (2008)), transitions between design artifacts and views (e.g. Terry et al. (2007)), availability and accessibility of design artifacts (e.g. Tang and Leifer (1988)) practitioner participation in coordination meetings (e.g. Liston (2009)), and BIM platform evaluation strategies (e.g. Shafiq et al. (2013)). Previous literature has addressed interactions with design artifacts in BIM-based coordination meetings and characterized design coordination issues in BIM design coordination settings, but few studies have investigated the entire process for design coordination – from design and design issue preparation to on-site construction.

I conducted a multi-year ethnographic case study of two complex building projects that both involved a design development phase and a construction phase. To achieve a greater understanding of the work practices, I chose to study two teams in depth rather than multiple teams. The research employed a mixed-method contextualist research approach that involved iterative grounded theory and co-production of knowledge within research cases (Glaser, 1978; Glaser and Strauss, 1967; Green, Kao, and Larsen, 2010; Jordan and Henderson, 1995). I compared collected data and searched for resonance with conceptual ideas derived from literature. Specifically, the research involved observation of live and video-recorded design coordination meetings and in-depth qualitative analysis of meeting segments. Initially, I analyzed these meetings qualitatively (through five-minute vignettes), which led to a deep understanding of design coordination processes and challenges. I then verified the findings against current literature to identify the bottlenecks in BIM-based coordination meetings. Finally, expert reviews and further reviews of the literature were conducted to identify design considerations for future BIM-based coordination tools.

To address research question one, I characterized the design coordination processes (as shown in Figure 3), identified the bottlenecks practitioners face during design coordination, and proposed design considerations for BIM tools. I Identified numerous bottlenecks (as shown in Figure 4); the most noteworthy were the lack of concurrent BIM updating functionality, the frequency of transitions between artifacts, the inconsistency of design information across artifacts, and the lack of support for design issue documentation and tracking. I also proposed functionality to better support these bottlenecks. Finally, I benchmarked widely used state-of-the-art BIM platforms (as shown in Figure 5), and found Solibiri followed by Autodesk BIM 360 Glue to be the most effective platforms. The results of this research will be useful for AEC industry researchers, professionals, and the BIM software development community.

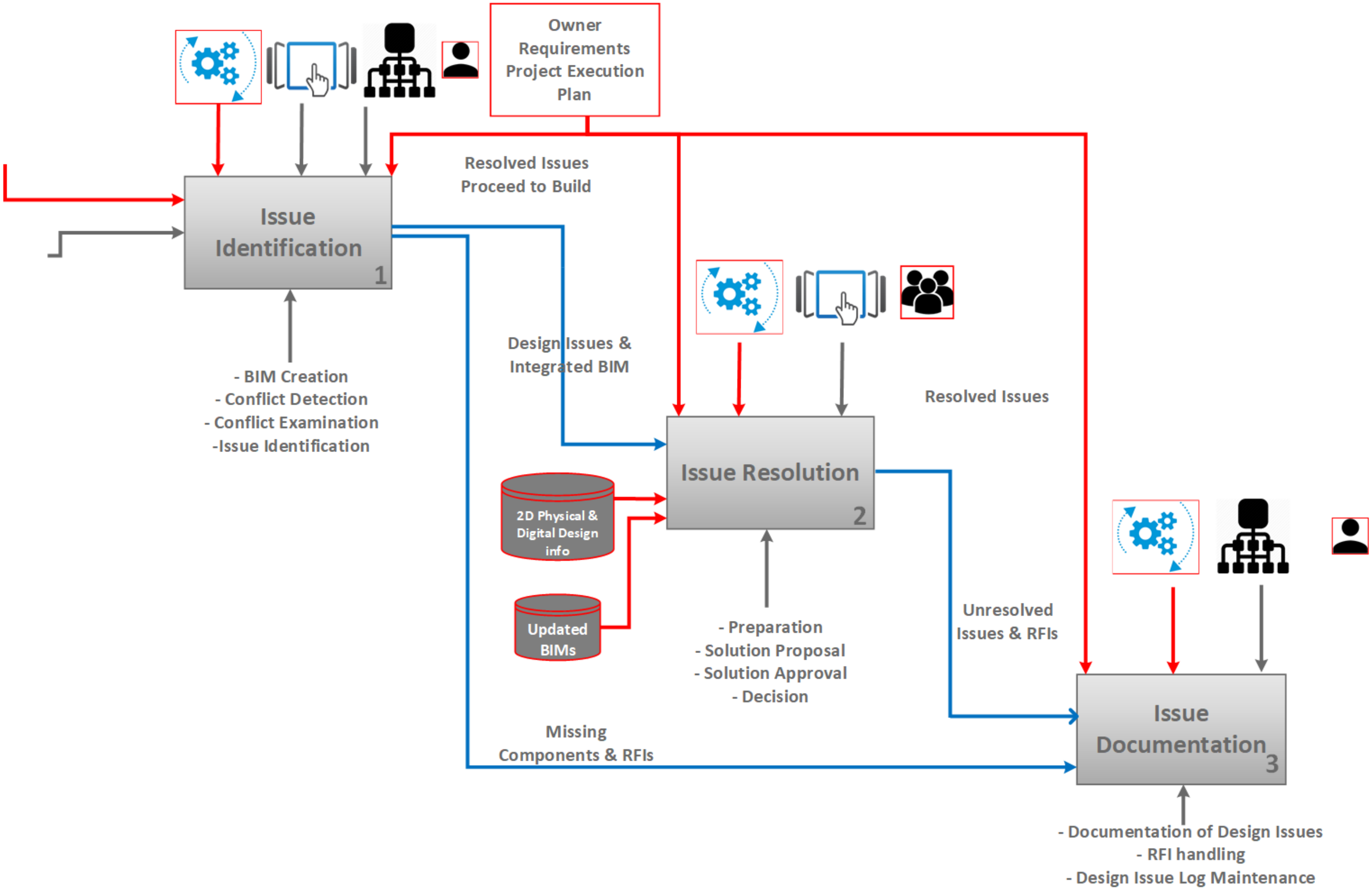


Figure 3: BIM-based building design coordination process. Red outlines Research Question 1 components. Blue outlines flow of data.

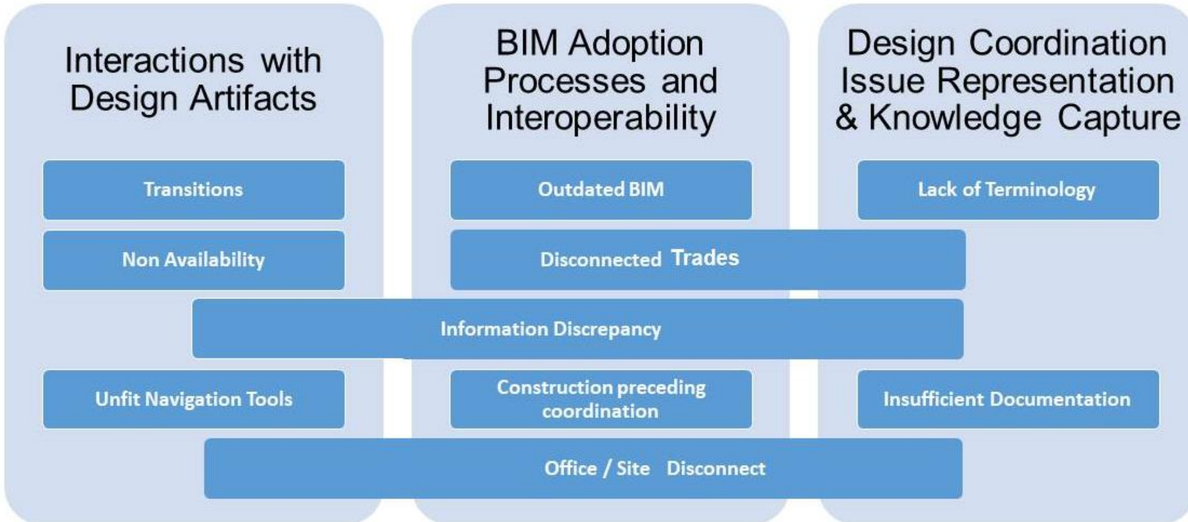


Figure 4: The domain of the bottlenecks influencing the efficiency of BIM-based design coordination.

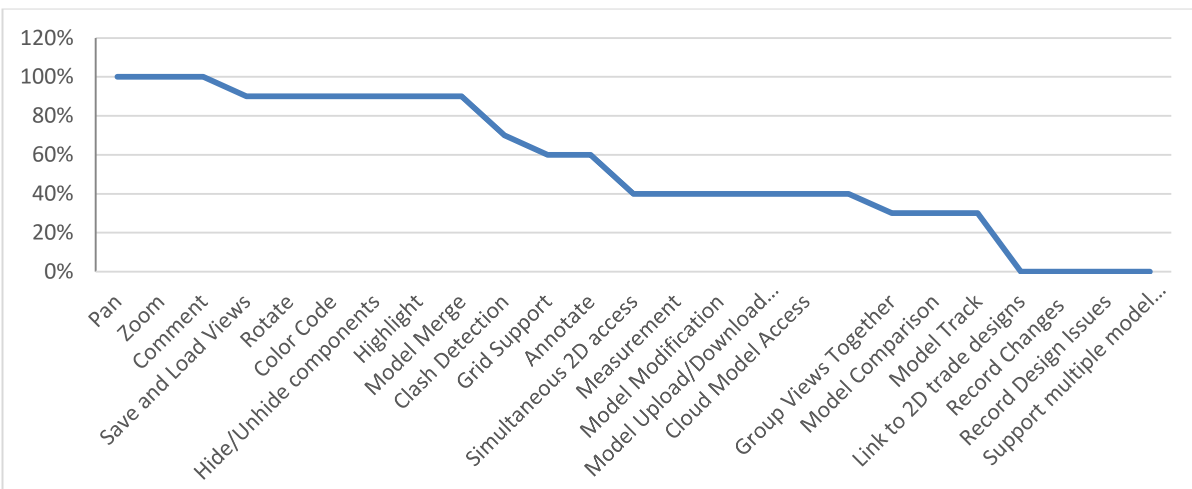


Figure 5: Analysis of availability of functionalities across the tested state of the art BIM platforms.

Research Question 2

How do participants interact with design artifacts to resolve design coordination issues in co-located meetings?

Even when BIM tools are readily available in building design coordination settings, project participants face significant challenges when interacting with BIM, which disrupts and hinders the design coordination process (Mehrbod et al., 2013; Park et al., 2016). Practitioners often revert back to 2D paper-based technical drawings as their first choice for technical data exchange between project members (Fiorentino et al., 2012), and 3D design information is still underutilized (Leicht et al., 2014). The transitions from one form of design representation to another are time-consuming (Terry et al., 2007), and result in loss of information when attempting to document the knowledge or outcome of design issue discussion. Although it is reasonable for practitioners to require multiple views when reviewing design information (Korman, 2009), my observations and prior studies confirm that a large portion of transitions occur when there is limited information about the design issue available (Tommelein and Gholami, 2012), design information is not accessible or available (Liston, 2009), or difficult to interact with (Tory et al., 2008).

The goal of this research is to better understand how and why participants interact with different types of design artifacts when analyzing and resolving design coordination issues, and to identify necessary functionality for BIM-enabled coordination environments. Specifically, I analyzed the frequency of BIM use in coordination meetings, the purpose of participant interactions with different design artifacts, and the transitions between artifacts. I developed a taxonomy (Figure 6) to outline the relationship between goals, artifacts, interactions and transitions. An important contribution of this research is the identification and characterization of the transitions participants had between design artifacts and views, which has previously not been studied in depth. I also characterized the reasoning behind participants' transitions between design artifacts and the frequency of their occurrence.

I employed a mixed-method research methodology that involved observation of design coordination meetings, in-depth qualitative analysis of meeting segments, followed by extensive quantitative data collection and analysis through data transcription and coding. I then enriched my collected data using axial coding, and then I verified my findings against current literature. Finally, I sought validity of my findings through examining interactions, goals, and transitions of a second case study. I found that 2D paper, 2D digital and 3D digital artifacts were utilized almost equally during the meetings. I characterized design artifact interactions into four major categories: preparation, annotation, navigation, and recording. I classified practitioner's goals into six categories: prepare, orient, visualize, inspect, document, and query. The outcome of this research can be beneficial to the BIM software development community, and project teams adopting state of the art BIM tools in design coordination.

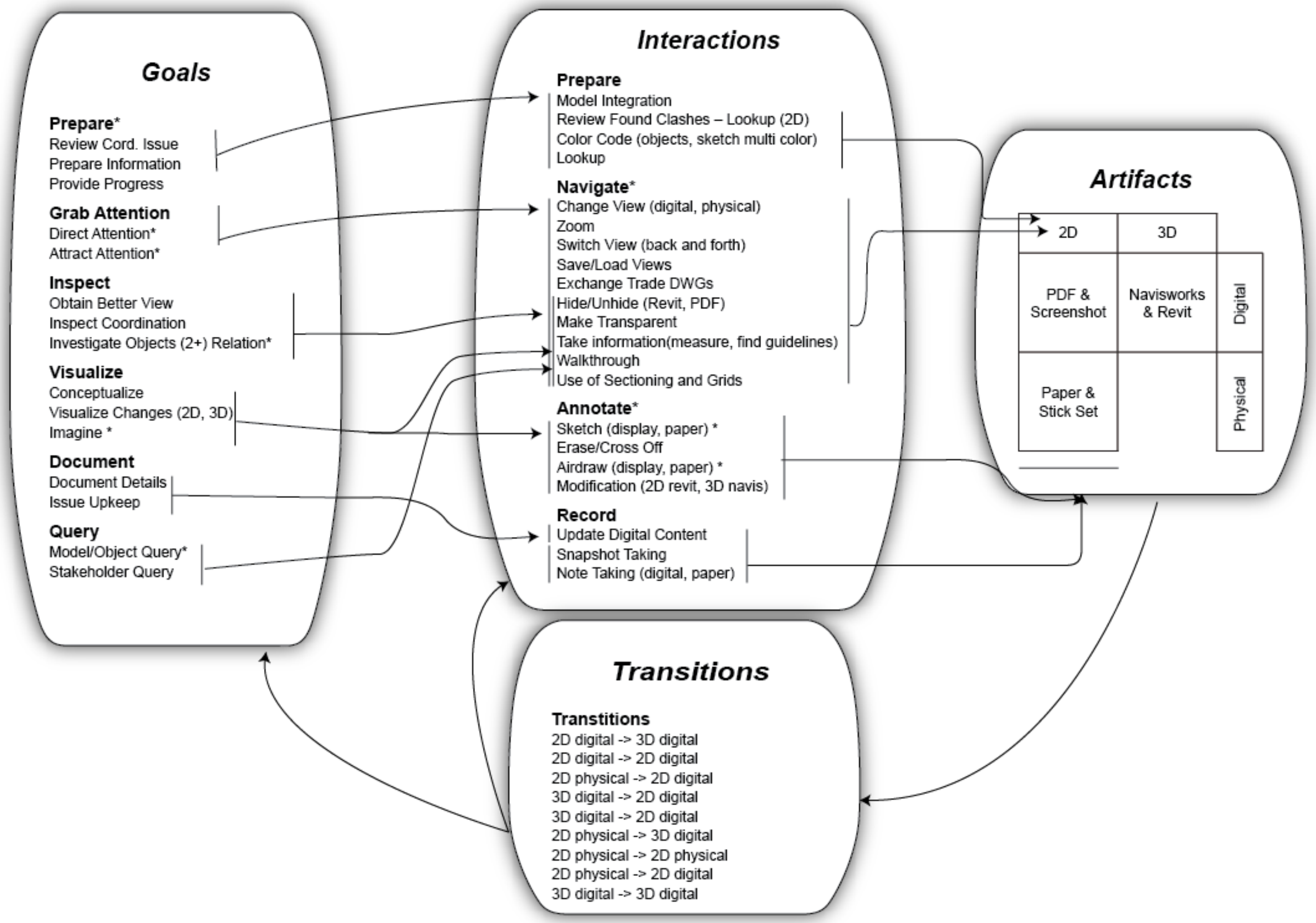


Figure 6: Interaction taxonomy - summary of goals, sub-goals, interactions, transitions and artifacts. Note that items labeled with an * build on Tory et al. (2008).

Research Question 3

How can design coordination issues be characterized in a representation schema to support future BIM-based design coordination processes?

The ultimate goal of design coordination is to avoid potential conflicts prior to construction. Some have estimated that each detected clash between MEP systems can save over $300 USD per clash (Wang et al., 2016), while others believe the impact of unresolved coordination issues on project time and cost can be as much as $10,000 USD per issue (Azhar, 2011). Similar to Lee et al. (2012), I have found that many design coordination issues still go undetected using state of the art BIM tools, often leading to on-site fixes with additional costs and delays to the project (Assaf and Al-Hejji, 2006). Frequently, the low-level details regarding the complexity, priority and severity of design issues are not sufficiently documented during and after meetings, making it difficult for practitioners to understand and revert back to these issues from prior meetings. Furthermore, management of design coordination issues remains a challenge for practitioners, with design coordination issues often being comprised of what I call *process-based* and *model-based* conflicts. These types of design coordination issues are resource intensive, time-consuming, involve multiple building systems and go beyond the traditional definition of a 'clash.'

The goal of this research question was to better understand and formalize design coordination issue representation, resolution and documentation. Specifically, I developed a taxonomy of design coordination issues and an ontology that defines the relationships between physical, process, and model-based design issues. I then applied the taxonomy to two case studies to develop insights into the frequency of issue types, the distribution of issue types across disciplines, and the resolution rates of issue types. I employed a mixed-method approach based on observation and analysis of two case studies through the entire design coordination process. I transcribed the observations and enriched the collected data using axial coding, and then verified the findings against current literature. To gain a better understanding of the design issue identification process, I conducted think-aloud observation of practitioners performing coordination analysis. The coding process was validated through inter-coder reliability testing and the findings of this study were validated by conducting expert interviews with practitioners.

In terms of prior work, in the domain of BIM-based design coordination issue characterization, Korman, Fischer and Tatum (2003) classified design issues into three main categories of design criteria, construction, and operations issues. They also identified design issue attributes as geometric and topological characteristics. Their work later became a foundation on which Tabesh and Staub-French (2006) built to further classify design issues as tasks of conceptual and spatial reasoning and the underlying reasons behind the constraints identified in each discipline. Wang and Leite (2016) provided a formalized representation schema for MEP coordination to help in clash analysis, resolution, and management. Furthermore, Lee et al. (2012) classified design issues in terms of their cause, the likelihood of identification, and the impact on schedule, quality, and direct cost. Few studies go beyond 'clashes' in BIM-based building design coordination, what I refer to simply as 'design coordination issues,' which often demand more expertise and knowledge, more time to resolve, and are often undetectable using state of the art BIM tools. Although some researchers have explored design coordination more broadly (e.g. Lee et al. (2012), little research has been done on the process of identifying complex design issues or to provide a classification that is capable of characterizing these design coordination issues, particularly in terms of addressing the complexity, priority and severity of design coordination issues.

I developed a taxonomy of design coordination issues (Table 1) and an ontology (Figure 7) to represent design coordination issues. I found that many process-based and model-based design coordination issues are the result of further examination of actual physical ‘clashes,’ and that many design coordination issues remain unresolved by the end of the design coordination stage. On both projects I studied, *design discrepancy, design error, clashes* and *missing items* were respectively the most common, and *as-built inconsistency, functional,* and *clearance,* the least common design coordination issues types. I found little correlation between the complexity of design issues and their resolution time. Design coordination issues occurred the most at mechanical rooms, their adjacent spaces and within condensed spaces between architectural ceilings and structural floors. The experts I interviewed attributed unresolved design issues with unexpected additional costs and delays, and confirmed that the potential integration of the developed taxonomy along with maintaining sufficient LOD across key project stakeholders could improve identification, documentation and communication of design coordination issues in practice. The outcome of this research can be beneficial to the BIM software development community, teams adopting state of the art BIM tools, and future research better understanding relationship between design coordination issues and their low-level details.

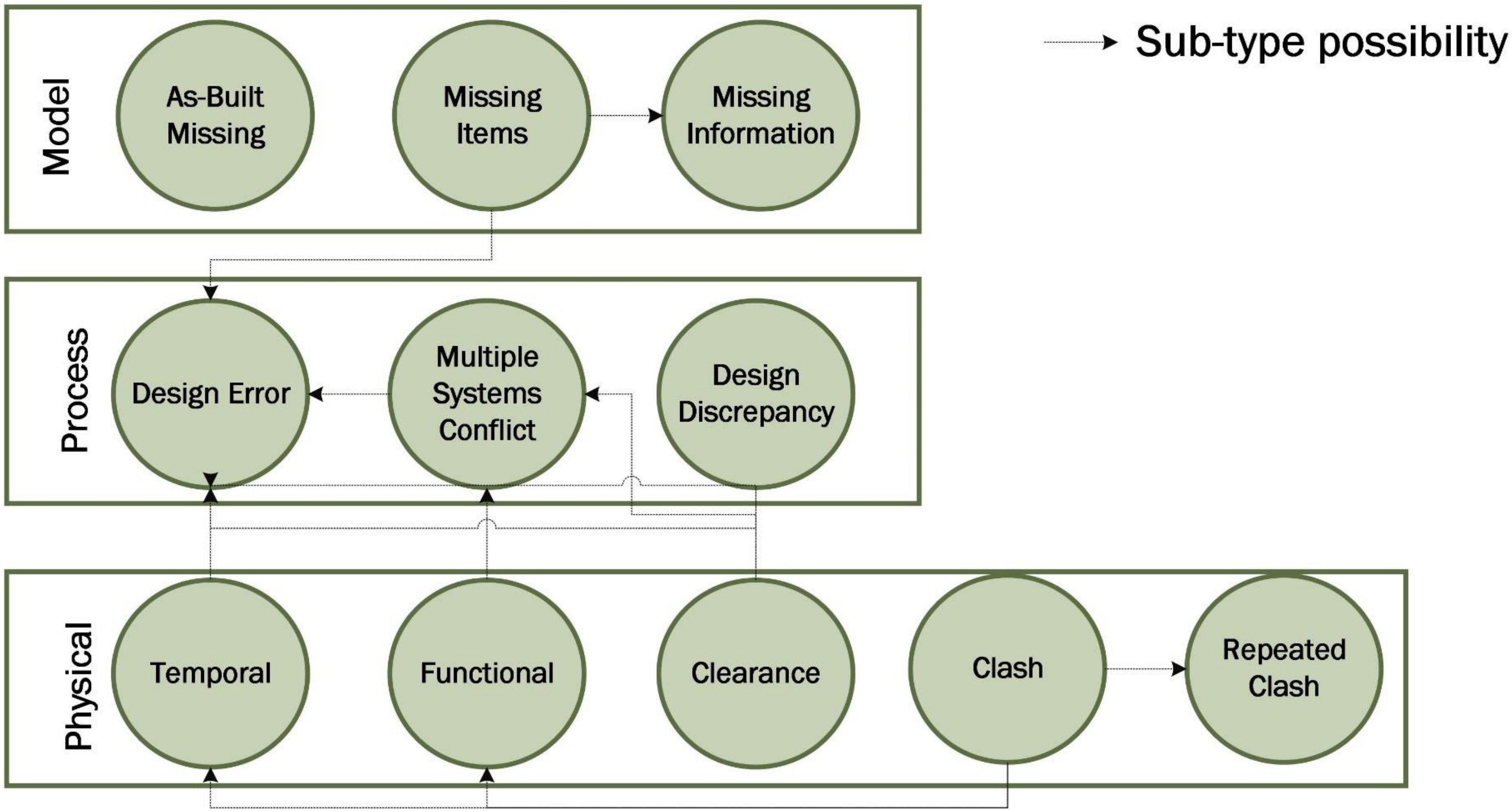
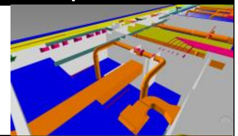
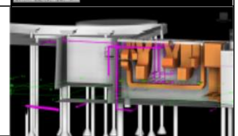
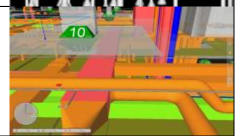
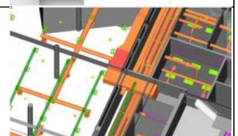
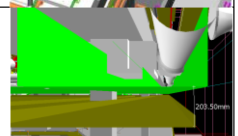
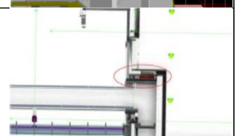
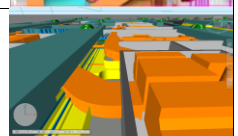
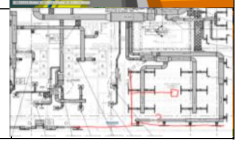


Figure 7: Ontology that represents the potential relationships across the design issue categories.

Table 1: BIM-Based building design coordination issue representation taxonomy. Bold font indicates issues not previously identified in prior work. Notations: 1: Korman et al (2003), 2: Tommelein and Gholami (2012), 3: Wang and Leite (2016), and 4: Lee et al (2012).

Category	Sub-Category	Description	Example	Snapshot
Physical	Temporal [1,2]	2 or more components occupying the same space- constructability /operability issues.	Duct collide with the cable tray. Tray to move down.	
	Functional [1,2]	locations of components jeopardize the intended function of component	Location of heating unit next to HVAC duct interferes with function of systems.	
	Clearance [1,2,3]	Components interfere with extended spaces (e.g. Access).	Plumbing conflicts with access ladder, due to insufficient space surrounding it.	
	Clash [1,2,3]	Single conflict of 2 systems. Only 2 trades required to resolve in the meeting.	HVAC duct collides with structural column cap.	
	Repeated Clash (es)	Substantial conflicts of 2 or more systems which require e-design of a system(s).	All ducts conflict with structural columns. Zone C ducts require redesign.	
Process	Design Error [4]	2 or more building systems designed independent from each other.	All level 3 mechanical ducts conflict with structural concrete beams.	
	Multiple Systems Conflict	Multiple building systems can not fit in confined space.	Heating, hot water, sprinkler, cable tray all required to fit in ceiling under slab band.	
	Design Discrepancy [4]	Design Information on trade designs do not match.	Structural floor opening is not designed big enough for mechanical duct.	
Model	**As-Built Inconsistency**	The built system on site does not match the BIM.	Duct openings in wall panels are moved when built. Routing stops until as-built location known.	
	Missing Items [4]	Details related to components, or parts of BIM are missing.	Dimensions of mechanical component not specified. Elect. Fixture are missing.	
	Missing Information	Lack of sufficient information about building system(s) stop coordination & building	How do building users control HVAC unit above? is noise level a concern?	

1.2 Research Contributions

The contributions of this research are summarized in this section, according to each focus of the research. Figure 8 illustrates the research questions, major contributions and chapter numbers within the thesis. The contributions and validation methods are described in detail in Chapter 5 of this thesis. The following briefly summarizes the three research contributions resulting from this research.

Research contribution 1 – Characterization of BIM-Based building design coordination processes, identification of bottlenecks, and design considerations for BIM tools: Chapter 2 characterizes the design coordination process, identifies the bottlenecks practitioners face during BIM-based design coordination, analyzes the literature and proposes design considerations. Prior work (Yung et al. 2014) provided a foundation that characterized model creation, model integration and conflict detection of the design coordination issue identification stage, and others (e.g. Saram & Ahmed, (2001)) identified the coordination activities involved in construction projects. I built on their findings and characterized the full design coordination process cycle with the ten sub-processes involved within the design coordination issue identification, resolution and documentation stages. I also identified the bottlenecks within each design coordination stage.

Research contribution 2 – Taxonomy of interactions with design artifacts, outlining the relationships between goals, artifacts, interactions and transitions: Chapter 3 provides a detailed description of the taxonomy of interactions with design artifacts I developed. An important contribution of this research is the identification and characterization of the transitions participants had between design artifacts and views, which has not been studied in depth. The work builds on findings of Tory et al. (2008) who investigated non-BIM design coordination projects in the past, and Liston (2009) who studied the richness of interactions and artifact use from the lens of human computer interaction (HCI) and high level interaction categories. The taxonomy provides categories for the high level goals driving interactions with design artifacts (which contain some of the low-level goals identified previously), identifies two new interaction categories of *preparation* and *recording,* and identifies the transitions between the design artifacts and views.

Research contribution 3 – Taxonomy of design coordination issues that explicitly represents process-based, model-based, and physical design issues: Chapter 4 classified BIM-based design coordination issues through a classification taxonomy. I built on prior findings of Korman et al. (2003) and Wang and Leite (2016a) who classified auto generated clashes in BIM-based design coordination, , and Lee et al. (2012) who identified some design coordination issues beyond clashes, including '*discrepancy'* and *'missing items'* design coordination issues. Prior studies did not go beyond physical clashes (model and process based design coordination issues), and did not identify the relationship of physical, process, and model based design coordination issues. The taxonomy classifies prior findings and adds four new design coordination classifications of *'repeated clash'*, *'multiple-systems conflict'*, *'as-built inconsistency'*, and *'missing information'*. In addition, I provided an ontology to represent the relationship between different design coordination issue types.

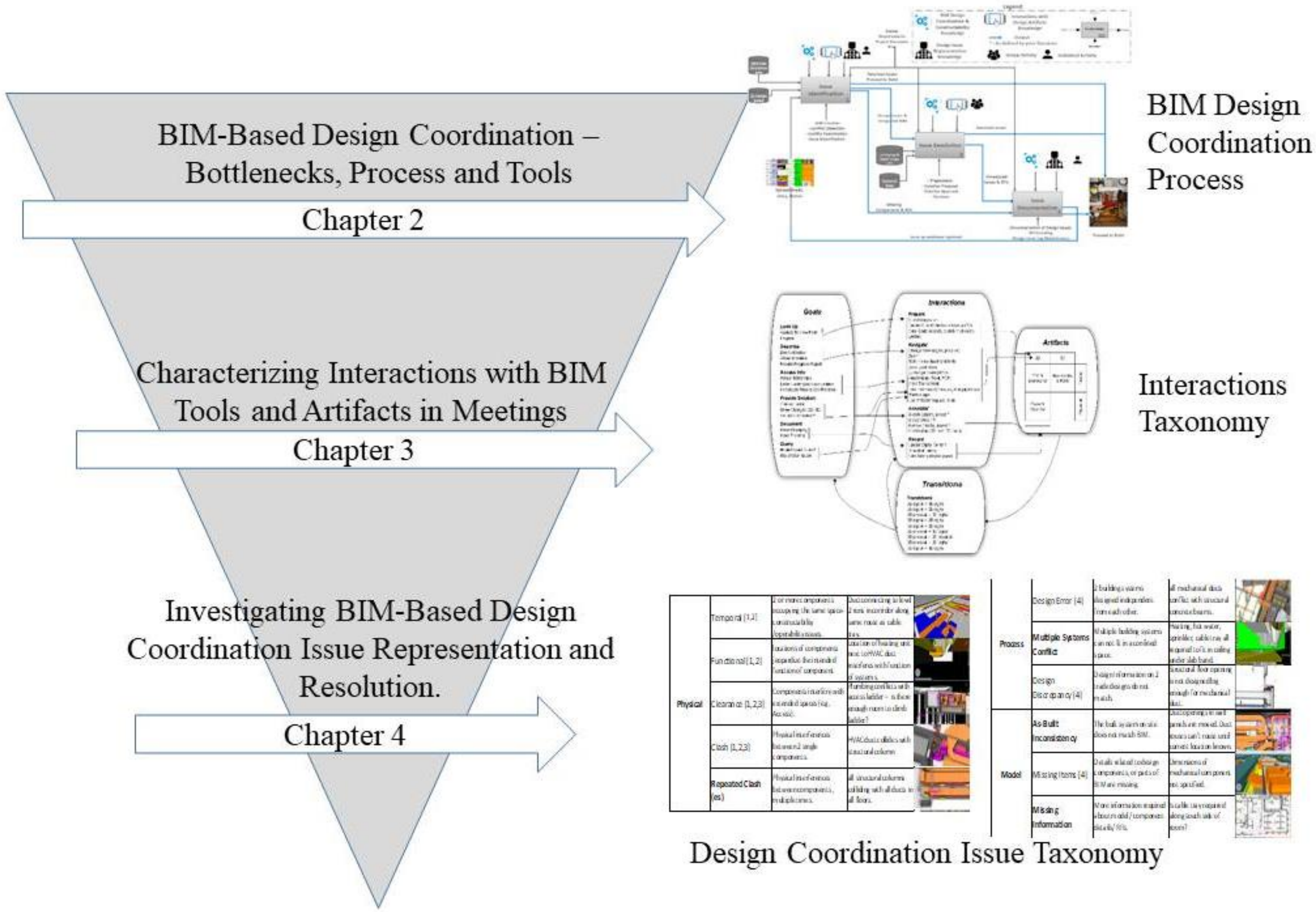


Figure 8: Research contributions presented in chapters 2-4 of this thesis.

1.3 Research Methods

In this section, the methods used to conduct this research are described. I conducted a multi-year ethnographic case study of two complex building projects involving the design development and construction phases. To achieve a greater understanding of the work practices, I chose to study two teams in depth rather than multiple teams across many projects. Case study research is appropriate when investigating a contemporary phenomenon in a real-word context (Yin, 2003). Similar to many other research efforts, e.g. (Becerik-Gerber et al. 2012), this research focused on large institutional complex projects to understand BIM-based design coordination processes. The research employed a mixed-method contextualist research approach that involved iterative grounded theory and co-production of knowledge within research cases (Glaser, 1978; Glaser and Strauss, 1967; Green et al., 2010; Jordan and Henderson, 1995).

Figure 9 presents the research activities implemented to conduct the research presented in each of the manuscript-based chapters. Specifically, the research involved (1) review of prior of work in the field. (2) Observation of live and video-recorded design coordination meetings, construction document tracking, BIM analysis, and in-depth qualitative analysis of meeting segments. (2) I analyzed the meetings qualitatively (through five-minute vignettes), which led to a deep understanding of design coordination processes and challenges. (3) I analyzed the meetings quantitatively (by data transcription and coding). The meetings were selected based on based on the level of interaction with artifacts, the participation of participants and stage of construction. I continuously compared collected data and searched for resonance with conceptual ideas derived from literature. (4) I conducted expert reviews, think-aloud observations, inter-corder reliability testing and further reviews of the literature were conducted to identify design considerations for future BIM-based coordination projects and the software development community.

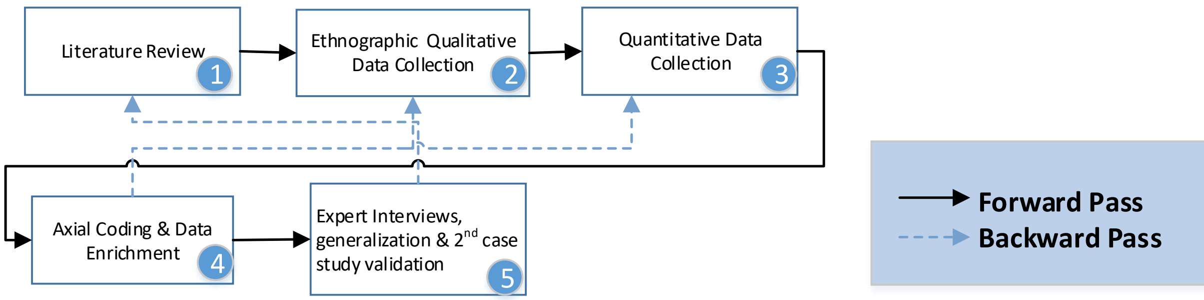


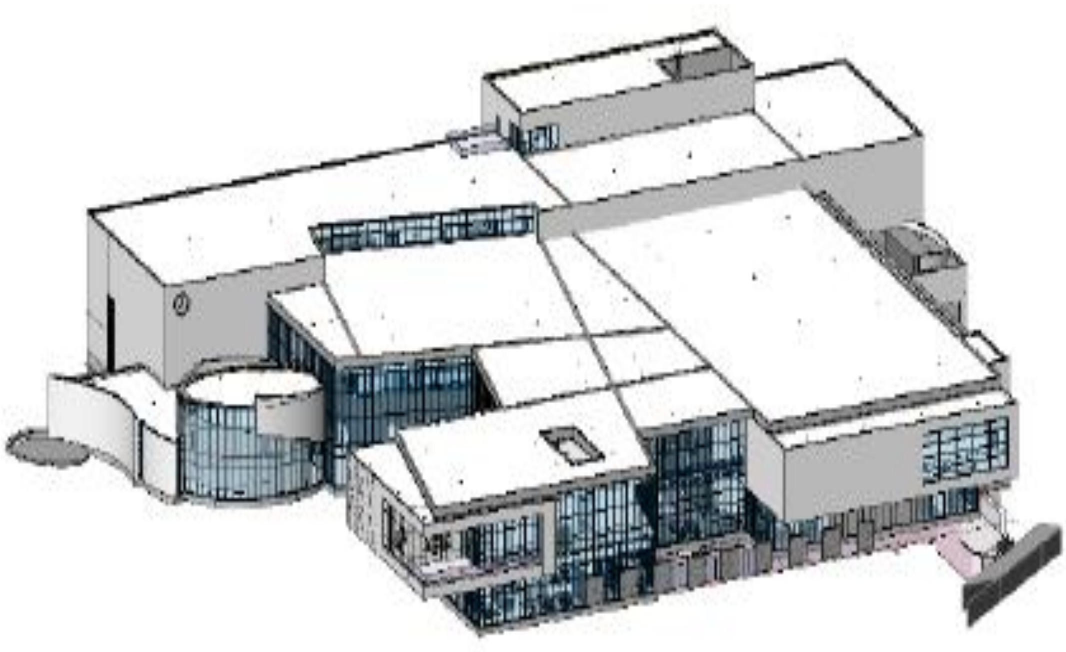
Figure 9: Research methods used to drive this research

1.3.1 Case Studies

I analyzed the BIM-based design coordination processes of two case-study projects. These fast-track projects had extremely complicated MEP systems along with unique architectural designs that made design coordination and constructability key concerns. Over the course of design and construction, BIM was used extensively to coordinate designs from different consultants and sub-trades. In both case studies, the meetings typically had six to nine participants from different disciplines, including the general contractor, consultants, and subcontractors. I observed the same meeting settings, design artifacts placements, and stake holder participation across both case studies, as well as many other observed BIM-based design coordination projects. Regarding the leadership of the meetings, the MEP Coordinator was in charge of overall coordination of building design issues, while the BIM Coordinator was in charge of integrating the BIMs, detecting "clashes" and navigating the 3D and 4D models during meetings.

Royal Alberta Museum (RAM): the newly constructed Royal Alberta Museum (RAM), located in downtown Edmonton, Alberta, is the largest museum in western Canada. The building is 25,349 m^2 on a site measuring 20,024 m^2 (Figure 10). The project was a design-build delivery and involved early and active engagement from most of the key trades. I participated remotely in the design coordination meetings and recorded and observed participants conducting design coordination; I also analyzed relevant project documentation, construction drawings, and BIM files. I had access to meetings from the planning phase through completion of the building structure.

Pharmaceutical Sciences Building at the University of British Columbia (Pharmacy): an 18,000 m^2 facility provides a variety of teaching and learning spaces from lecture halls and seminar rooms to a pharmacy clinic and three floors of research laboratories (Figure 11). The project was a construction management delivery, and the MEP trades were engaged early in the design process. I observed meetings both in-person and remotely, recorded and observed participants during design coordination, and analyzed relevant project documentation, construction drawings, and BIM files.



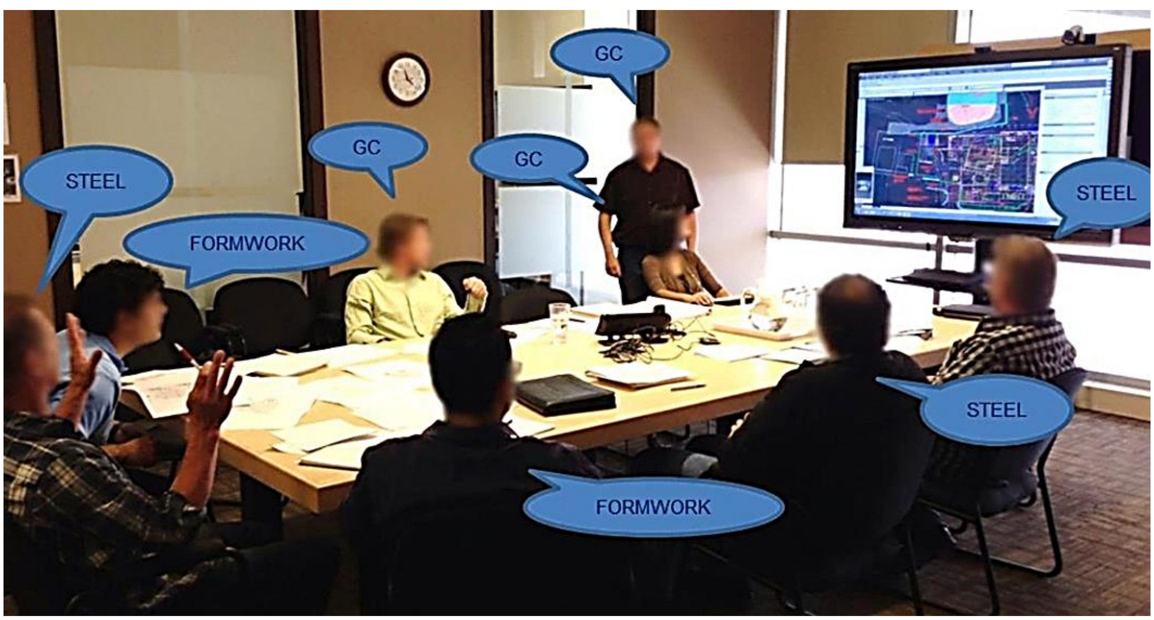
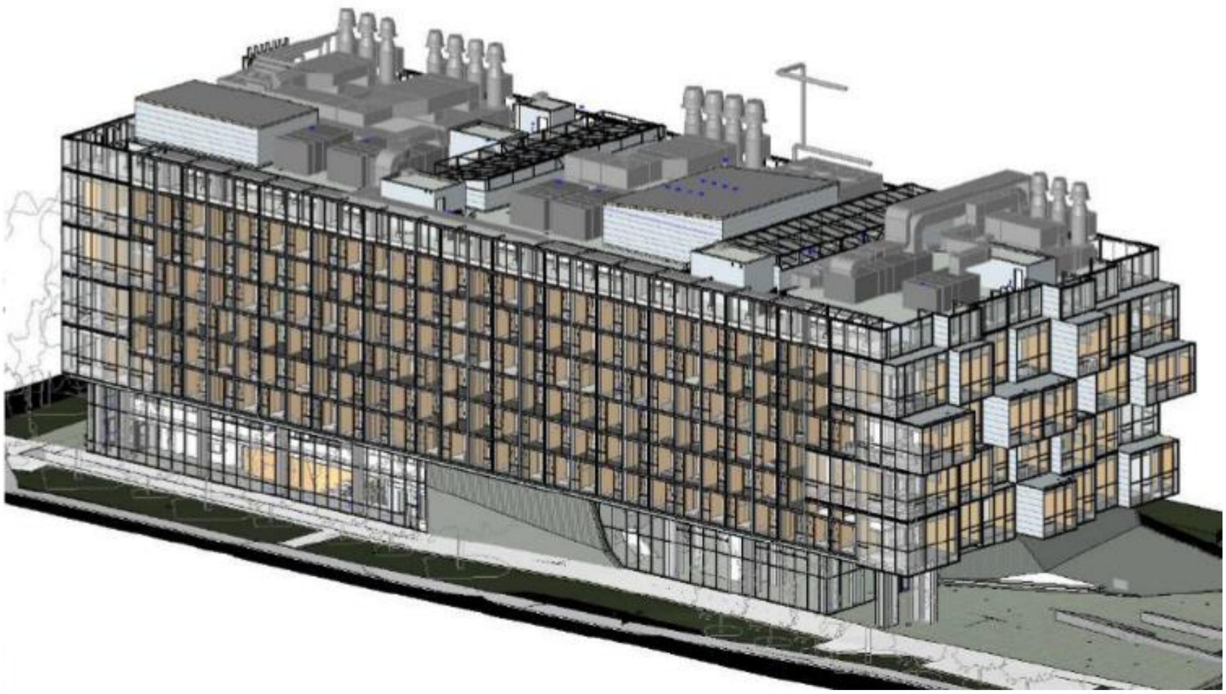


Figure 10: The Royal Alberta Museum - an architectural model of the RAM project (top) (image courtesy of Dialog Architects) and a snapshot of the design coordination meeting environment for the RAM case study (bottom) (GC indicates general contractor).



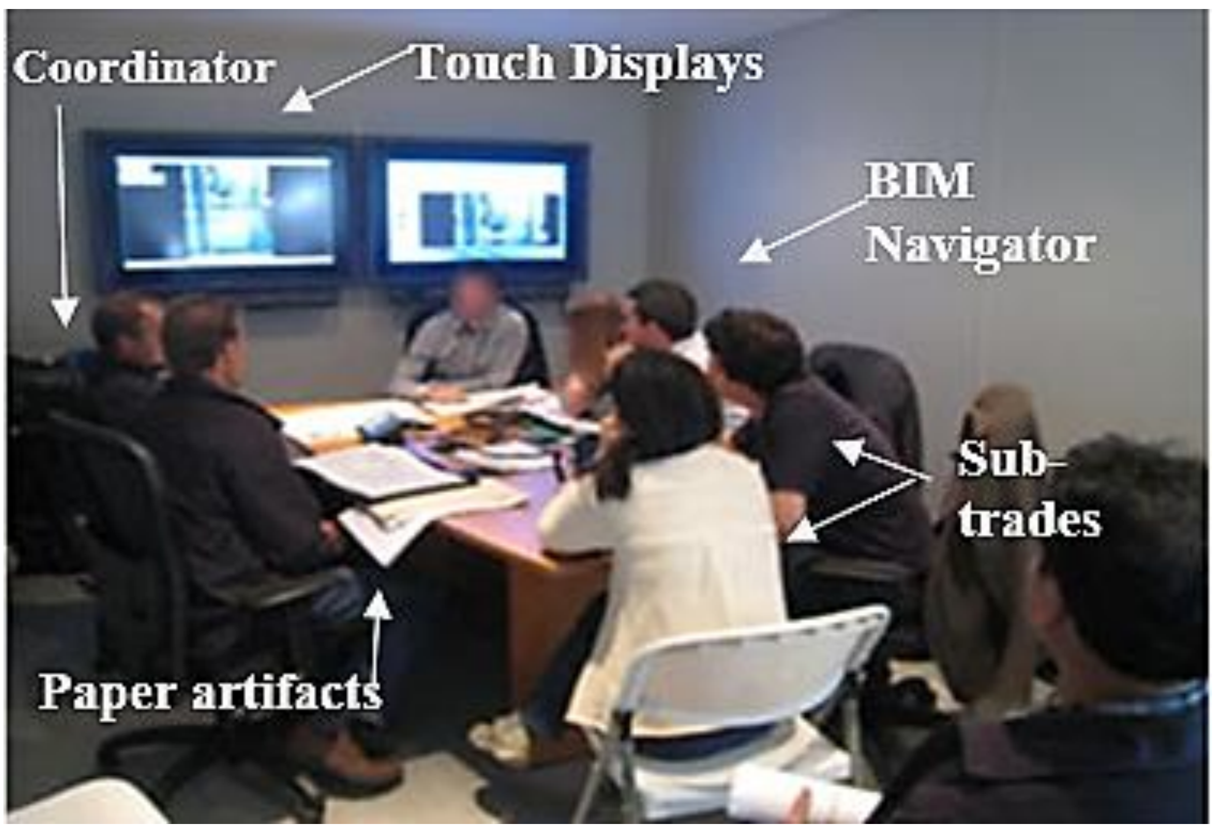


Figure 11: Integrated BIM model of the UBC Pharmaceutical Building Project (top) (image courtesy of Hughes Condon Marler Architects) and BIM Trailer used during design coordination on site (bottom).

1.3.2 Limitation of Case Studies

The approach in this thesis was to analyze the two case studies in depth, rather than a surface level analysis of numerous case studies. These two case studies represent state of the art public sector projects involving some of the largest general contractors, and the most BIM-savvy design consultants and sub-contractors in western Canada. The general contractor had substantial prior BIM experience from prior projects and the organizations had sufficient prior BIM adoption experience.

The case studies focused on different stages of project construction. One case study focused on the design to mid-construction stage, and the other on the period from mid-construction to the end of construction. Although the project were delivered using different delivery methods (Design-Build, and Construction-Management) both projects were delivered on a fast-track procurement mode, both shared the same general contractor (Ledcor Group), both had early engagement from construction trades and the expectation on both projects was the trades would implement fabrication level (LOD of 350 to 400) BIM.

It is extremely hard for researchers to gain full access to construction projects, particularly ones that involve similar level of complexity, scale, significance, and level of BIM development. Although we were fortunate enough to get full access to the two BIM-based projects, we tried to identify additional projects to complement the two primary case studies. These complimentary case studies helped to address some of the bias that could arise, given the similarity of the two primary case studies. The complimentary case studies I studied included UBC's Orchard Commons and Center for Interactive Research and Sustainability (CIRS) projects, the SEARS building in downtown Vancouver, the Vancouver Marine Gateway project, and projects involving Pomerleau Construction, a prominent general contracting firm in eastern

Canada. These additional projects shared the same properties with the case studies investigated in this thesis. Specifically, they shared similar BIM-based design coordination processes, meeting settings, design information representations, participant engagement, and utilization of state of the art BIM tools for design coordination. in the complimentary case studies the team did not adopt a full BIM-based design coordination process or our access to the project was limited, which is why they were not included in the primary case studies.

Specifically, the fast-track delivery mode and consistent general contractor for both projects could limit the type of design coordination issues encountered and how often practitioners met to resolve design coordination issues. In addition, the fast-track delivery meant that construction for some parts of the buildings was underway while BIM-based design coordination meetings were taking place. Moreover, the design coordination process outlined in this thesis, could be biased based on how this specific general contractor adopted BIM. Therefore, I recognize that other projects with different procurement mode, and general contractors could provide varied design coordination issue types and slightly different BIM coordination processes. I tried to address this limitation through complementary case studies analyzed, but they were limited in scope.

1.3.3 Relation of Case Studies with Research Questions

Figure 12 shows the contribution of each case study to the different chapters of this thesis. As described above, Chapter 2 was developed based on observations of both case studies, Chapter 3 was developed based on observations of the Pharmacy case study and validated based on the findings emerging from the RAM case study. Chapter 4 was developed based on observations of the RAM case study and validated based on the findings emerging from the Pharmacy case study.

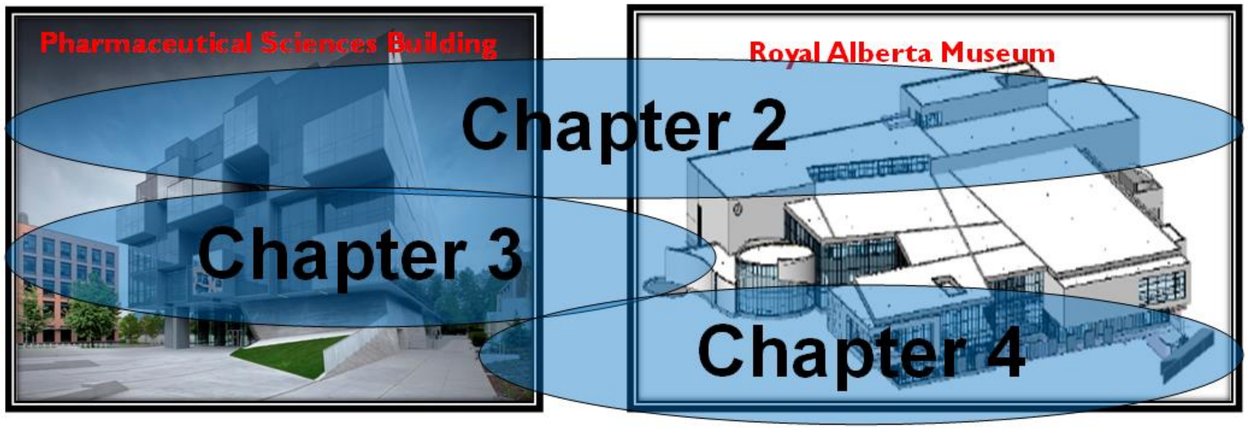


Figure 12: Coverage of case studies in each of the main chapters

This research was conducted in three phases of (1) characterization of design coordination process, (2) analysis of interactions with design artifacts, and (3) representation of design coordination issues (Figure 13). Phase (1), was developed based on ethnographic observation and qualitative data collection of both case studies with the tasks of summarization of video catalogs and tracking of design coordination issue resolution. Phase (2) was conducted based on qualitative data collection and analysis of video catalogs, followed by quantitative analysis of the meetings, complemented by axial coding of the quantitate analysis, based on the Pharmacy case study and validated based on the RAM case study. Finally, Phase (3), was developed based on qualitative data collection and analysis of design coordination issues, followed by their quantitative analysis, complemented by think aloud experiments based on the RAM case study and validated based on the Pharmacy case study.

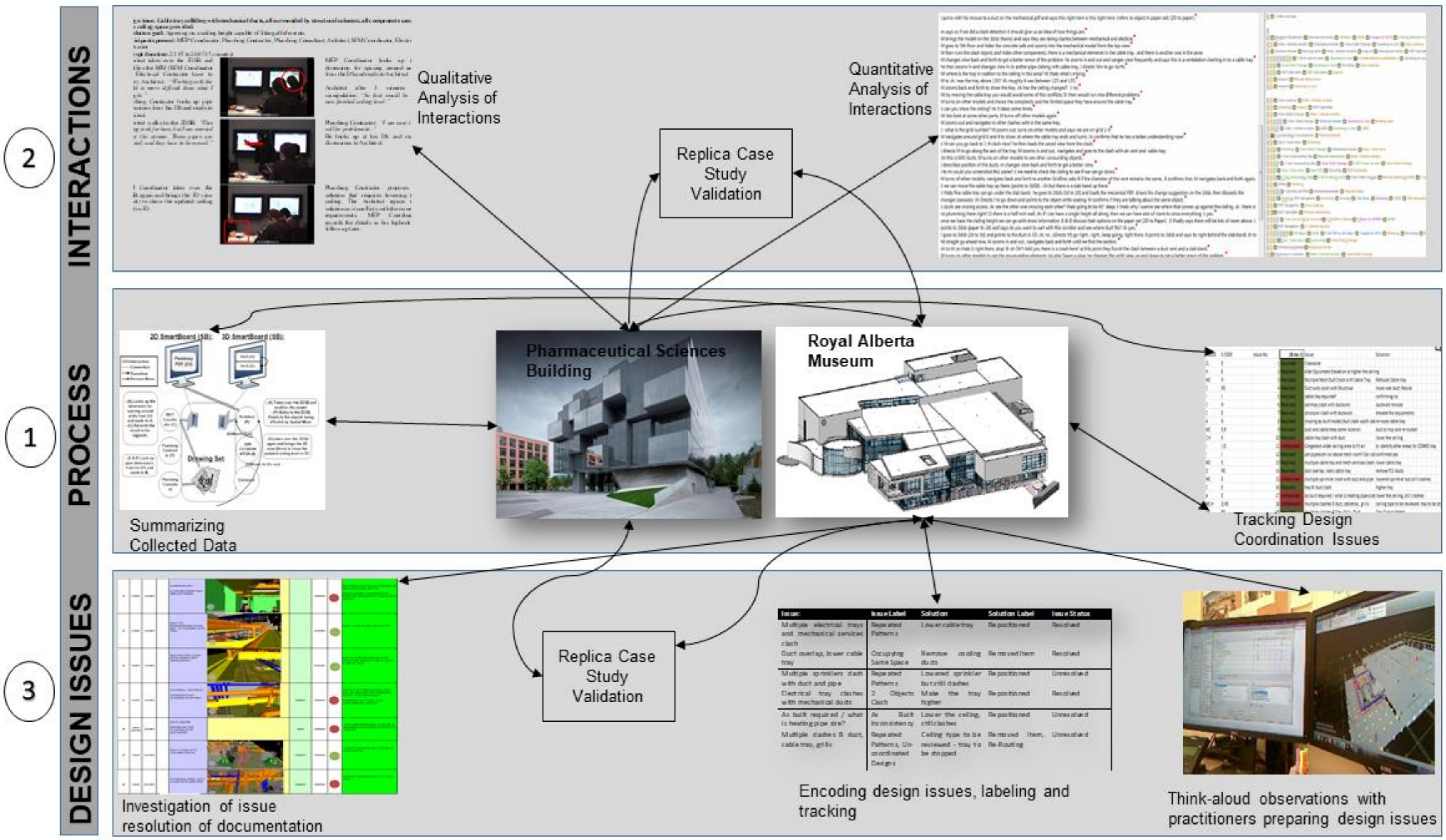


Figure 13: This research used a 3-phase research methodology, focusing on (1) process, (2) interactions and (3) design issues

1.4 Validation

This section describes how the results of this thesis were validated. The validation for each phase (research contribution) is explained individually in this section, it is also worth mentioning that the validation methods used for each contribution of this research informed one another, so the validation did not happen in complete isolation. For validation of Contribution (1) - the findings were validated through interviews with experts in the field. For validation of Contribution (2) - a replica case study was used to seek validity of the interaction taxonomy, followed by informal interviews with two BIM experts in the field. Finally, to validate Contribution (3) - reliability assessment, inter-coder reliability testing, and expert interviews were performed.

For validation of Contribution 1 – the analysis of design coordination processes, bottlenecks, and tools described in Chapter 2 – the findings were validated through interviews with experts in the field. Similar to prior research (Howard and Bjork, 2007; Kreider, Messner, and Dubler, 2010), five interviews with BIM and trade experts in the field, and three interviews with other researchers were conducted. The five industry experts included two of the BIM experts involved in the case studies, and the other three were actively involved in BIM-based design coordination. I asked interviewees to evaluate the bottlenecks presented in Chapter 2 and compare their knowledge and experience with the findings. The interviewees initially needed help understanding the scope and relationship between bottlenecks and design considerations. In their feedback, they found the bottlenecks reported in this study realistic, while they could not comment on the processes and BIM implementation protocols. They also found most proposed technical design considerations feasible and easy to implement.

For validation of Contribution 2 – the characterization of interactions described in Chapter 3 – the RAM case study was used as a replica case study similar to (LeCompte and Goetz, 1982), throughout this process I sought validity of the characterization of interactions and goals observed. Similar to the qualitative analysis of the primary case study (Pharmacy), short vignettes from the second case study (RAM) were selected to verify whether the interactions and goals could be classified using the taxonomy presented in Chapter 3. In addition, I performed an informal interview with two BIM experts in the field, including one from Pharmacy. Similar to others (Kreider et al. (2010), Howard and Bjork, (2007), and Wang and Leite, (2016)), I asked the BIM experts to comment on the interaction taxonomy presented in Chapter 3 and compare their own experience with the findings of this research. I then asked them to capture word by word (encoding using taxonomy codes) three 5-minute video catalogs from the case studies using the taxonomy. The feedback of the experts was rigorously analyzed and the wording of the taxonomy was later revised to improve clarity. During this process, I constantly sought interviewee's opinions as to the interaction and artifact utilization analysis of this research and attempted to capture their thoughts regarding the results.

Finally, to validate findings of Contribution 3 – the design issue characterization described in Chapter 4 – reliability assessment, inter-coder reliability testing, and expert interviews were performed. A secondary case study (Pharmacy) transcriptions were coded with the categories that emerged from the primary case study (RAM). Also, inter-coder reliability testing (Tinsley and Weiss, 2000) was performed on 10% of the issues in RAM, which occurred during the later phase of the study. During this process, I asked a mechanical engineer who had sufficient BIM expertise to code these issues based on the design issue taxonomy. I provided a brief description of the findings, the taxonomy, and some coded examples to the coder to initially train the coder, then asked them to code the design issues using the taxonomy. The resulting Cohen's Kappa coefficient was 0.85, which is an acceptable value for reliability (Sabelli et al., 2011). Finally, similar to the validation methods in Chapter 2, I asked three BIM experts, including the MEP and BIM Coordinators involved in the case study, to evaluate the design issue taxonomy and compare their own knowledge and experience with the findings. I then asked them to code 20 design issues from both case studies using my taxonomy, and analyzed the feedback from the experts (this evaluation was done separate from the inter-coder reliability testing) .

1.5 Thesis Organization

The subsequent chapters of this thesis are organized according to the three phases of the research, as shown in Figure 14. This thesis is manuscript-based and consists of three manuscripts for Chapters 2, 3, and 4. Chapter 2 was submitted to the Canadian Journal of Civil Engineering in May 2018, with a minor revision submitted in September 2018. Chapter 3 was submitted to Automation in Construction in December 2016, and has undergone several major revisions and a minor revision, which was submitted in September 2018. Chapter 4 was submitted to Information Technology in Construction in October 2017, with a minor revision submitted in September 2018.

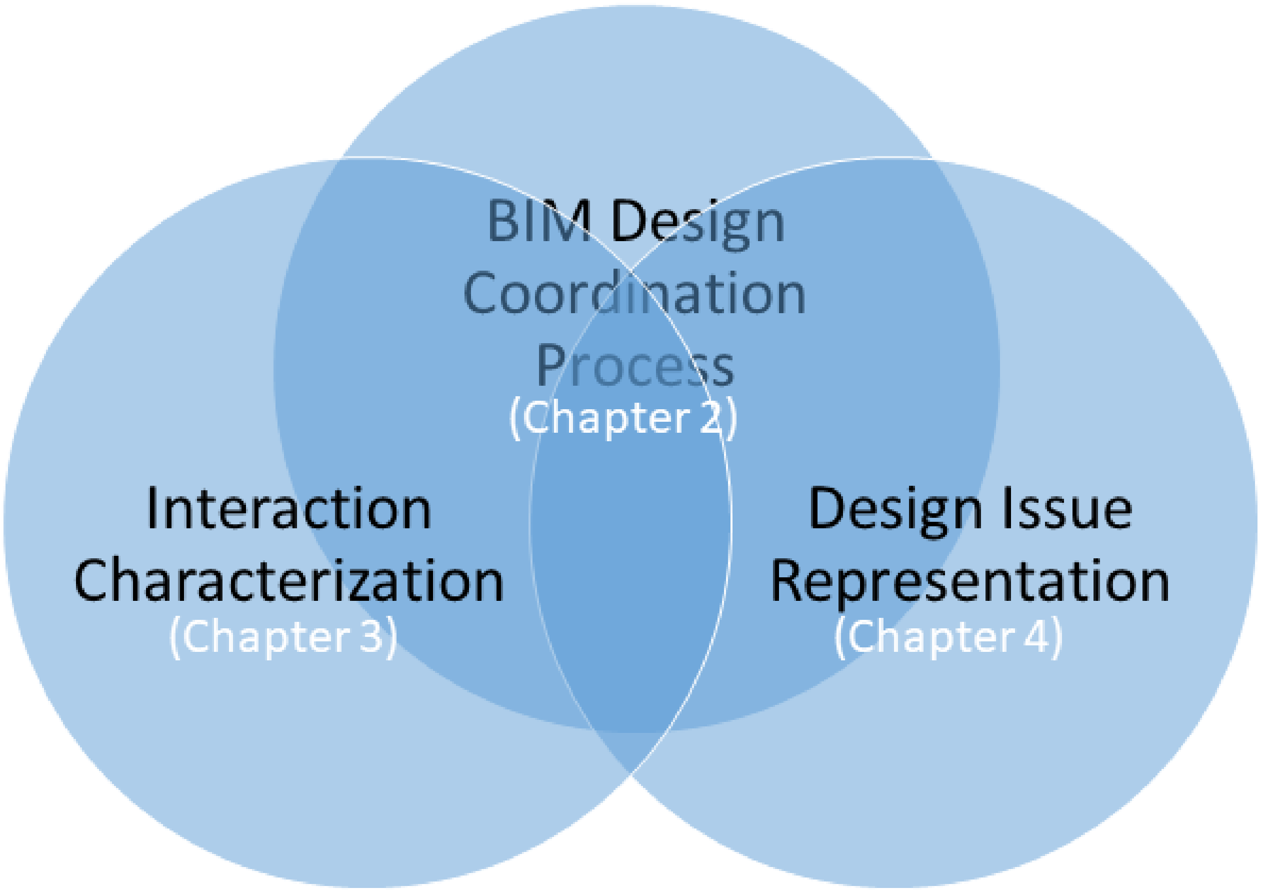


Figure 14: Organization of the thesis main chapters.

1.6 Readers' Guide

Readers are reminded that this thesis follows the manuscript-based thesis guidelines. Efforts have been made to minimize reproduction of content from chapter to chapter and to present the entire content in a unified and coherent form. The remainder of this thesis is organized as follows:

Chapter 2 investigates design coordination processes on two BIM-based construction projects. It presents the current processes, identifies the bottlenecks practitioners face during

BIM-based design coordination, analyzes the literature, and proposes design considerations for BIM tools. The research benchmarks widely used platforms used state of the art BIM platforms.

Chapter 3 investigates how and why participants interact with different types of design artifacts when analyzing and resolving design coordination issues, and identifies necessary functionality for BIM-enabled coordination environments. It also analyzes the frequency of BIM use in coordination meetings, the purpose of participant interactions with different design artifacts, and the transitions between artifacts. The research contributes a taxonomy to outline the relationship between goals, artifacts, interactions and transitions.

Chapter 4 focuses on better understanding and formalizing design coordination issue representation, resolution and documentation. Specifically, it presents a taxonomy of design coordination issues and an ontology that defines the relationships between physical, process, and model-based design issues. It then applies the taxonomy to two case studies to develop insights into the frequency of issue types, the distribution of issue types across disciplines, and the resolution rates of issue types.

In Chapter 5, the conclusions are presented, focusing mainly on the contributions of this research and the validation studies conducted. Also, the practical implications of this research are highlighted, some limitations of the research are described, and recommendations for future research are suggested.

Chapter 2: BIM-Based Building Design Coordination: Processes, Bottlenecks, and Tools

2.1 Introduction

Building design coordination is a critical and challenging task to ensure that the design meets the functional, aesthetic, and economic requirements of project stakeholders. During the process, the components of building systems are defined and routed to avoid interferences and to comply with diverse design and operations criteria (Barton et al., 1983). The cost of design coordination can be significant, with some estimates as high as 6% of the mechanical electrical plumbing (MEP) cost or 2% of the total cost on light industrial construction projects (Tatum and Korman, 1999). In a traditional setting, building design coordination is conducted through visual inspection, comparing 2D drawings and identifying potential conflicts. This process is inefficient and error-prone. As a result, numerous conflicts often remain undetected and must be addressed in the field, which is costly and inefficient (Liston et al., 2001). Prior studies estimate that 57% of design coordination errors have a direct impact on construction costs; some design errors may add up to over $26,000 per design error (Lee et al., 2012). While the benefits of design coordination meetings are well established, they are generally costly, particularly in fast-track projects with significant sustainability goals (Alwan et al., 2017). Our own estimates of the cost of design coordination meetings range from $8,000 to $23,000 per meeting.

Building Information Modelling (BIM) has proven valuable for design coordination and conflict detection in the construction sector (Bernstein and Jones, 2012). Teams using BIM tools for MEP coordination are more likely to be satisfied with the meeting process (Liston et al., 2001) and spend less time arguing over issues compared to teams using paper-based design coordination (Fischer, 2006). For instance, BIM helped practitioners to identify over 3 million and resolve over 2.4 million conflicts prior to construction on a large hospital project (Khanzode, 2010). Furthermore, BIM has been shown to reduce on-time completion, change orders and requests for information (RFIs) (Barlish and Sullivan, 2012), improve labor productivity (Khanzode and Reed, 2009), and reduce deficiencies on site (Rankin et al., 2008).

Although the benefits of BIM are well established, project participants still face significant challenges that disrupt and hinder the coordination process, even when BIM tools are readily available (Park et al., 2016; Mehrbod et al., 2017). Practitioners often revert to 2D paper-based technical drawings as their first choice for technical data exchange (Fiorentino et al., 2012). Consequently, 3D design is still underutilized (Leicht et al., 2014), and transitions from one form of design representation to another are frequent (Terry et al., 2007; Mehrbod et al., 2013). Even when state-of-the-art BIM tools are used, many design coordination issues still go undetected (Lee et al., 2012), which often leads to on-site fixes with additional costs and delays to the project (Assaf and Al-Hejji, 2006). Practitioners face difficulty managing the complexity, priority, and severity of design issues when reverting to documented design issues from prior meetings. Many have recognized that the most critical issue of BIM-based design coordination remains not from the absence of enabling technologies or methodologies but from the lack of efficient coordination strategies for integrating fragmented work processes (Dossick and Neff 2010; Lee and Kim 2014).

To elaborate on the inefficient coordination process and poor communication between project stakeholders, we present an example form the case studies (described on section 3.1). Figure 15 shows a design issue which occurred to due to insufficient coordination among building trades. In this instance, all mechanical ducts were routed on the same route as electrical trays in level 2. A re-route and re-design of the entire floor ducts was required. Approximate time impact: 1 month at discovery of the issue. Actual time impact: 2.5 months. Initially, the snapshot with a description of the issue was recorded (shown as documented) on the first meeting (number n). One week later, the electrical trade asked for the reason why this issue was flagged; on meeting (n+2), the mechanical contractor stated they could not find the viewpoint and whereabouts of the design issue; eight meetings later (n+10), the Coordinator proposed a solution to help with resolution of the design issue. This design issue was never documented as resolved (resolved on site).

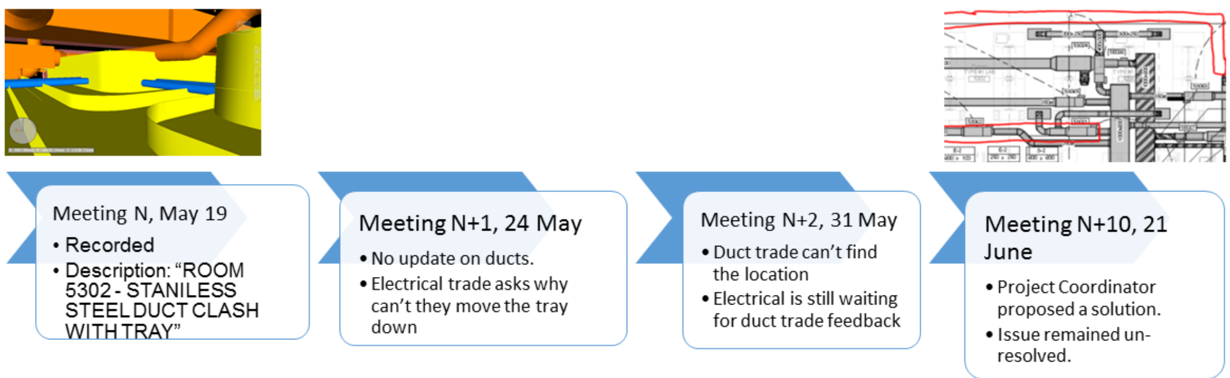


Figure 15: Example illustrating the slow progress of a design coordination issue resolved over many meetings.

Few studies have addressed design coordination issues that go beyond physical conflicts, and the existing work in the field of BIM-based design coordination process fails to go beyond preparation and integration of discipline's designs, the bottlenecks in the BIM design coordination process are yet to be formalized. The knowledge in design coordination process characterization and formalization of bottlenecks in the process not only informs future construction projects, but also the software development community. The software development community benefits by learning what practitioners need to do and why, and gets to understand the new requirements including necessary functionality, and underlying design principles and strategies.

This research is based on the findings of a multi-year, non-intrusive observation of two MEP-intensive building projects. The research first involved observations of design coordination meetings and the analysis of artifact utilization, as well as of changes on BIM files. This was followed by an in-depth qualitative analysis of meeting segments, and the verification of findings against relevant literature and expert interviews.

This research is based on the findings of a multi-year, non-intrusive observation of two MEP-intensive building projects. The research first involved observations of design coordination meetings and the analysis of artifact utilization, as well as of changes on BIM files. This was followed by an in-depth qualitative analysis of meeting segments, and the verification of findings against relevant literature and expert interviews.

This research provides an in-depth study of BIM-based design coordination practices and processes, the bottlenecks encountered, and the required functionality of BIM coordination tools. We provide an in-depth study of BIM-based design coordination practices and processes through characterizing the design coordination process, identifying the bottlenecks practitioners face during BIM design coordination, analyzing the literature and proposing design considerations. We also propose the functionalities to support these bottlenecks and design considerations.

2.2 Definitions and Literature Review

In this paper use the term BIM in the broader sense of “BIG BIM” (Redmond et al., 2012) that can be divided into interrelated functional, informational, technical, and organizational/legal issues (Volk et al., 2014). We see BIM as a key component for efficient design coordination and review processes. We refer to the “MEP Coordinator” as the person(s) in charge of overall design coordination of building system designs and the "BIM Coordinator" as the person in charge of obtaining and integrating all the different BIMs from the trades, identifying and presenting clashes during the meeting, and navigating the integrated BIM during meetings. We refer to "clashes" as conflicts that are detected through an automated clash detection function of BIM tools when two or more building elements occupy the same space (Eastman et al., 2011). We define "design coordination issues" as more complex conflicts between systems that are either not detected through automated "clash" detection or require further examination.

In Table 2, we present the most closely related prior studies that have enabled us to gain a deeper understanding of the BIM-based building design coordination. These include findings related to characterization of issues in design coordination (e.g. Wang and Leite (2016a) and Lee et al. (2012)), knowledge capture strategies in design coordination (e.g. (Awad and Ghaziri 2007)), design coordination process (e.g. Yung et al. (2014), and Saram and Ahmed (2001)), interactions with design artifacts (e.g. Tory et al. (2008)), transitions between design artifacts and views (e.g. Terry et al. (2007)), availability and accessibility of design artifacts (e.g. (Tang and Leifer (1988)), practitioner participation in coordination meetings (e.g. Liston (2009)), and BIM platform evaluation strategies (e.g. Shafiq et al. (2013)).

In the domain of design coordination process, Yung et al. (2014) characterized the high-level BIM coordination process, the coordination tasks and activities proposed in their study was limited to automated clash detection of physical design conflicts, and limited by only looking at model creation, model integration and conflict detection cycles. We build on their findings to characterize the process for more complex, time consuming design coordination issues, characterizing design issue identification, meeting preparation, solution proposal and approval, decision making, documentation, request for information (RFI) handling, and log maintenance activities. In addition, the work of Saram and Ahmed (2001) enabled us to better understand the activities involved in construction coordination and build on their findings to develop our own BIM-based design coordination process characterization, since prior studies did not provide a characterization of full BIM-based design coordination processes.

We address the progress in relation to design coordination issue characterization and knowledge-capture strategies for design coordination. We also describe the literature reacted to interactions with design artifacts, transitions between different design representations, availability, and accessibility of design artifacts, practitioner participation, and BIM platform evaluation strategies.

Table 2. Literature for relevant research domains and their contributions.

Domain	Reference	Description of contribution
Characterization of issues in design coordination	Korman et al. (2003)	Classified design issues into three categories of design, construction, and operations issues. Provided the foundation for other studies.
	Tabesh and Staub-French (2006)	Classified design issues as tasks of conceptual, spatial, and underlying reasons behind constraints identified in disciplines.
	Lee et al. (2012)	Classified likelihood of design issue identification, and the impact on schedule, quality, and direct cost.
	Mehrbod et al. (2015)	Classified design coordination issues into seven categories; analyzed design issues' frequency of occurrence and resolution rate.
	Wang and Leite (2016a)	Provided a formalized representation schema for the analysis and management of physical issues ("clashes") in MEP coordination
Knowledge capture strategies in design coordination	Awad and Ghaziri (2007)	Provided and reviewed observational techniques to capture the spontaneous nature of a particular process or procedure.
	Lindlof and Taylor (2010)	Provided expert interview methods to record and capture tacit construction knowledge.
	Wang and Leite (2016b)	Proposed a repository platform for storing physical design issues identified during "clash" detection.
Design coordination process	Yung et al. (2014)	Formalized how design institutes without 3D modelling capabilities can use modellers to perform MEP coordination.
	Saram and Ahmed, (2001)	Characterizing the activities involved in construction coordination.
	Jung and Joo (2011)	Developed a three-dimensional framework to address the variables for theory and implementation of BIM.

Interactions with design artifacts	Tory et al. (2008)	Characterized interactions with paper and 2D digital artifacts, provided a taxonomy, and identified bottlenecks.
	Liston et al. (2007)	Provided qualitative methods for observation and analysis of the use of media during MEP coordination meetings.
	Liston (2009)	Investigated the richness of media use during meetings and compared the performance of different teams using artifacts.
	Mehrbod et al. (2013)	Conducted a study to examine how a building design team used BIM and other design artifacts to coordinate the design.
Transitions between design artifacts and views	Terry et al. (2007)	Developed tangible tools to navigate and interact with design artifacts using 2D-augmented technical drawings.
	Seo and Lee (2013)	Provided methods of incorporating intuitive interactions through the hand-touchable interface in various AR-based user experiences.
	Kato et al. (2003)	One of the first to propose the use of virtual reality (VR) to facilitate the transition from 2D to 3D information.
	Fiorentino et al. (2012)	Proposed augmented technical drawings that incorporate AR and tangible techniques for easy-to-use interface to navigation.
Availability and accessibility of design artifacts	Tang and Leifer (1988)	Defined the effect of location of media on interaction and identified three characteristics of use: orientation, proximity, and simultaneous access.
	Heath et al. (2000)	Defined "publicly available media", "semi-shared", and "private media" to distinguish differences in interaction with media.
	Hawkey et al. (2005)	Compared collaborative settings where members were placed near, far from, and one near and one far from a display.
Practitioner participation in coordination meetings	Liston (2009)	Examined the extent to which practitioners interacting with design artifacts used private vs. shared media.
	Weisband et al. (1995)	Identified increased participation leads to better outcomes and increased satisfaction with group process and outcome.
	Foley and MacMillan (2005)	Provided a concept of participation as a proportion of speaking time, turns, or counts.
BIM Platform evaluation strategies	Redmond et al. (2012)	Surveyed industry practitioners to assess and benchmark BIM tools regarding their capabilities and interoperability.
	Shafiq et al. (2013)	Benchmarked BIM cloud platforms, identifying the strength and shortcomings of different model collaboration systems.
	Mehrbod, Staub-French, and Bai (2017)	Identified challenges of BIM-based design coordination process, proposed required functionalities, and benchmarked BIM tools.

2.3 Methods

We conducted a multi-year ethnographic case study of two complex building projects that both involved a design development phase and a construction phase. To achieve a greater understanding of the work practices, we chose to study two teams in depth rather than multiple teams. Specifically, the research involved observation of live and video-recorded design coordination meetings and in-depth qualitative analysis of meeting segments. Initially, we analyzed these meetings qualitatively, through five-minute vignettes, and then verified our findings against current literature to identify the bottlenecks in BIM-based coordination meetings. Finally, expert reviews and further reviews of the literature were conducted to identify design considerations for future BIM-based coordination tools (Figure 16).

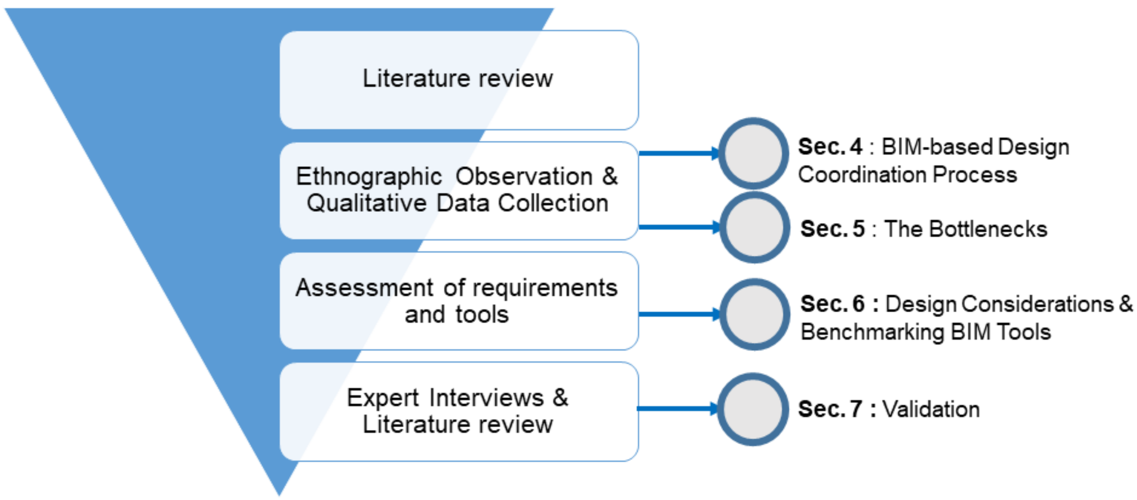
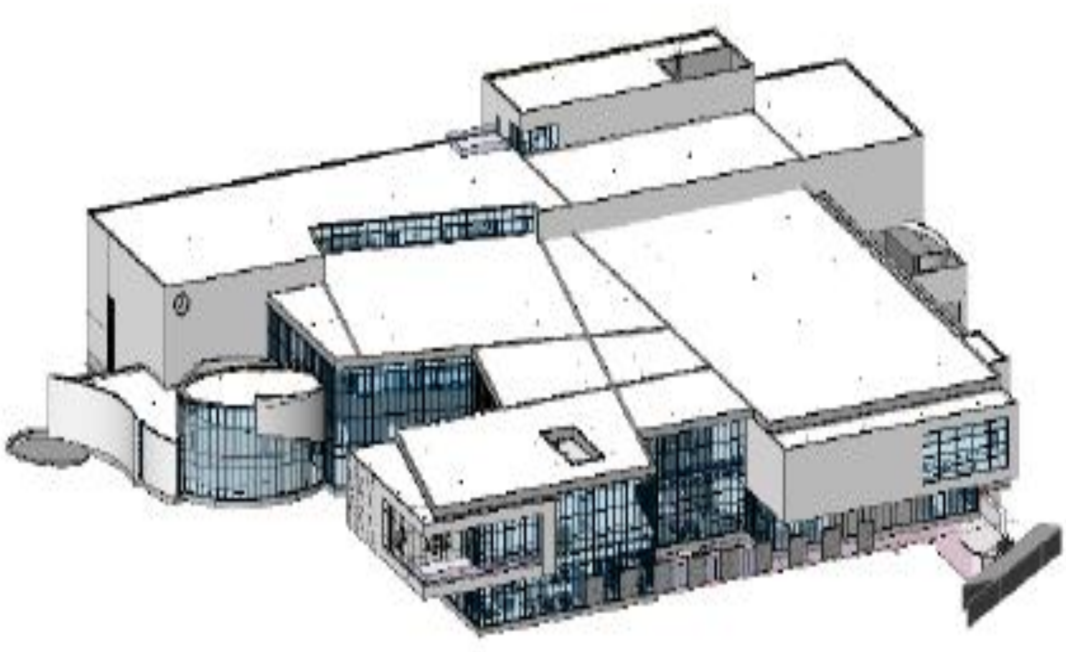


Figure 16: Methodology used to conduct this research. Circles represent the outcome and resulting chapters from each research method.

2.3.1 Case Studies

Royal Alberta Museum (RAM): the newly constructed Royal Alberta Museum (RAM), located in downtown Edmonton, Alberta, is the largest museum in western Canada. The building is 25,349 m^2 on a site measuring 20,024 m^2 (Figure 10). The project was a design-build delivery and involved early and active engagement from most of the key trades. I participated remotely in the design coordination meetings and recorded and observed participants conducting design coordination; I also analyzed relevant project documentation, construction drawings, and BIM files. I had access to meetings from the planning phase through completion of the building structure.

Pharmaceutical Sciences Building at the University of British Columbia (Pharmacy): an 18,000 m^2 facility provides a variety of teaching and learning spaces from lecture halls and seminar rooms to a pharmacy clinic and three floors of research laboratories (Figure 11). The project was a construction management delivery, and the MEP trades were engaged early in the design process. I observed meetings both in-person and remotely, recorded and observed participants during design coordination, and analyzed relevant project documentation, construction drawings, and BIM files.



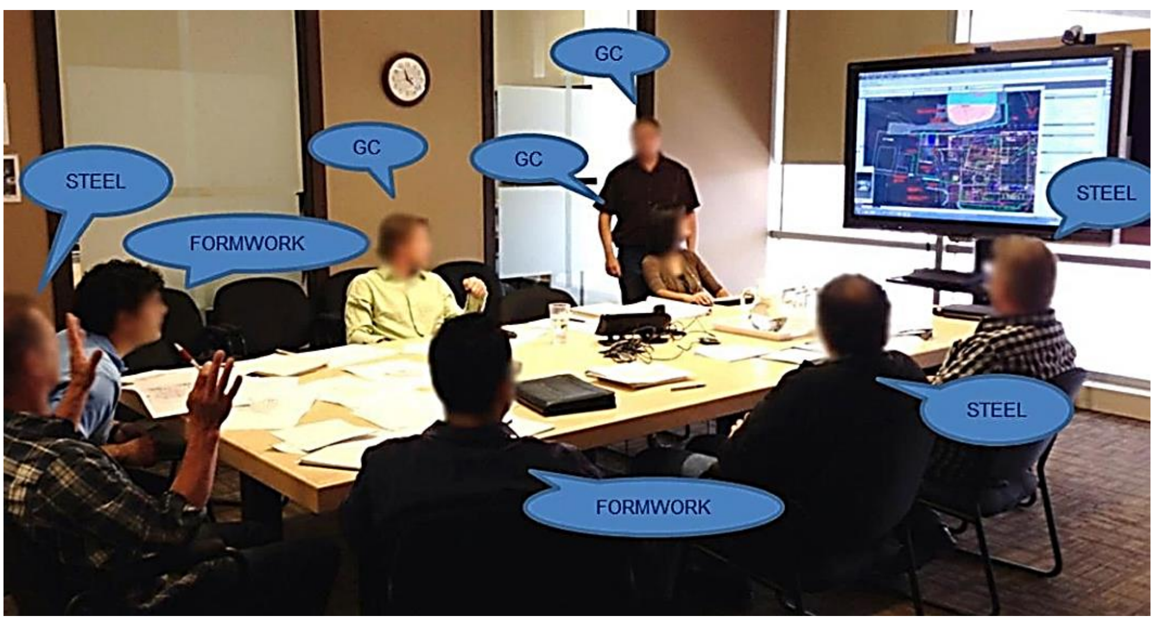


Figure 17: The Royal Alberta Museum - an architectural model of the RAM project (top) (image courtesy of Dialog Architects) and a snapshot of the design coordination meeting environment for the RAM case study (bottom) (GC indicates general contractor).

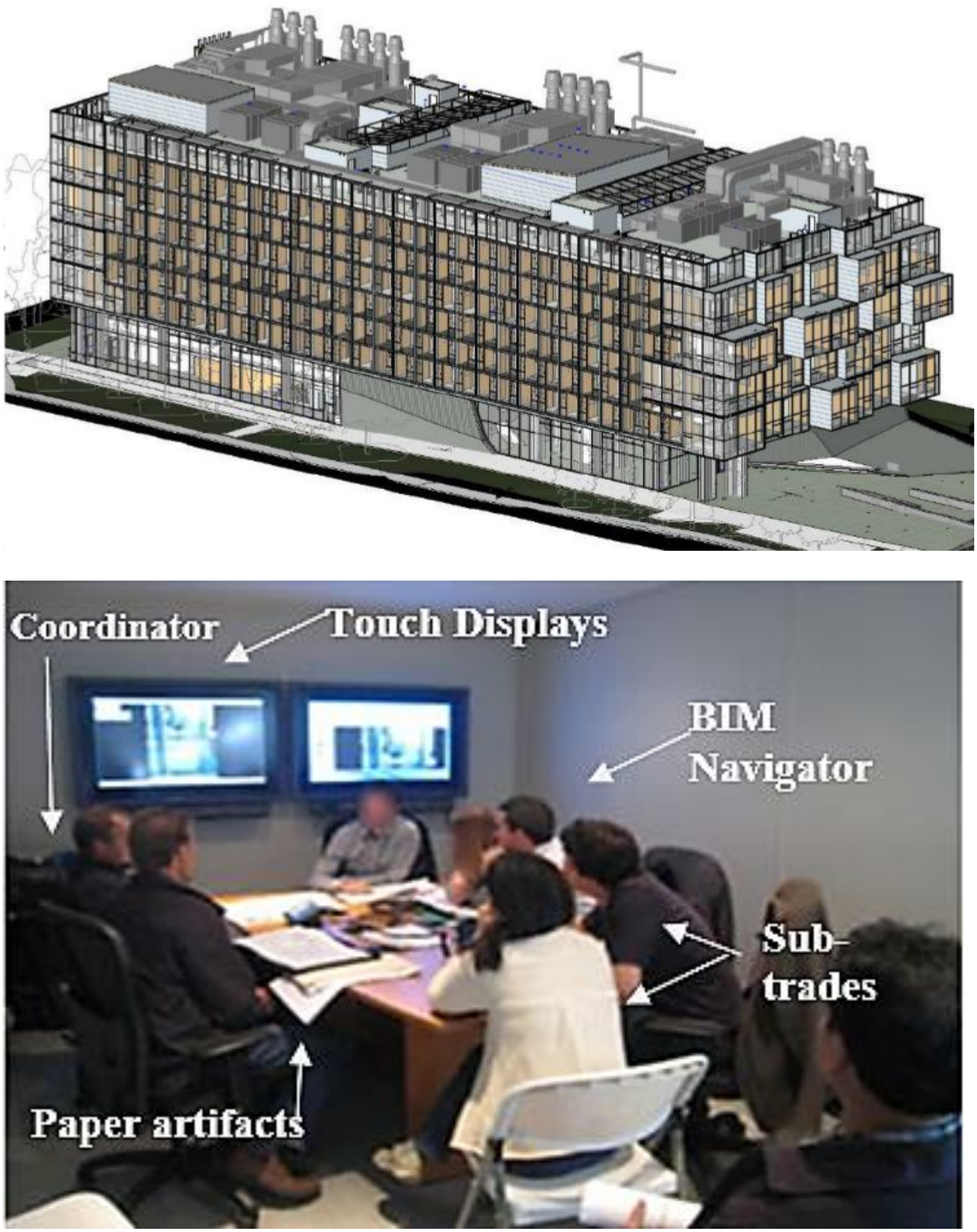


Figure 18: Integrated BIM model of the UBC Pharmaceutical Building Project (top) (image courtesy of Hughes Condon Marler Architects) and BIM Trailer used during design coordination on site (bottom).

The case studies represent state of the art public sector projects involving some of the largest general contractors, and BIM-savvy design consultants, and sub-contractors in western Canada. The general contractor had substantial prior BIM experience from prior projects. Generally, it is extremely hard for researchers to gain access full level access to such projects which involve similar level of complexity, scale, significance, and BIM level of development. Hence, in this research we chose to analyze the case studies in depth, rather than a breadth of numerous smaller scale case studies.

We analyzed the BIM-based design coordination processes of two case-study projects, which were chosen to capture the breadth of design issues that practitioners encounter at different stages of design coordination. Both projects had extremely complicated MEP systems along with unique architectural designs that made design coordination and constructability key concerns. Over the course of design and construction, BIM was used extensively to coordinate designs from different consultants and sub-trades. In both case studies, the meetings typically had six to nine participants from different disciplines, including the general contractor, consultants, and subcontractors. Regarding the leadership of the meetings, the MEP Coordinator was in charge of overall coordination of building design issues, while the BIM Coordinator was in charge of integrating the BIMs, detecting “clashes”, and navigating the 3D and 4D models during meetings.

The case studies focused on different stages. One case study focused on the design to mid-construction stage, and the other on the period from mid-construction to the end of construction. The two case studies were chosen to capture depth rather than breadth of the challenges that practitioners encounter at different stages of design coordination. On both projects, there was early engagement from construction trades and the expectation was that trades would implement BIM to fabrication level (LOD 350 to 400)

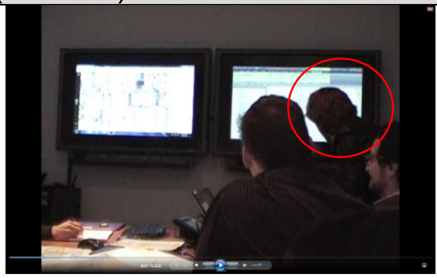
2.3.2 Ethnographic Observation and Qualitative Data Collection

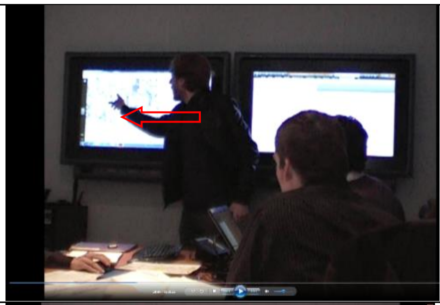
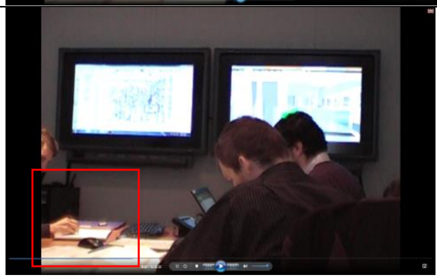
An ethnographic approach was chosen to collect the "richest possible data" (Lofland and Lofland, 1995), and to observe meeting participants in their natural setting (Denzin, 2006). In both case studies, we analyzed BIM files, RFIs, meeting lengths, construction communications, and other communications among project participants. After we observed meetings (remotely, recorded, or in-person), we went back to prior communications among project participants and tracked how design issues were communicated among the teams. We also tracked BIM changes, design issue spreadsheets, emails, and internal memos. We took detailed field notes on BIM use, as well as the interaction among participants. We observed and video-recorded over 90 weekly design coordination meetings (with a typical length of 100 to 140 minutes) from the early stages of design through construction of the building systems. We had access to construction documents, BIM files, site progress, design issue spreadsheets, and internal emails distributed among project participants. We also collected all information that circulated among meeting participants such as logs of design coordination issues, "clash" detection logs, emails about the coordination schedule, and digital snapshots of the digital model showing "clashes" between different building systems. We tracked the integrated BIM from each of the design coordination meetings, analyzed the memos and communications among stakeholders through word-by-word scanning, and pinpointed documented design coordination issues to BIMs and meeting segments.

We conducted qualitative data collection and analysis mainly in two forms – interaction analysis and design issue analysis. However, while we attempted to collect the data in an unbiased way through both qualitative and quantitative observations, as per guidelines of Skalski et al. (2017), we were unable to observe the interactions that were done outside of the meetings, which would have helped to inform to how practitioners interact with information privately.

We first conducted a qualitative assessment of the meetings in which we looked at 14 whole meetings (90 to 120 minutes each) to layout the model for our initial data collection and analysis. We selected these meetings based on different stages of building design and construction. From the meetings, we selected 39 5-minute vignettes based on the level of interaction with artifacts, the participation of practitioners, and the construction stage. For instance, we ensured an average number of participants plus one person was present, and a design coordination issue was being discussed. Figure 19 and Table 3 shows an example from the RAM case study which presents the details of what we captured from each 5-minute vignette. A summarized discussion chart presenting how we documented interactions, intentions, locations, artifacts, participants, and dialogues is shown in Figure 19.

Table 3: Video catalog summarizing interactions and movements of practitioners in a 5-minute vignette from a meeting in the RAM case study, which was focused on resolving a complex design coordination issue and deciding on a dropped ceiling height. (Legend: 2DSB: 2D smart board; 3DSB: 3D smart board; DS: drawing set)

<table>
<tr><td colspan="3">Design issue: Cable tray colliding with mechanical ducts, all surrounded by structural columns; all components cannot fit in ceiling space provided.
Resolution goal: Agreeing on a ceiling height capable of fitting all elements.
Participants present: MEP Coordinator, Plumbing Contractor, Plumbing Consultant, Architect, BIM Coordinator, Electrical Contractor
Excerpt duration: 21:07 to 26:07 (5 minutes)</td></tr>
<tr><td>The Architect takes over the 3DSB and modifies the BIM (the BIM Coordinator and the Electrical Contractor have to move). The Architect: “Working with the model is more difficult than what I thought.”
The Plumbing Contractor looks up pipe dimensions from his DS and reads to the Architect.</td><td></td><td>The MEP Coordinator looks up the dimension for spacing around units from the DS and reads to the Architect.

The Architect after 3 minutes of manipulation: “So that would be my new finished ceiling level.”</td></tr>
<tr><td>The Architect walks to the 2DSB: “This ceiling is ok for here, but I am worried about the atrium. These pipes are affected, and they have to be moved.”</td><td></td><td>The Plumbing Contractor: “I am sure this will be problematic.”
He looks up at his DS and reads dimensions to the Architect.</td></tr>
<tr><td>The BIM Coordinator takes over the 3DSB again and brings the 3D view (Revit) to show the updated ceiling level in 3D.</td><td></td><td>The Plumbing Contractor proposes a solution that requires lowering the ceiling. The Architect rejects the solution as it conflicts with the owner’s requirements. The MEP Coordinator records the details in his logbook to follow up later.</td></tr>
</table>

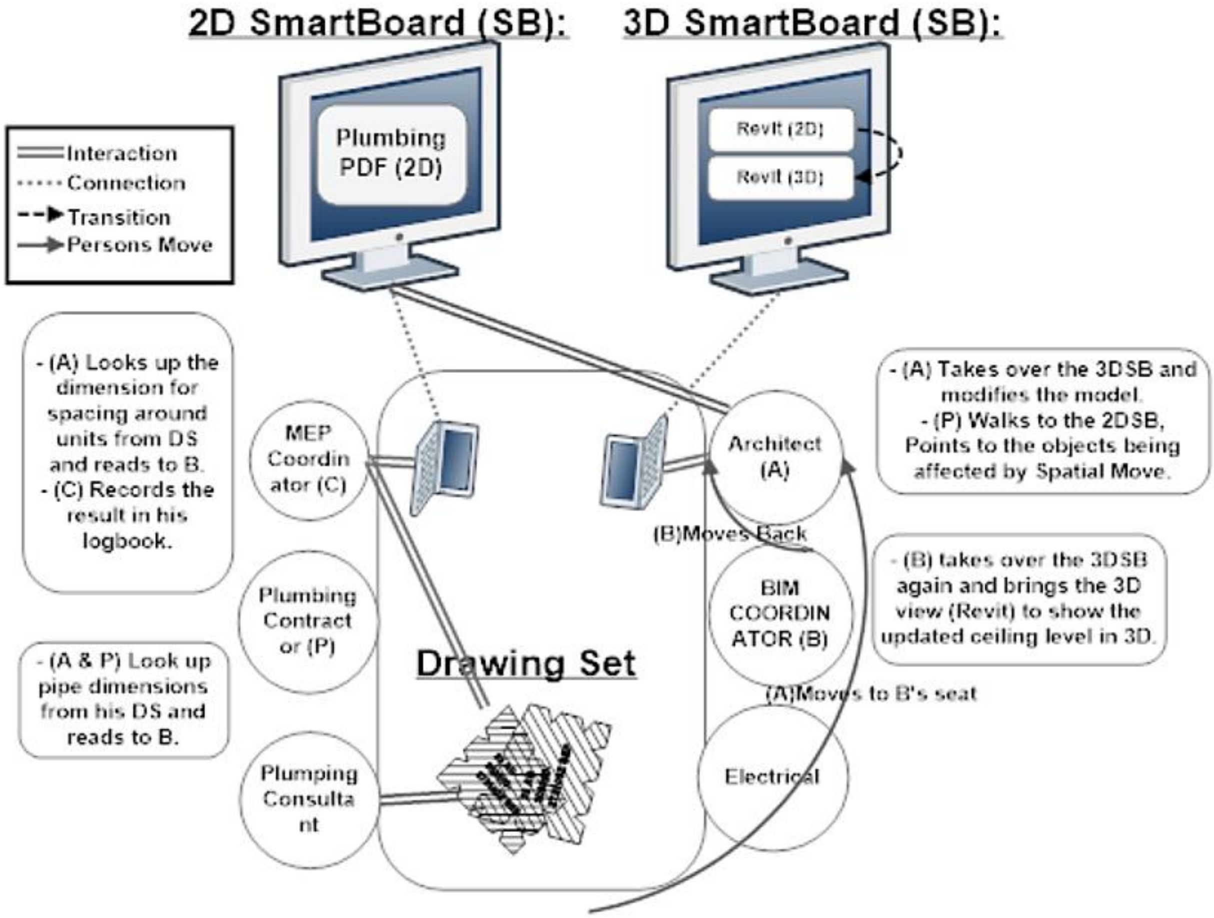


Figure 19: A summarized discussion chart showing locations, interactions, movements, practitioners, and dialogues from Table 3

We investigated how coordination issues were identified and communicated among the project team, and how the team presented, documented and resolved these issues. Through the analysis of the BIM files of each meeting, we tracked how the issues were identified; and through specific segments of the meeting related to those issues, we observed how the issues were resolved. We also analyzed participants' notes and issue documentation spreadsheets regarding each issue. In total, we analyzed 98 design coordination issues from the RAM case study, and 120 design issues from the Pharmacy case study. We also tracked the time it took for the design issues from being identified, discussed, and documented, to being resolved. We analyzed all emails and notes to update our records of design coordination issues that were discussed outside meetings. The described process is shown in Figure 20.

I CODE	S CODE	Issue No.	28-Jun-11	Issue:	Solution:
CL	E	1	Resolved	Clearance	
H	E	2	Resolved	Alter Equioment Elevation to higher the ceiling	
MC	R	3	Resolved	Multiple Mech Duct Clash with Cable Tray	ReRoute Cable tray
C	RS	4	Resolved	Duct work calsh with Structrual	move over duct. Resize
I	I	5	Resolved	cable tray required?	confirming no
C	R	6	Resolved	sanitray clash with ductwork	ductwork reroute
C	E	7	Resolved	structural clash with ductwork	elevate the equipments
A	R	8	Resolved	missing as built model/duct clash wqith cab	re-route cable tray
MC	E,R	9	Resolved	duct and cable treay same location	duct to trop and re-routed
C,H	E	10	Resolved	cable tray clash with duct	lower the ceiling
I	I,D	11	UnResolved	Congested under ceiling area to fit all	to identify other areas for COMMS tray
I	I	12	Resolved	can pipework run above mech room? Can cat	confirmed yes
MC	E	13	Resolved	multiple cable tray and mech servises clash	lower cable tray
O	RE	14	Resolved	doct overlap, loers cable tray	remove FCU ducts
MC	E	15	UnResolved	multiple sprinkler clash with duct and pipe	lowered sprinkler but still clashes
C	E	16	Resolved	tray W duct clash	higher tray
A	E	17	UnResolved	As built required / what is heating pipe size	lower the ceiling, still clashes
MC,H	D,RE	18	UnResolved	multiple clashes B duct, cabletray , grills	ceiling type to be reviewed- tray to be stc
MC	RS	19	Resolved	mulitple clashes B Tray, Grill , Duct	Tray Consolidated

Figure 20: A sample spreadsheet showing the description and categorization of design issues and solutions, as well as tracking their status.

2.3.3 Assessment of Requirements and Tools

An essential part of technology development is the analysis of user requirements. Numerous methods are used in the software industry to explore, consolidate, and validate user requirements (Shafiq et al., 2013); through the most common include surveys or interviews. Based on the identified bottlenecks from the qualitative study, we identified design considerations and functionalities required to improve these bottlenecks. The recommended functionalities emerged from an analysis of the findings from the prior stage and a definition of user requirement categories. These were later broken down to specific functionalities and aligned with existing findings in each field.

2.3.4 Expert Interviews

We interviewed experts in the field to assess our results. We carried out five interviews with BIM and trade experts in the field, and three interviews with other researchers. The duration of interviews was between 50 and 90 minutes. The interviewees were asked to comment on the table of bottlenecks presented in Table 4 and compare their own experiences with the findings of this study. Participants stated that organizational constraints, existing software in use from prior projects, knowledge of BIM tools, and contractual obligations often dictated what tools were used for BIM creation. We transcribed the interviews and analyzed the feedback from the experts, and revised the terminology and details of our findings to reflect this feedback. The revisions mostly included terminology of bottlenecks and design considerations, as well as descriptions of each category.

2.4 BIM-Based Design Coordination Process and Challenges

Based on our observations and the analysis of BIM-based building design coordination processes, we have come to understand the design coordination process as a cycle of three interconnected steps: (1) issue identification, (2) issue resolution, and (3) issue documentation. Figure 21 shows the observed BIM-based design coordination process based on the two case studies, along with the set of inputs, outputs, mechanisms, and controls of each function in IDEF-0 format (Kim et al., 2003). While we have benefited from the prior efforts to formalize the BIM-based design coordination process e.g. (Seo et al., 2012; Staub-French and Khanzode, 2007; Tabesh and Staub-French, 2006; Yung et al., 2014), we believe the process can be viewed as a cycle varying in different stages of MEP design coordination. We would like to emphasize that the process outlined in this section reflects the process observed in many BIM-based design coordination projects, but we recognize that the process below does not apply to all BIM-based building design coordination and does not represent an optimum or ideal BIM-based design coordination process.

Regarding terminology (figure legends), we define “interaction knowledge” as the expertise and knowledge of interacting with state-of-the-art BIM tools, as well as the use of 2D PDF and paper drawing sets, which are widely adopted among practitioners. “Process knowledge” is defined as the knowledge of constructability, the interconnectedness of different systems, discipline-specific know-hows, and general understanding of the BIM-based design coordination. “Issue representation knowledge” is defined as the knowledge of how BIM-based design coordination issues are represented, communicated, and documented throughout the coordination process. the “*” refers to typical owner requirements, project execution plan, project documents, guidelines, etc., as defined by prior research (Seo et al., 2012; Staub-French and Khanzode, 2007; Tabesh and Staub-French, 2006; Yung et al., 2014)

2.4.1 Identification of Design Issues

A set of activities is performed to prepare the participants and design information before meetings. Figure 22 demonstrates the issue identification process in detail. The steps include the creation of discipline BIMs based on 2D digital files, conflict detection, examination of conflicts, elimination of “false positives” (Leite et al., 2011), and, finally, determination of design issues. The process is often performed by the BIM Coordinator or MEP Coordinator.

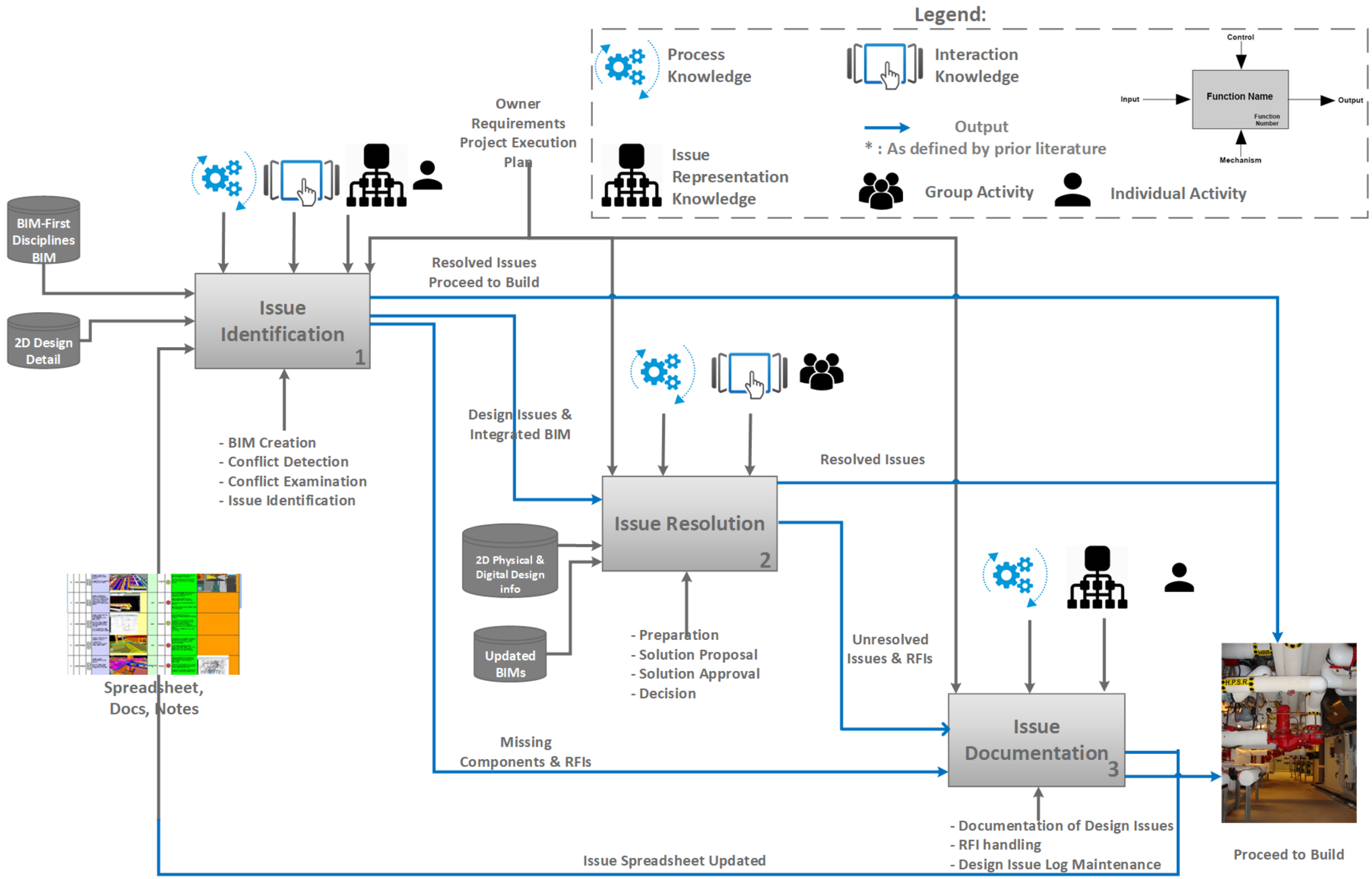


Figure 21: The overall BIM-based design coordination process.

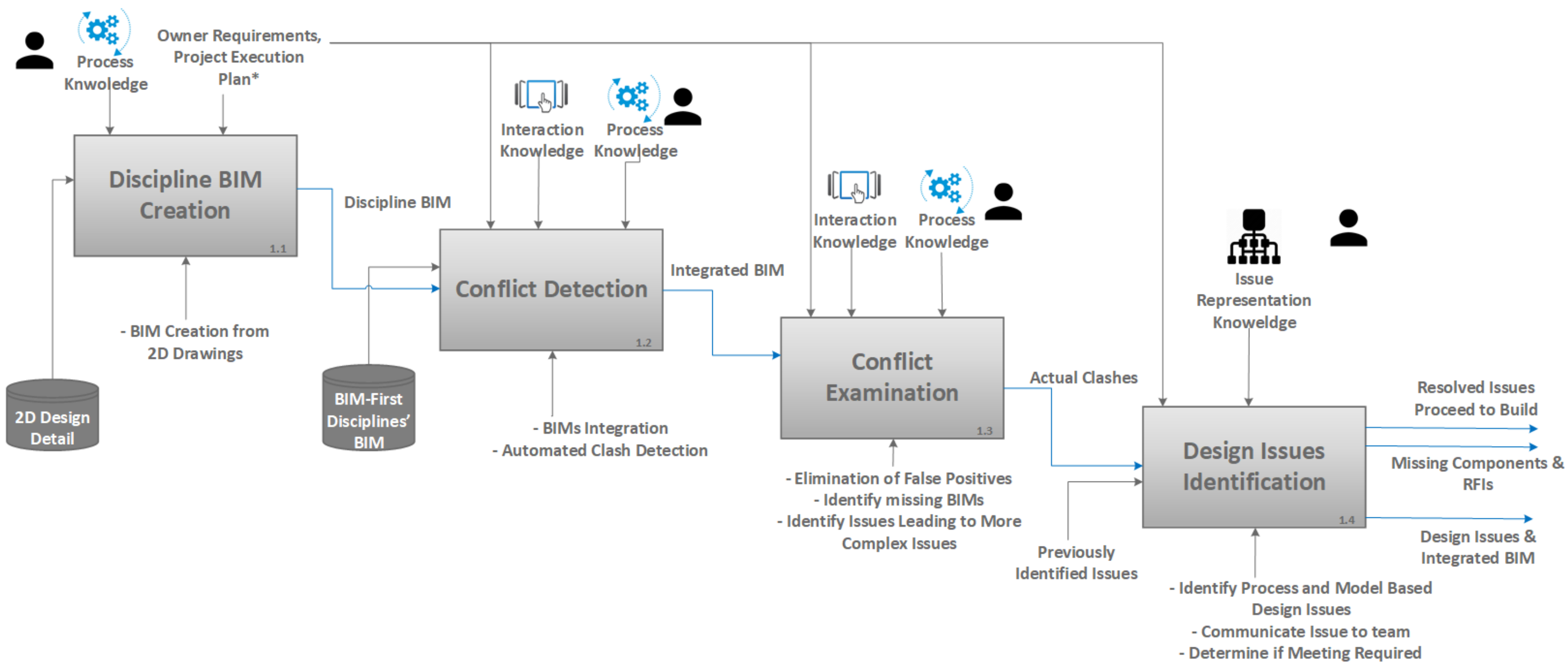


Figure 22: BIM-based process for identifying design coordination issues.

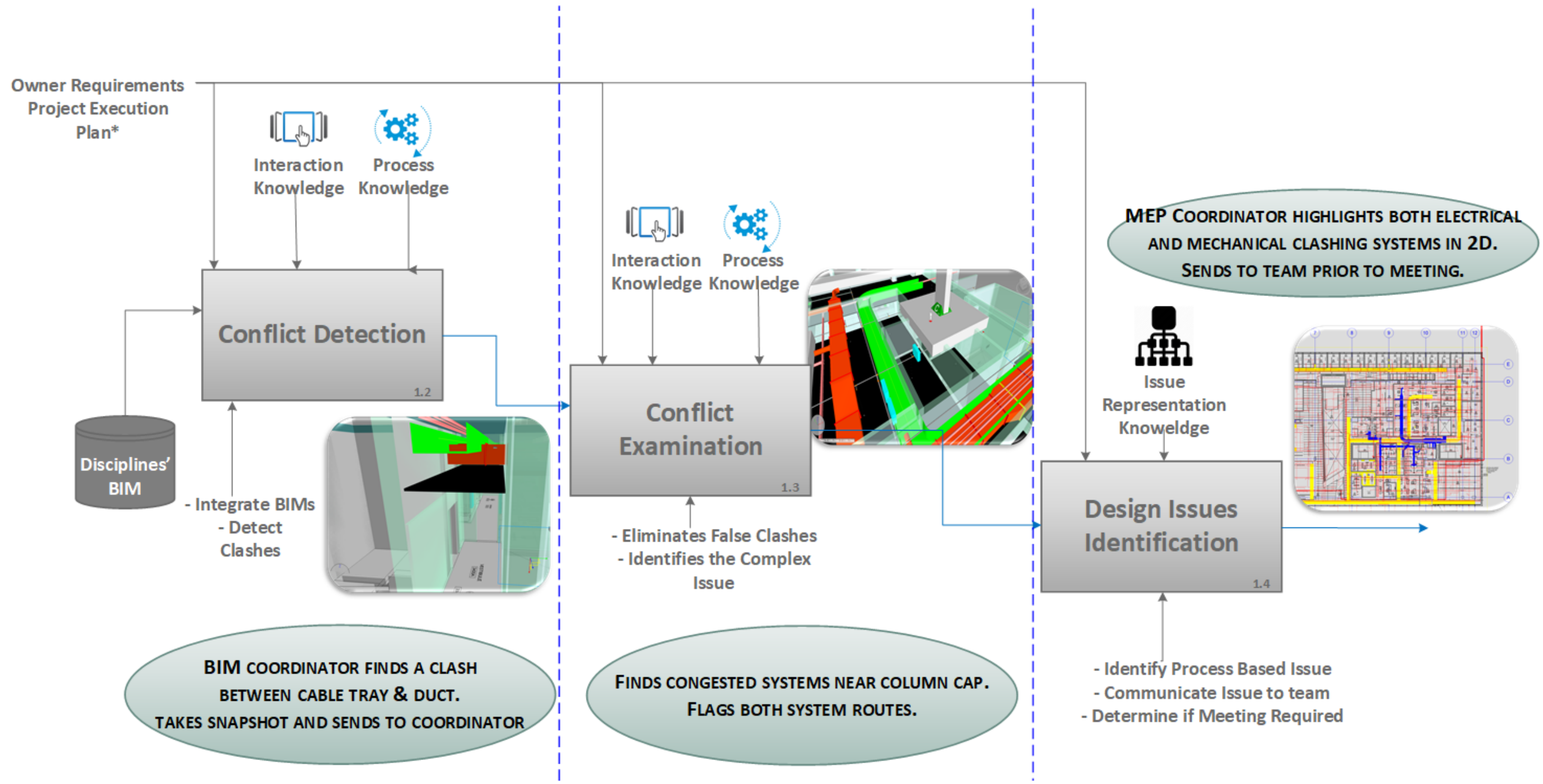


Figure 23: Example of the process of identifying a design coordination issue. Because BIMs are integrated, a simple coordination clash leads to a more complex design issue.

Figure 23 provides a detailed example of how an issue evolved from a "clash" within disciplines' BIMs into a process-based design issue. First, a "clash" between the duct and cable tray from the RAM case study was examined in detail, and the BIM Coordinator found that the duct could not be moved as it collided with other building systems. Further examination revealed that the building systems were congested near the column cap, and the BIM Coordinator communicated the issue to the MEP Coordinator. The MEP Coordinator inspected the issue and communicated the issue by sending a snapshot of the relevant systems to the different disciplines with a request for a group discussion, which meant this issue would be discussed in the coordination meeting (step 2)

Challenges with the identification of design issues:

- *Unclear characterization of design coordination issues*: We found that the scope, priority, and rationale of design issues were rarely defined. Practitioners often had difficulty relating to the design issues. Over time, they needed help understanding the relationship between the initial "clash" and the more complex design coordination issues. There also were many instances where terminology and inability to categorize design coordination issues caused time-consuming errors.
- *Inefficient communication among stakeholders*: Similar to Dossick and Neff (2010), we found insufficient communication among stakeholders contributed to an inefficient design coordination process. Our observations show there was often a lack of clarity as to the urgency of design issues and the dependency of their design issues to them for resolution. Moreover, there was insufficient communication across the supply chain, even within the same building system. Different disciplines were often done by the same trade,

but since the BIM was created by different segments of the organization, their BIMs often clashed with each other.

2.4.2 Resolution of Design Issues

Once the design coordination issues were identified, the project team held a meeting to discuss issues raised from the issue identification stage. The participants included representatives from the different parties including the Owner, Construction Manager, Architect, Engineering Consultants, and Construction Sub-trades. As Figure 24 demonstrates, design coordination issues were first brought up in the meetings, the solution was proposed by practitioners based on the issue, and the solution went through the approval process. Once no further proposals went through approvals, a decision was made.

To elaborate on the steps involved in the resolution of a coordination issue, we describe a 5-minute vignette from the meeting described in Table 3, we show how the same design issue from design issue identification step was presented, discussed, and resolved in the coordination meeting (Figure 25) we also provide details on how practitioners interacted with the design artifacts in the coordination meeting (Figure 26).

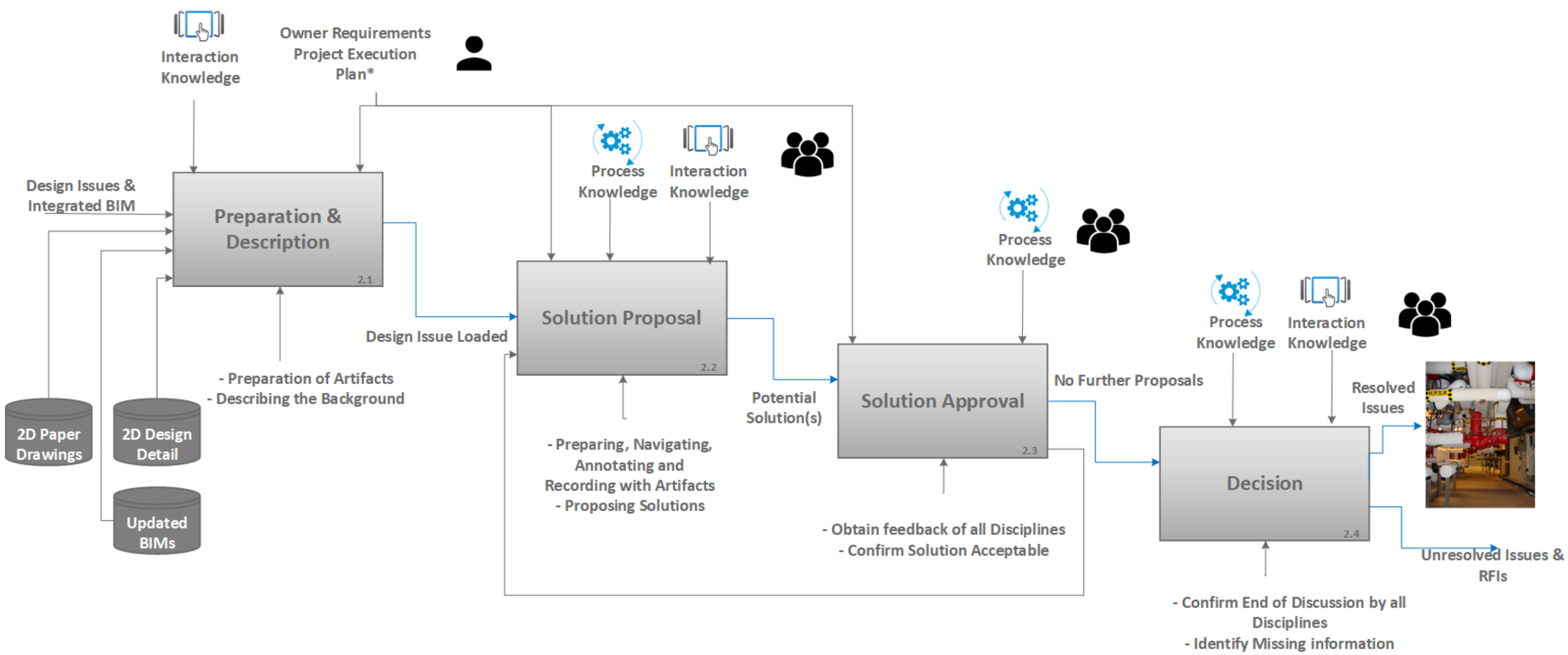


Figure 24: Resolution process of design coordination issues.

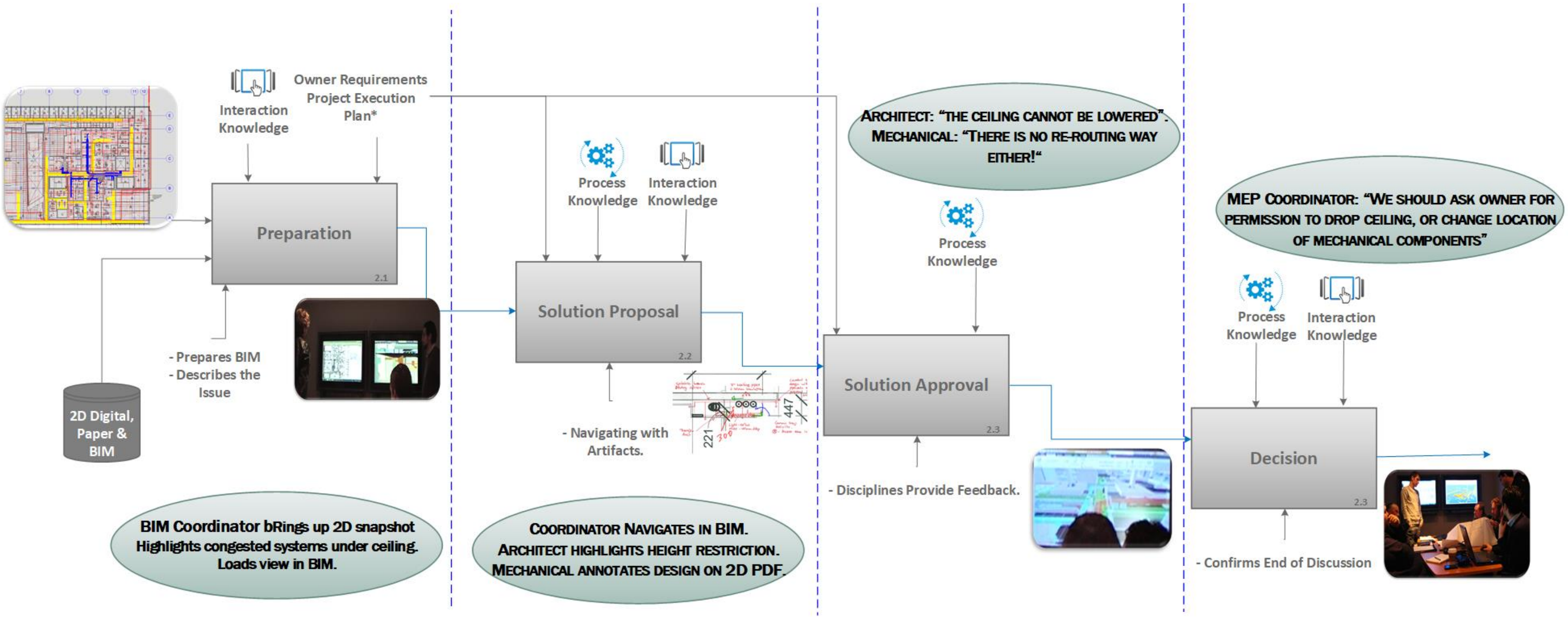


Figure 25: Example of a resolution of design issue coordination issues.

First, the design issue was brought up for discussion by the BIM Coordinator. Participants then interacted with digital artifacts using various navigation techniques, proposed a solution, and then the solution was rejected. At this stage, the MEP Coordinator determined that the issue needed to be documented for future follow-up. While discussing the issue on 2D digital, the participants transitioned to 3D digital, then to 2D digital (PDF), back to 3D digital views, and then to paper drawings. The transition process often happened multiple times through discussions of each design issue. The transitions often occurred since practitioners required a better view from other angles, more detail, or information related to another discipline.

Figure 26: The Architect interacted with paper plans as they were more accessible (left). The practitioners walked to the board instead of interacting with BIM from the desk (right).

Challenges of design issue resolution:

- *Inefficient transitions between design information representations*: Transitions across design artifacts and views were time-consuming and error prone.
- *Hard to interact with design artifacts, that are not accessible*: Participants directed others to interact with artifacts instead of them. For example, the Mechanical Contractor failed to interact with BIM efficiently, went back to his seat, and directed the BIM Coordinator

instead (Figure 26, left panel). He then drew alternative pipes on a large paper saying "*It is a bit easier to write on this!*"

- *Unfit navigation tools for fast-paced BIM coordination meetings:* Current BIM navigation tools are not sufficiently responsive for group use. For example, the Architect takes over BIM, but he is unable to interact with it (Figure 26, right panel): "*This is too difficult, I can't navigate with Navisworks.*" He directs the BIM Coordinator instead. Meanwhile, the Mechanical Contractor keeps activating different features on SMART Boards accidentally when using his hand.

2.4.3 Documentation of design issues

Finally, once the discussion of a certain issue reached an end (e.g., resolved, required further input from a different source, or needed a follow-up in the future), the MEP Coordinator documented the details of each issue. In both the Pharmacy case study and the RAM case studies, the same documentation format and details were used to document the issues. Figure 28 shows the documentation process of design coordination issues in detail. As the figure demonstrates, the unresolved issues got documented, and RFIs were sent to related parties as necessary. The MEP Coordinator then followed up with project stakeholders based on the design issue spreadsheets and notes (Figure 27).

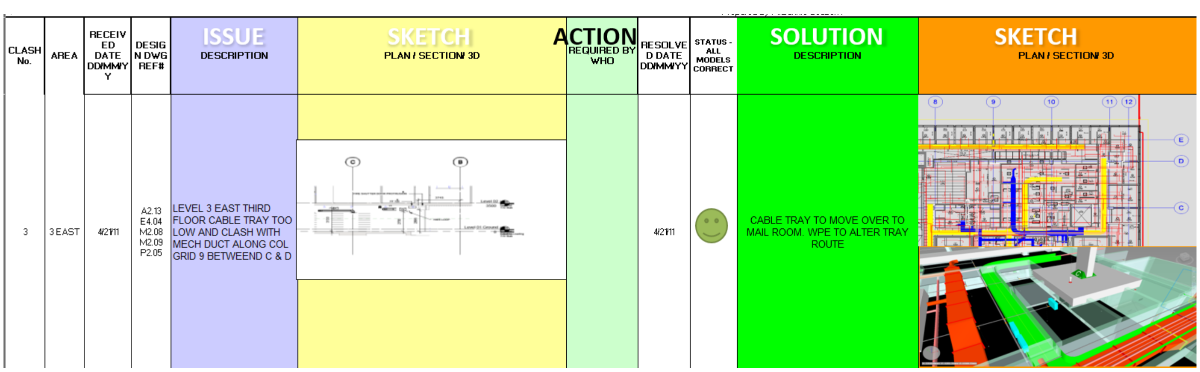


Figure 27: Typical design issue documentation shared after the coordination meeting.

Figure 27 highlights the details captured by the BIM Coordinator for the design issue shown in Figure 25, which includes the location, involved systems, snapshot(s) if available, entry and solution dates, status, and a brief description of the possible resolution. Both case studies followed the same format for documenting design coordination issues. However, in the Pharmacy case study, design issues were tagged with trade-specific drawing page number and a zone on each floor (e.g. Level 4 Center, M5, A3). In the RAM case study, the general contractor added an extra notation of grids on the BIM itself (e.g. GL-F 14) when documenting design issues. In addition, the same excel sheet was used to maintain and track all design issues throughout the RAM case study, but numerous excel sheets were used to track design issues in the Pharmacy case study.

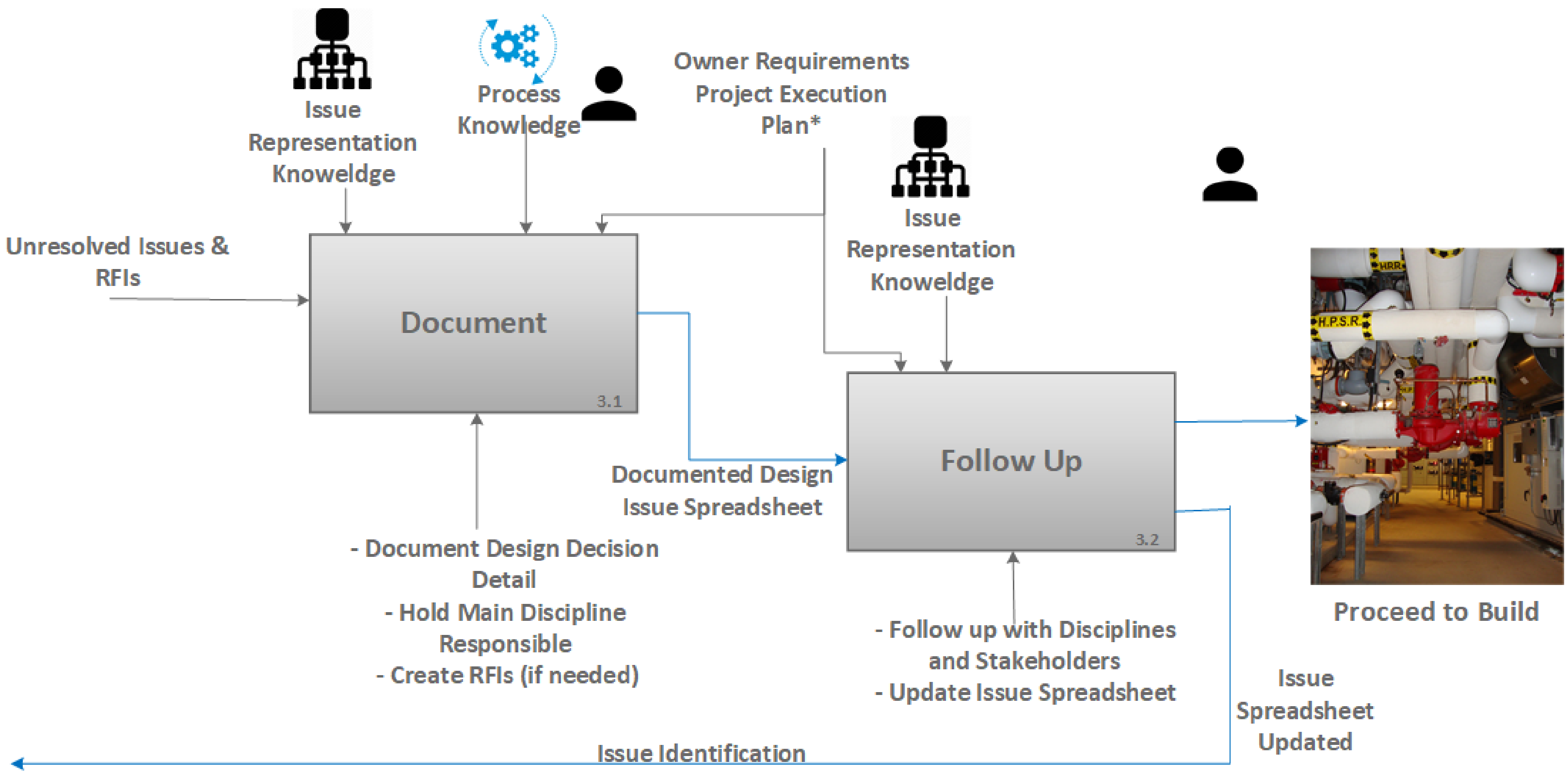


Figure 28: Documentation process of design coordination issues.

Trades Coordination/Clash Detection meeting minutes (held April 9, 2015):

Feature Gallery:

Ledcor has reviewed all of the elements in the Feature Gallery. Some of the elements have not been shown in 3D such as the Moveable wall motors required, the upright sprinkler heads and the fire damper clearances. There are other elements that are shown for intent and not to the shop drawing sizes such as the Coffer Lights (A14 and A16), and the Linear diffusers.

- Update – Moveable wall motors (clearances) are not shown in the model. The motor sizes will be confirmed when we get shop drawings.
- Update – The linear diffusers may need to be revised once the required moveable wall motor clearance is known.
- Update – The strip lights A14 and A16 may need to be revised once the required moveable wall motor clearance is known. The track lights will be ceiling mounted, they will not conflict with the moveable wall.
- Update – The Trusses in the Gallery will be sprayed with Intumescent paint (fire proofing) this coating will expand if it were to ever get hot. Ledcor to confirm if there is a recommended clearance needed from the manufacture. Note: Anything passing through the trusses should provide a 2" clearance.

1. The Cable trays that run in the Feature Hall between G.1' and H.1' (2 locations) will not be able to fit into this space. MCL to pipe on the underside of the Level 2 Q-deck instead of Cable tray.
2. Gisborne to follow up with their designers to see if the upright sprinkler heads and piping can be shown in the model. Further coordination will need to be done to verify that there will be no conflicts.

Figure 29: Screenshot of an email sent by the MEP Coordinator to trades, highlighting the issues not communicated previously, and new owner's requirements and guidelines.

When design coordination was performed remotely, or when all participants were not present, the MEP and BIM Coordinators also performed design coordination on their own and communicated the design issues through email. Figure 29 shows how the MEP Coordinator communicated and documented new design issues on one of the case studies.

Challenges of design issue documentation:

- *Insufficient issue documentation:* We found participants' knowledge of how different systems work together and the protocol and tools for documentation was lost during design issue documentation. When design coordination meetings were poorly documented, the result also had a direct impact on issue identification at the next meeting. When participants were asked to comment on the spreadsheet of documented design issues, they stated that they did not have sufficient understanding of what the document represented. As one interviewee stated, *"This spreadsheet is really ambiguous. I do not understand most of the design issue scopes. I really need more detail and the description."*
- *Inefficient design coordination issue retrieval:* Our observations reveal inefficiencies in how practitioners follow up on previously discussed design coordination issues. Some design issues took over ten weeks to resolve, and some were never documented as resolved by the end of the construction.

Finally, the above processes and challenges highly depend on the recursive involvement of all disciplines during BIM-based design coordination process. As one interviewee stated, "*You can't just go and do your own clash detection. This is part of a systematic approach; you may change unnecessary things or do more damage.*" The stakeholders across the supply chain may also often misunderstand the concept of BIM, or implement BIM in different ways, while others have a deeper understanding of the implications of BIM and its associated set of processes. As one interviewee stated: *"Every trade is following* their own rules and understanding when it comes to BIM."

2.5 BIM-Based Design Coordination Bottlenecks and Design Considerations for BIM Tools

Throughout our observations of the case studies and a review of previous findings, we found that many factors influence the efficiency of BIM-based design coordination processes. Specifically, the bottlenecks in the design coordination process found in this study come from three major research domains. These three domains are presented in Figure 30, which includes BIM adoption processes and interoperability (mostly at the stage of issue identification), interactions with design artifacts (mostly at the stage of issue resolution), and design coordination issue representation and knowledge capture (mostly at the stage of issue documentation).

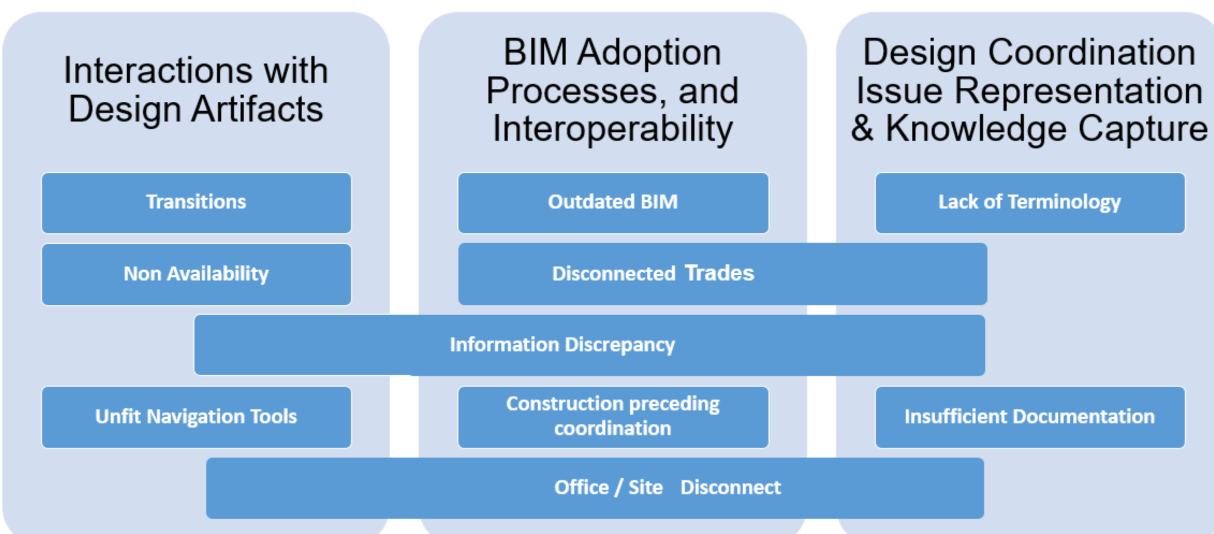
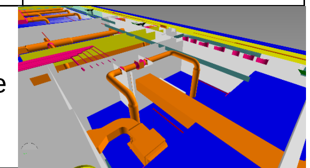
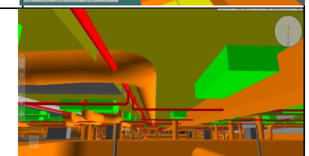
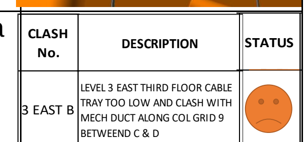
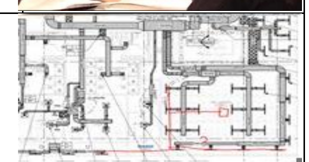


Figure 30: The domains of the bottlenecks influencing the efficiency of BIM-based design coordination.

We found eight main bottlenecks that impede the efficiency and efficacy of BIM-based design coordination processes. Table 4 summarizes these bottlenecks along with their descriptions, examples from the case studies, and BIM snapshots. Based on our observations of these bottlenecks, we present some possible directions for future BIM projects and the software development community. Although many of these observations showed advantages for in-person, co-located resolution meetings, we do not assume that co-located meetings are uniformly superior to non-co-located ones. Similar to Dossick and Neff (2011), our approach is to suggest new techniques that will support the BIM-based design coordination process within digital systems. Table 5 summarizes our design consideration proposals, followed by their description, advantages, disadvantages, and related research. We have also highlighted the related bottlenecks that would be partly or completely mitigated through the adoption of each design consideration.

Table 4: BIM-based design coordination bottlenecks, their description, examples, and snapshots.

Bottleneck	Description	Example	Snapshot
Outdated BIM: Lack of concurrent BIM updates during construction as per discussion or as-built.	Project stakeholders rarely updated BIM to incorporate as-built components or post-design coordination.	Already constructed ducts (orange) are not updated on BIM, which creates a challenge for the plumbing and electrical consultants to route systems. Typical impact: 2 weeks.	
Disconnected trades: Lack of direct communication and coordination between trades.	Aside from construction management, design and trades were rarely in direct contact to coordinate designs and sequences.	All ducts are routed on the same route as slab bands. A re-route and re-design of the entire floor ducts were required. Typical impact: 2 months.	
Lack of terminology: Inconsistent terminology for design coordination issues.	Different trades interpreted various design issues differently regarding the issue, complexity, and steps involved in its resolution.	Interpretation 1: Sprinkler to move down. Electrical consultant to move lights. Interpretation 2: Sprinkler floor changes, essential re-design of lights required. Typical impact: 1 week.	
Insufficient documentation: Inefficient design issue documentation and retrieval.	It is inefficient and error-prone for practitioners to revert to previously documented issues.	Details recorded about the issue were kept to a few words and a screenshot, which limited the team's ability to retrieve information. Typical impact: 3 days.	 CLASH No. / DESCRIPTION / STATUS 3 EAST B / LEVEL 3 EAST THIRD FLOOR CABLE TRAY TOO LOW AND CLASH WITH MECH DUCT ALONG COL GRID 9 BETWEEND C & D
Transitions: Inefficient transitions between artifacts.	Frequent error-prone and inefficient transitions between design artifacts.	• View of the issue is shown in 3D. • Architect takes the paper out and measures dimensions from paper. • Coordinator loads 2D-PDF elevation.	
Unavailability: Lack of availability and accessibility of design artifacts.	Participants directed others to perform interactions with artifacts instead of them.	Sub-trade failed to interact with BIM efficiently, went back to his seat, and directed the BIM Coordinator instead. He then drew alternative pipes on paper.	
Information discrepancy - Inconsistency of design information across different artifacts.	Information in one representation did not match the information in other representations.	• A: (3D) "Where is the step in the ceiling? Where is the corridor?" • B: (points to paper): "That's the step right here!" • A: "That's messed up, 2D doesn't show it."	

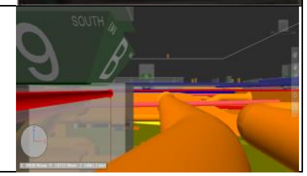
Unfit navigation tools: Unfit navigation tools for fast-paced BIM coordination meetings.	BIM navigation tools are not sufficient for group use.	Architect takes over BIM, but is unable to interact with it: “This is too difficult, I can’t navigate with Navisworks.” He directs the BIM Coordinator instead.	
Office/site disconnect: practitioners in the meeting room interpreted design issues differently from site personnel.	An interview stated, “We recorded some issues as an issue, but for the site personnel it was a non-issue, they just carried on building.”	The issue was flagged in meeting as pipes colliding with ducts. On construction site, however, technicians made it work to bypass the ductwork.	

Table 5: Design considerations, their pros and cons, and related literature. Bold indicates the related bottlenecks

Design consideration	**Pros**	**Cons**	**Related literature and bottleneck (bold)**
BIM First: Adoption of BIM-first approach to encourage trades to start design within BIM early, and extract 2D out of BIM.	• Reduce the frequency of design discrepancies Improve the LOD across all disciplines • Help with transitions	• Requires design to start and finish early • Requires additional cost and resources in the design phase • Insufficient interoperability and information exchange across BIM platforms (interoperability challenges)	Czmoch and Pękala (2014) - **Information discrepancy**
Cloud BIM: Adoption of cloud-based collaborative platforms to get trades working individually or simultaneously.	• Trades being aware of other trades' designs • Knowledge of what spaces are already occupied • Avoiding parts involving potential conflicts	• Lack of a unified BIM • Unclear responsibility, ownership, and liability of BIMs • Limited memory and processing power available per user • Not equivalent to desktop functionalities • Security concerns for BIM data • Lack of requirements for BIM collaboration in AEC industry	Armbrust et al. (2009), Shafiq et al. (2013), Mahamadu, Mahdjoubi, and Booth (2013), Bernstein et al. (2014) – **Disconnected trades, information discrepancy**
Coordination protocol: Implementation of design coordination protocol and issue representation taxonomy. Adopt and implement a process protocol and a unified taxonomy early on through design coordination process.	• Clear design coordination schedule • Frequent coordination helps to avoid bigger issues later • Identifying issue types, their significance, and priority	• Hard to adopt and implement • Time-consuming and error-prone if not integrated well • Process simulation workshops required to verify the protocol and taxonomy before implementation	(Kassem et al. 2014; Succar, 2015), Succar and Kassem, 2015), Rekola, Kojima, and Mäkeläinen (2010) - **Lack of terminology, insufficient documentation, information discrepancy**
2D/3D integration: Integration of 2D and 3D digital information, a repository to link 3D viewpoints to 2D digital viewpoints.	• Could enhance transitions and reduce errors • Combining 2D and 3D views to understand better and navigate content	• Time-consuming implementation • Availability and accessibility still an issue • Insufficient interoperability and information exchange across BIM platforms. • The practicality of transition mechanisms have not been tested in construction	Lewis and Séquin 1998; Tory (2004), Carlbom and Paciorek, (1978)' Terry et al., (2007), Seo and Lee, (2013) - **Transitions, unfit navigation tools**

Digital stick-set: Provision of a digital platform to replicate paper. A 2D digital platform which replicates the functionalities of the paper stick-set on the tangible digital surface (tabletop).	• Enhance interactions with digital design information • Improve availability and accessibility of design information. • Improve engagement	• Design guidelines required • Availability and accessibility not tested • Not all tasks are done best using fingers on tangible interfaces • Conflicts and frustrations may arise during simultaneous incompatible actions	Forlines, Wigdor, Shen, and Balakrishnan (2007), Terry et al. (2007), Morris, Ryall, Shen, Forlines, and Vernier (2004), Tory et al. (2008) - **Unavailability, unfit navigation tools**
Gesture-based interaction: Incorporating frequent BIM navigational interactions through the use of gesture-based techniques; use of gesture-based and proximity sensor techniques.	• Could improve the efficiency of navigational interactions • Could improve participant engagement and ease navigational interactions	• Limited testing of gesture-based user experiences in construction practice • Producing VR experiences are still mainly geared toward game development	Seo and Lee (2013), Annett, Grossman, Wigdor, and Fitzmaurice (2011) **Transitions, unfit navigation tools**
AR/VR integration: Use of AR/VR techniques to enhance visualization and quality. VR headsets can be used by practitioners during design coordination meetings and on-site to compare as-built vs. proposed.	• Improve efficiency of navigational interactions. • A light BIM, with a subset of design information extracted from a heavy BIM • AR/VR becoming more affordable and accessible to AEC industry	• Limited testing of user experiences using VR headsets in construction practice • Producing VR experiences are still mainly geared toward game development, which their structure and file types are different compared to those traditionally used in the AEC industry	Rogers, Lim, and Hazlewood (2006), Froehlich and Azhar (2016), Kiral, Comu, and Kavaklioglu (2015), Sampaio and Martins (2014) - **Outdated BIM, transitions, unavailability, unfit navigation tools**
3D scan: Adoption of frequent 3D scan or laser scan of already constructed spaces. Also, progress photograph logs and 4D as-planned models could be used.	• Compare as-built construction versus BIM • Designing based on current site progress • Gaining a better understanding of spaces. • AR/VR techniques can be used to visualize BIM on existing structures or partly constructed projects	• Poor quality assessment of point clouds derived from terrestrial laser scanners • Laser scanners suffer from internal, systematic errors leading to systematic effects in the point cloud • Inaccurate in obstructed points	Golparvar-Fard et al. (2011), Armeni, Sax, Zamir, and Savarese (2017), Holst and Kuhlmann (2016) - **Outdated BIM, transitions, unfit navigation tools, office/site disconnect**
Model documentation: Enforcing on-the-fly model-based design issue documentation to capture the knowledge of the design coordination process.	The knowledge documented utilized for: • Referring back to the issue. • Subsequentissues in future projects	• More time required to document • Documentation process could become more complex	Wang and Leite (2016) - **Lack of terminology, insufficient documentation, information discrepancy**

2.6 Benchmarking BIM Tools

In this section, we describe the process of deriving functionalities based on the bottlenecks and design considerations explained above. The second half of this section elaborates on the details of how these functionalities were used to evaluate existing state-of-the-art BIM tools.

Similar to Shafiq et al. (2013), we developed a set of functionalities that tools were required to support based on the bottlenecks and design considerations identified. Table 6 describes the relationship between each function, its related bottlenecks and the design considerations that will be supported by this function. Also, priorities are noted based on the frequency of use and importance of each function. Items with "*" had higher priority compared with other functionalities. In addition, the functionalities mentioned in prior studies are noted with numbers 1 and 2, referring to the study. Legend: 1: Tory et al. (2008); 2: Shafiq et al. (2013); *: high priority.

Table 6: Summary the functionalities required to support the bottlenecks and design considerations. The numbers next to functionalities indicate items mentioned in prior studies.

Functionality	Bottleneck(s)	Design Consideration(s)
Save and load views (1)*	Transitions, unfit navigation tools	Digital stick-set, gesture-based interaction
Group views together	Transitions, unfit navigation tools	Digital stick-set, gesture-based interaction
Simultaneous 2D and 3D access*	Transitions, unavailability, unfit navigation tools	2D/3D integration, digital stick-set, gesture-based interaction
Link 2D to other 2D trade designs*	Transitions, information discrepancy, unfit navigation tools	Digital stick-set, AR/VR integration
Pan (1)*	Unfit navigation tools	Digital stick-set, gesture-based interaction, AR/VR integration
Zoom (1)*	Unfit navigation tools	Digital stick-set, gesture-based interaction, AR/VR integration
Rotate (1)*	Unfit navigation tools	Digital stick-set, gesture-based interaction, AR/VR integration
Measurement	Unavailability, unfit navigation tools	Gesture-based interaction
Model modification	Outdated BIM, insufficient documentation	Gesture-based interaction, model documentation
Grid support*	Insufficient documentation, transitions, unfit navigation tools	3D scan, model documentation
“Clash” detection (2)*	Disconnected trades, lack of terminology	Cloud BIM, coordination protocol, model documentation
Model comparison (2)*	Outdated BIM, disconnected trades, lack of terminology	Cloud BIM
Color code	Insufficient documentation, transitions	Gesture-based interaction
Hide/unhide components	Transitions, unfit navigation tools	2D/3D integration, digital stick-set, gesture-based interaction
Comment*	Disconnected trades, lack of terminology, insufficient documentation, information discrepancy	Cloud BIM, coordination protocol, model documentation
Annotate (1)*	Information discrepancy, unfit navigation tools	Gesture-based interaction, model documentation
Highlight	Disconnected trades, insufficient documentation, unfit navigation tools	Model documentation
Record changes*	Insufficient documentation	Model documentation
Record design issues*	Lack of terminology, insufficient documentation, unfit navigation tools	Coordination protocol, model documentation
Model upload/download (2)*	Outdated BIM, disconnected trades, lack of terminology	BIM First, cloud BIM
Model merge (2)*	Outdated BIM, disconnected trades	BIM First, cloud BIM, 3D Scan
Cloud model access (2)	Outdated BIM, disconnected trades, unfit navigation tools	BIM First, cloud BIM, gesture-based interaction, AR/VR integration
Dedicated hardware and bandwidth	Transitions, unavailability, unfit navigation tools	Cloud BIM, AR/VR integration, model documentation
Model track*	Outdated BIM, insufficient documentation	BIM First, cloud BIM, 3D scan
Support multiple model format (2)*	Outdated BIM, disconnected trades, transitions, unfit navigation tools	BIM First, cloud BIM, 2D/3D integration, digital stick-set

Based on the functionalities identified, we analyzed widely used BIM tools including Autodesk Revit 2016 and Autodesk Navisworks 2016. Afterwards, this evaluation was expanded to explore BIM tools based on the Industry Foundation Class (IFC), such as Solibiri Model Checker and Graphisoft Archicad. Other platforms evaluated include Autodesk BIM 360 Glue, BIMServer, and Tekla BIMSight. Over the course of this study, improvements and new releases of navigation and design software were also monitored and benchmarked.

Figure 31 (left), shows a snapshot of the BIMServer application, an open-source, IFC-based platform (setup as a server, conducting model integration and model change tracking). Figure 31 (right) shows Autodesk BIM 360 Glue; Autodesk's cloud-based tool to navigate and detect conflicts for Revit created BIMs it shows the same area of the left image, but going through the "clashes" one-by-one. In addition, Figure 32 shows Solibiri Model Checker, performing version checks between two BIMs in the Pharmacy case study, highlighting the components added, deleted and modified on the newer version of the same BIM.

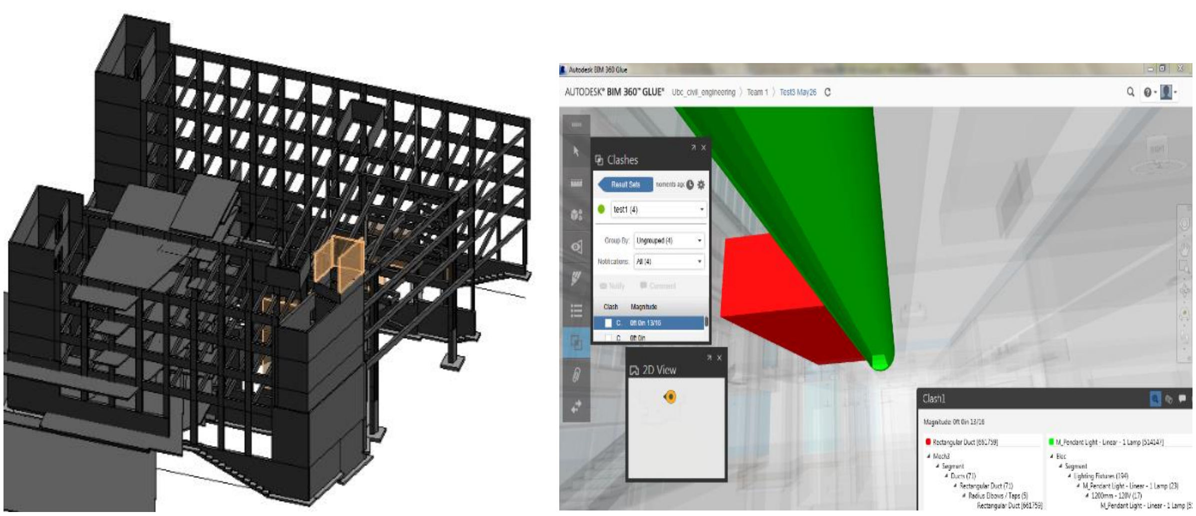


Figure 31: Evaluation of BIMServer errors and conflicts when merging different discipline's models (left). Navigating through merged models and performing clash detection using BIM Glue 360 (right).

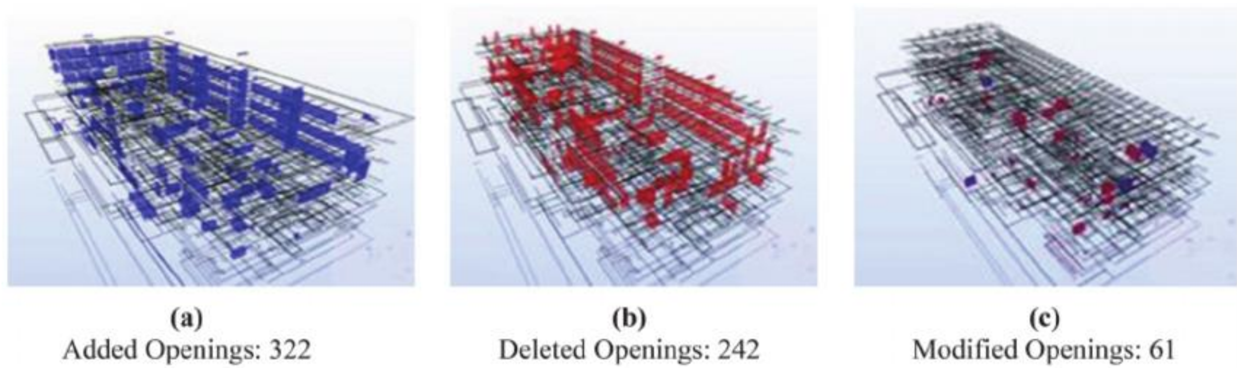


Figure 32: Solibiri screenshot comparing added, deleted, and modified components in the Pharmacy case study (Pilehchian et al., 2015).

Figure 33 demonstrates how well our requirements were supported by these platforms. The criteria for evaluation were based on functionalities presented in Table 6, illustrating the availability of each function in the analyzed platforms. The best-supported functionalities across all platforms were zooming, panning, and commenting; other well-supported functions were model merging, rotating, saving/loading views, commenting, and highlighting. It is worth mentioning that none of the platforms supported the multi-model format (e.g. ifc, rvt, dwf, etc.) and design issue documentation (recording) without information loss. Moreover, only 30% supported model tracking, view grouping, and remote viewing. The full set of availability of functionalities across different platforms can be seen on the chart below.

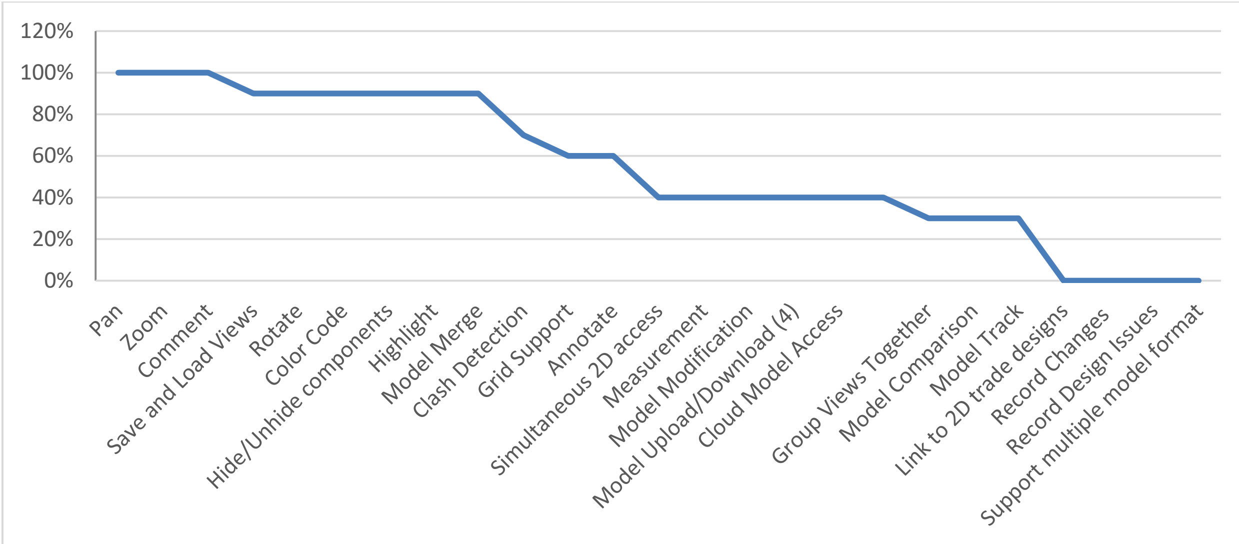


Figure 33: Analysis of availability of functionalities across the tested state of the art BIM platforms.

As Figure 34 demonstrates, we benchmarked the platforms based on each functionality. The ideal platform was to support all functionalities. Based on the platforms, we found Solibiri to rank as the most compatible platform with our proposed functionalities addressing the bottlenecks. Solibiri supported 69% of the functionalities, followed by Autodesk BIM 360 Glue supporting 62% of the functionalities. The least favourable platforms were Autodesk Revit and Tekla BIMSight. They both only supported 43% of the functionalities. BIMServer, Graphisoft Archicad, Revizto, and Navisworks ranked in the mid-range of supporting the required functionalities.

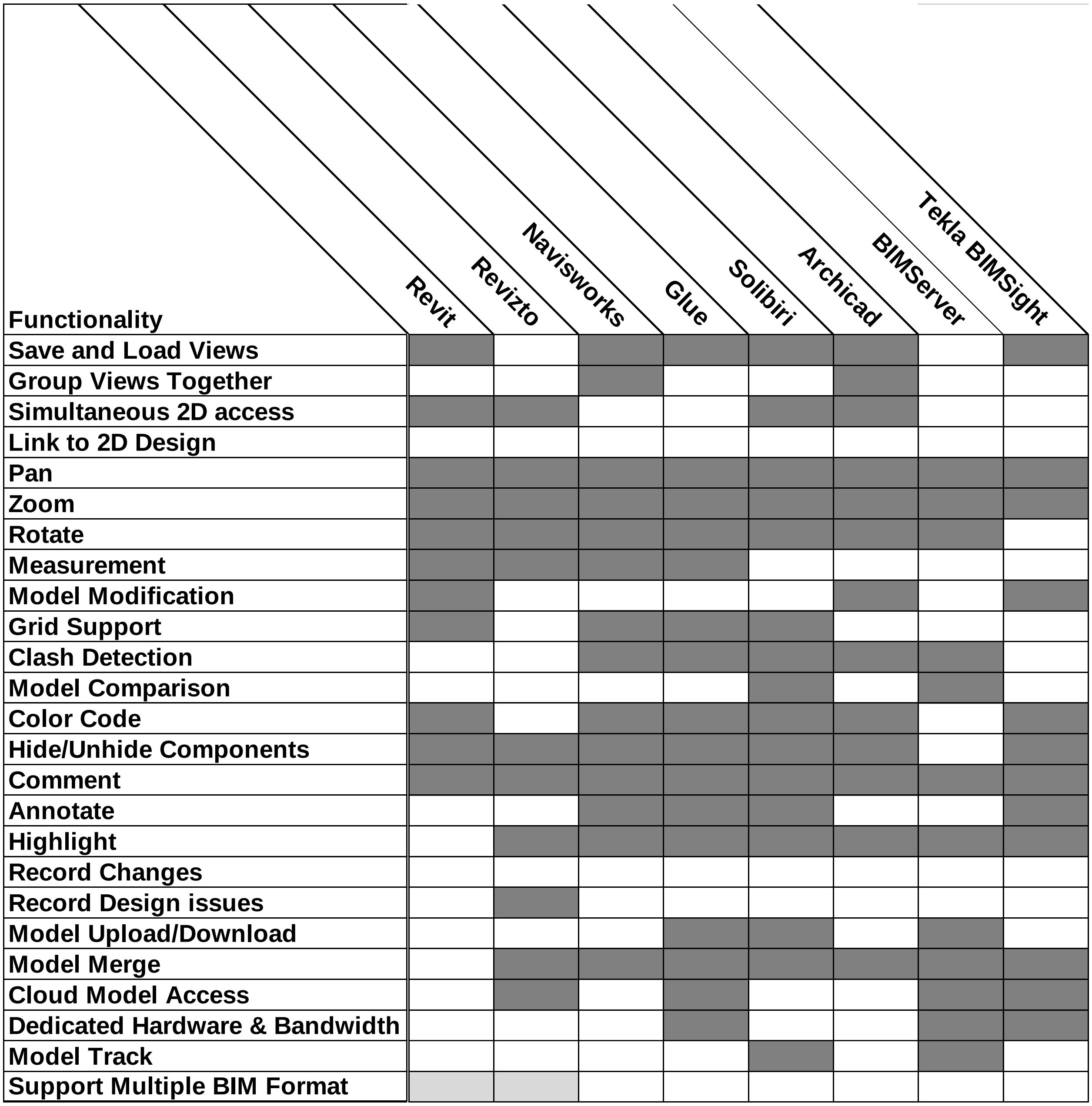


Figure 34: Analysis of state-of-the-art BIM tools against proposed functionalities. Dark grey represents availability; light grey represents partial or inadequate availability.

2.7 Validation

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Similar to prior research (Kreider et al. 2010; Howard and Bjork, 2007), we validated the findings of this paper through interviews with experts in the field to assess the extent of validity. Five interviews with BIM and trade experts in the field and three interviews with other researchers were conducted. The five industry experts included two of the BIM experts involved in the case studies, and the other three were actively involved in BIM-based design coordination. We asked interviewees to evaluate the bottlenecks found in this research and compare their knowledge and experience with our findings. The interviewees initially needed help understanding the scope and relationship between bottlenecks and design considerations. In their feedback, they found the bottlenecks reported in this study realistic, while they could not comment on the processes and BIM implementation protocols. They also found most proposed technical design considerations feasible and easy to implement. However, they highlighted that the design considerations might be best utilized when all trades involved were able to maintain a sufficient level of development in BIM. One interviewee stated, *"To me, this works best if minimum requirements are applied to project. You might have LOD 350 mechanical, but it may lack the whole fire protection system. So it goes hand in hand. To me this is assuming a minimum set of pre-requisites are checked."*

In terms of bias, one of the primary reasons qualitative methods have not been embraced by all researchers in the past, is the types of bias and subjectivity associated with such approaches (Leicht, Hunter, Saluja, and Messner, 2010). That is, many have argued that a researcher's personal bias plays too great of a role in gathering, synthesizing, and analyzing qualitative data (Hammersley and Gomm, 1997). While we acknowledge that observer bias is inherent bias created by the observer seeing what is expected during the observation, selectively remembering, or identifying only that data which support their claims (Yin, 2003), use of recorded sessions allowed for verification of the coding (Poole and DeSanctis, 1992). In addition, as described below, use of various methods of verification such as a replica case study, and interviews with the practitioners helped eliminate the bias to a great extent

2.8 Conclusions

In this research, we identified the bottlenecks practitioners face during BIM-based design coordination, analyzed the literature and proposed design considerations. As discussed above, it is imperative that coordination issues get resolved as efficiently as possible. Design coordination issues may cost as much as $10,000 per design issue (Azhar, 2011), while the cost of design coordination meetings can range from $8,000 to $23,000 per meeting. Compared to paper-based design coordination meetings, BIM has been shown to increase satisfaction among practitioners within design coordination meeting processes (Liston et al., 2001) and reduce the time spent arguing over issues (Fischer, 2006). While numerous benefits of BIM in design coordination are well established, project participants face significant challenges that disrupt and hinder the design coordination process even when BIM tools are readily available in building design coordination settings. This research presented the bottlenecks in design coordination processes, evaluated state-of-the-art BIM tools compared with the bottlenecks, and proposed design considerations for BIM tool development. We believe these results are useful for AEC industry researchers, professionals, and the BIM software development community.

We also proposed functionalities to better address the observed bottlenecks and design considerations, and benchmarked the widely used BIM platforms. We found Solibiri followed by Autodesk BIM 360 Glue as the most compatible platforms regarding our proposed functionalities; BIMServer, Graphisoft ArchiCAD, and Navisworks were in the mid-range, and the least favourable platforms were Autodesk Revit and Tekla BIMSight. The best-supported functionalities to improve bottlenecks across all platforms were zooming, panning, and commenting. The least supported functionalities were model tracking, view grouping, remote viewing, multi-BIM format support, and documentation of design issues without loss of information.

We suggest future research to focus on the three domains of BIM adoption processes and interoperability, interactions with design artifacts, and design coordination issue representation and knowledge capture. The causes of coordination issues and the factors that affect their resolution also requires further understanding.

We believe that future state-of-the-art BIM tools development community should aim to support the functionalities and attempt to alleviate the bottlenecks presented in this paper. We emphasize that further research is required to identify factors influencing implementation of BIM for design coordination, interoperability across various platforms, and barriers to start with BIM First design approach, as well as testing and validating the process and bottlenecks developed in this study on further in-depth case studies.

Chapter 3: Characterizing Interactions with BIM Tools and Artifacts in Building Design Coordination Meetings

3.1 Introduction

Building design coordination is a critical and challenging task to ensure that the design meets the functional, aesthetic, and economic requirements of project stakeholders. The design coordination process allows project stakeholders to detect potential issues and conflicts in building systems before they become an issue on the construction site. Building design coordination typically includes architectural, structural, mechanical, electrical and plumbing (MEP) designs and requires extensive knowledge of building systems. The cost of design coordination can be significant, with some estimates of six percent of the MEP cost or two percent of the total cost on light industrial construction projects (Tatum and Korman, 1999). The level of difficulty of the design coordination process correlates with the complexity and number of building systems in a facility (Tatum and Korman, 2000). Many construction industry professionals cite MEP coordination as one of the most challenging tasks encountered in the delivery of building construction projects (Korman et al., 2003). In a traditional setting, building design coordination is usually conducted through visual inspection, where 2D drawings are compared and potential conflicts are identified. This process is inefficient and error-prone, and as a result, numerous conflicts often remain undetected and must be addressed in the field where it is costly and inefficient (Liston et al., 2001). In contrast, teams using Building Information Modeling (BIM) tools for MEP coordination are more likely to be satisfied with the meeting process (Liston et al., 2001) and spend less time arguing over issues compared to paper-based design coordination meetings (Fischer, 2006). BIM-based design coordination improves schedule performance, cost control and productivity, and reduces deficiencies on site (Khanzode et al., 2007; Rankin et al., 2008). Studies have shown that design coordination and conflict detection are the most frequent and valued uses of BIM in the construction sector (Bernstein and Jones, 2012). For instance, in one project, BIM-based design coordination enabled project stakeholders on a large hospital project to identify over three million clashes and resolve over 2.4 million of the clashes prior to construction (Khanzode, 2010). Although it is difficult to quantify the benefits of clash avoidance, some have estimated that each detected clash between MEP systems can save over $300 US per clash (Wang et al., 2016).

The transition to BIM, however, constitutes a departure from traditional practice (Dossick and Neff, 2011). Despite the many cited advantages, many design coordination issues still go undetected using state of the art BIM tools (Lee et al., 2012), often leading to on-site fixes with additional costs and delays to the project (Assaf and Al-Hejji, 2006). The impact of these unresolved coordination issues on project time and cost can be significant, with some estimating as much as $10,000 per issue (Azhar, 2011). It is therefore imperative that coordination issues get resolved as efficiently as possible, particularly given that thousands of conflicts may be identified during design coordination (Wang and Leite, 2016) and that many design issues take more than one meeting to resolve (Mehrbod et al., 2015). In addition, coordination meetings are also costly given the large number of project participants involved (Love, Frani, and Edwards, 2004), particularly in fast track projects with significant sustainability goals (Alwan et al., 2017). Our own estimates of the cost of design coordination meetings range from $8,000-$23,000 per meeting (Mehrbod et al., 2015). However, even when BIM tools are readily available in building design coordination settings, project participants face significant challenges when interacting with BIM, which disrupts and hinders the design coordination process (Mehrbod et al., 2013; Park et al., 2016). Practitioners often revert back to 2D paper-based technical drawings as their first choice for technical data exchange between project members (Fiorentino et al., 2012), and 3D design information is still underutilized (Leicht et al., 2014). The transitions from one form of design representation to another are time-consuming (Terry et al., 2007), error prone, and result in loss of information when attempting to document the knowledge, or outcome of design issue discussion.

It is therefore imperative that coordination issues get resolved as efficiently as possible, particularly given that thousands of conflicts may be identified during design coordination (Wang and Leite, 2016), and successful management of the design coordination process is critical to the efficient delivery of cost-effective and quality projects (Chua, Tyagi, Ling, and Bok, 2003). While there are many factors that influence BIM-based building design coordination, it is important to understand how participants interact with design artifacts because these interactions are a critical part of the coordination process in BIM environments. This study analyzed the nature and goals of interacting with design artifacts, with a particular emphasis on the interactions that hindered the meeting process. A better understanding of how practitioners interact with design information during coordination meetings will allow project teams and software developers to improve the functionality of BIM tools and better support the collaborative and dynamic nature of the design coordination process.

The specific goals of this research were to better understand how and why participants interact with different types of design artifacts when analyzing and resolving design coordination issues, and to identify necessary functionality for BIM-enabled coordination environments. Specifically, we analyzed the frequency of BIM use in coordination meetings, the purpose of participant interactions with different design artifacts, and the transitions between design artifacts. We developed a taxonomy to represent the relationships between goals, artifacts, interactions and transitions for BIM-based design coordination processes. This research builds on the previous work of two of the authors of this paper (Tory and Staub-French), which characterized interactions with design artifacts in traditional design coordination settings, including interactions with 2D physical and digital design artifacts (Tory et al., 2008). This research extends this prior work by analyzing the frequency of interactions with different design artifacts, characterizing interactions with state of the art BIM tools, and identifying the motivation behind interactions with design artifacts. An important contribution of this research is the identification and characterization of the transitions participants had between design artifacts and views, which has previously not been studied in depth. We also characterized the reasoning behind participants' transitions between design artifacts and the frequency of their occurrence.

In this research, we employed a mixed-method research methodology that involved observation of design coordination meetings, in-depth qualitative analysis of meeting segments, followed by extensive quantitative data collection and analysis through data transcription and coding. We then enriched our collected data using axial coding, and then we verified our findings against current literature. Finally, we sought validity of our findings through examining interactions, goals, and transitions of a second case study. We found that 2D paper, 2D digital and 3D digital artifacts were utilized almost equally during the meetings. We characterized design artifact interactions into four major categories: preparation, annotation, navigation, and recording. We classified practitioner's goals into six categories: prepare, grab attention, visualize, inspect, document, and query. The outcome of this research can be beneficial to the BIM software development community, teams adopting state of the art BIM tools, and future research better understanding relationship between and the details of goals, artifacts, interactions and transitions.

In the subsequent sections, we briefly describe the related work in Section 3.2. We explain our research methodology in detail in Section 3.3, describe the details of our case study in section 3.4, and present our findings regarding interaction analysis and design artifact utilization rate on section 3.6, as well as, characterizing these interactions in section 3.5. Finally, we describe our validation strategy in Section 3.8 and our conclusions and future work in Section 3.9.

3.2 Related Work

In this section, we briefly discuss relevant literature in the fields on interactions with design artifacts, transitions between different views and design representations, and availability and accessibility of design artifacts. We use the term BIM in a broader sense of 'BIG BIM'(Redmond et al., 2012) that can be divided into interrelated functional, informational, technical and organizational/legal issues (Volk et al., 2014). We see BIM as a key component to efficient design coordination and review processes and believe the taxonomy provided in this study represents how practitioners interact with design artifacts in BIM-based design coordination meetings. Throughout this paper, we refer to the 'MEP Coordinator' as the person(s) in charge of overall design coordination of building system designs and the 'BIM Coordinator' as the person in charge of obtaining and integrating all the different BIMs from the trades, identifying and presenting clashes during the meeting, and navigating the integrated BIM during meetings.

3.2.1 Design Coordination

The need for understanding building design coordination is vital since the process motivates and determines how practitioners interact with design information and what sequence of actions are necessary for resolution of design issues. In this paper, we refer to design coordination as coordination of building systems in which their location is defined and components of building systems are routed to avoid interferences and to comply with diverse design and operations criteria (Barton et al., 1983). As highlighted in the introduction, in a traditional setting, design coordination is usually conducted through visual inspection, where 2D drawings are compared and potential conflicts are identified. This process is inefficient and error-prone, and as a result, numerous conflicts often remain undetected and must be addressed in the field where it is costly and inefficient [5]. On the other hand, BIM simulates the construction project in a virtual environment. With BIM, an accurate virtual model of a building, containing precise geometry and relevant data needed to support the design, procurement, fabrication, and construction activities required to realize the building (Eastman et al., 2011). Many benefits of BIM, including visualization, code reviews, construction sequencing, and conflict detection are highly valued for building design coordination (Azhar, 2011).

In previous studies of design coordination using conventional 2D paper-based methods, Korman et al. (2003) classified design issues into three main categories: design criteria, construction, and operations issues. They also identified design issue attributes including geometric characteristics (component dimensions) and topological characteristics (spatial relationships). This work became a foundation to which others built on to further classify design issues (Tabesh and Staub-French, 2006), develop knowledge capture strategies (Wang and Leite, 2016), and assess return on investment (Lee et al., 2012).

Current research has provided an important point of departure for characterizing and classifying design issues. Additional research is needed to better understand the design issue resolution process, including the set of tasks and actions occurring before and after design coordination meetings, as well as the need to further clarify how practitioners interact with design artifacts while resolving design coordination issues.

3.2.2 Interactions with Design Artifacts

This section briefly describes relevant literature that investigated the use of design artifacts and the interactions with design artifacts. Understanding the details of interactions with design artifacts is crucial since it reveals the weaknesses and strengths of various design representations in coordination meetings. In terms of definitions, a ‘meeting’ is a type of interaction process and as such, is analyzable relative to its inputs and outputs (Bostrom et al., 1993). Interactivity is defined as “the extent to which users can participate in modifying the form and content of a mediated environment in real-time.” (Steuer, 1992). Researchers commonly use the term ‘artifact’ to describe an object of any medium (e.g. paper) that supports access to design information (Schmidt and Wagner, 2004). Finally, the project team is a multi-disciplinary group of three or more individuals who are interdependent in their tasks, interact intensively for a time-limited period, and are committed to providing a ‘built’ product, plan, or service (Cohen and Bailey, 1997; Tannenbaum et al., 1992).

Earlier work by members of our team conducted an ethnographic study exploring how meeting participants used representational artifacts in paper-based building design coordination (Tory et al., 2008). They characterized primary interactions with paper and limited 2D digital design artifacts, identified bottlenecks in the coordination process, and provided a taxonomy that characterized the different types of interactions and goals team members had with paper drawings, physical 3D models, and 2D digital information during meetings. Unlike this study, their observed meetings were paper based, did not include design coordination in the construction phase, had one co-author directly participating in the meetings as a consultant, little BIM use and BIM utilization for building design coordination, and did not address the numerous transitions participants had, between various artifacts and views. This research further builds on this earlier study by analyzing the artifact utilization rate in BIM-based design coordination meetings, analyzing the type and frequency of interactions and transitions between artifacts and views. We finally compare BIM-based design coordination versus paper-based design coordination meetings in section 3.7 of this paper.

In addition, other research studied the role of media use in team interactions (Liston et al., 2007). They observed and analyzed different teams during MEP coordination meetings qualitatively, and found that teams using BIM tools for MEP coordination were more likely to be satisfied with the meeting process and spent less time disagreeing with issues compared to paper-based design coordination meetings. Some also investigated the richness of media use during meetings and compared the performance of different teams using design artifacts (Liston, 2009). In these research efforts, ethnographic observation and qualitative data collection methods were also used, similar to this research, as they studied teams using BIM for design coordination in a similar meeting environment. This paper builds on and extends this work by analyzing the low-level participant interactions with design artifacts, it also investigates participants' artifact utilization rate, and explores reasons motivating (purpose) of these interactions.

3.2.3 Transitions between Design Artifacts and Views

Prior research found that 3D information is useful for providing an overview of the object being designed and conveys the 3D shape, while 2D information is better for displaying interior details, making precise measurements, and enabling simpler navigation (Tory, 2004). Our observations also confirm the value of 2D and 3D representations in design coordination. Although project information may be produced in an electronic form, in essence it is distributed among the various multi-disciplinary teams involved in the project as documents. The format of such information is also rich and multi-dimensional (Isikdag and Underwood, 2010).

Few research efforts have investigated the transitions between different views and artifacts in design coordination meetings. One notable project was the JUMP project (Terry et al., 2007), which developed tangible tools to navigate and interact with design artifacts using 2D augmented technical drawings. Although their work showed how tangible mixed reality with physical objects can be equally important as virtual ones (Lee, Rhee, and Seo, 2010), the practicality of using these tokens has not been tested in construction, (Seo and Lee, 2013). The project mainly addressed transitions between 2D digital and paper drawings, whereas transitions between more complex 3D digital design information and 2D digital drawings remained unaddressed.

Augmented reality tools have also proven to facilitate transitions between 2D and 3D design information. Early and ambitious effort on use of virtual reality (VR) investigated facilitation of the transition from 2D to 3D (Kato et al., 2003), others have added interaction means by tangible, eye cursors and visual tracking (Woodward et al., 2007). Other researchers have incorporated augmented reality technology and tangible interaction techniques to provide an easy-to-use interface to navigation (Fiorentino et al., 2012). While the above research helps to facilitate transitions across various media, this study aims to better understand *when* and *why* participants transition between design artifacts and views.

3.2.4 Availability and Accessibility of Design Artifacts

Various studies have found that the degree of availability and accessibility of design information can directly impact interaction level with design artifacts. Examining this aspect of artifact use can tell us how the accessibility of artifacts and transitions between them influence team interaction. Prior research has examined the extent of private vs. shared media use of participants while interacting with design artifacts (Liston, 2009; Tang and Leifer, 1988). Workplace and Design studies make particular note of the effects of the physical environment on interaction. Some use terminologies of “publicly available media”, “semi-shared” displays, and “private media” to distinguish differences in interaction with media available to the group (Heath et al., 2000). Tang and Leifer (1988), note the effect of location of media on interaction and identifies three characteristics of use: orientation, proximity, and simultaneous access (Tang and Leifer, 1988). In this paper, we use the term availability to refer to the extent to which a medium is available to all participants in a meeting space.

As one of the key points of departure, studies observed collaborative settings where two group members were near a display, far from a display, and one is near and one is far from the display and report more satisfaction when both members are near the display were compared together (Hawkey et al., 2005). They suggested that participants are less likely to interact with artifacts if they are not accessible. However, in the meeting context, accessibility of media is often considered dynamic. As the team moves its focus from one medium to another medium, changes in accessibility may occur. While we agree that the settings of the coordination environment are important and can impact how participants interact with design artifacts, in this paper we focus on the interactions through the lens of the capabilities of the BIM tools, interaction analysis and design artifact utilization. Most points of departure (e.g. Liston et al. (2007)) in this field have based their studies on findings of Bales (1950) and Olson et al. (1992). Some evaluated team performance utilizing Mintzberg's approach (Mintzberg, 1970) to perform two sets of observations with the same subjects performing the same tasks but in different meeting environments. In addition, with respect to the location of design information, others (Tang and Leifer, 1988) note the effect of location of media on interaction and identifies three characteristics of use: orientation, proximity, and simultaneous access. In this section, we have presented some of the prior studies which have enabled us to gain a deeper understanding of the four primary research areas described above. We have largely benefited and built on top of existing knowledge by frequently revisiting these findings throughout our research path. In the next section, we present the research methods employed by this research from the ethnographic case study to data triangulation and validation of findings.

3.3 Methods

We conducted a two-year case study of a complex building project that involved the design development and construction phases. We specifically chose to study one team in depth rather than multiple teams to achieve a greater understanding of their work practices, artifact utilization, and interactions. In this research, we employed a hybrid research method, inspired by prior research (Glaser, 1978; Glaser and Strauss, 1967; Jordan and Henderson, 1995). Our data included observation of design coordination meetings throughout the design process. Initially, we analyzed these meetings qualitatively (through five-minute vignettes), followed by extensive quantitative data collection and analysis (by data transcription and coding). We then enriched our collected data using axial coding and verified our findings against current literature. Since, some (e.g. LeCompte and Goetz (1982)) believe the results of ethnographic research are often regarded as unreliable and lacking in validity and generalizability, we cross-examined our findings on a replica case study.

In terms of bias, one of the primary reasons qualitative methods have not been embraced by all researchers in the past, is the types of bias and subjectivity associated with such approaches (Leicht et al., 2010). That is, many have argued that a researcher's personal bias plays too great of a role in gathering, synthesizing, and analyzing qualitative data (Hammersley and Gomm, 1997). However, as (Adorno et al., 1976) argues 'it is a mistake to assume that the objectivity of a science depends upon the objectivity of the scientist'. Hence we agree with Adorno et al. (1976) and Hammersley and Gomm (1997) that, the operation of the research community in enforcing objectivity depends on the commitment of individual scientists to that ideal. While we acknowledge that observer bias is inherent bias created by the observer seeing what is expected during the observation, selectively remembering, or identifying only that data which supports their claims (Yin, 2003), use of recorded sessions allowed for verification of the coding (Poole and DeSanctis, 1992). In addition, as described below, use of a replica case study, and interviews with the practitioners helped eliminating the bias to a great extent.

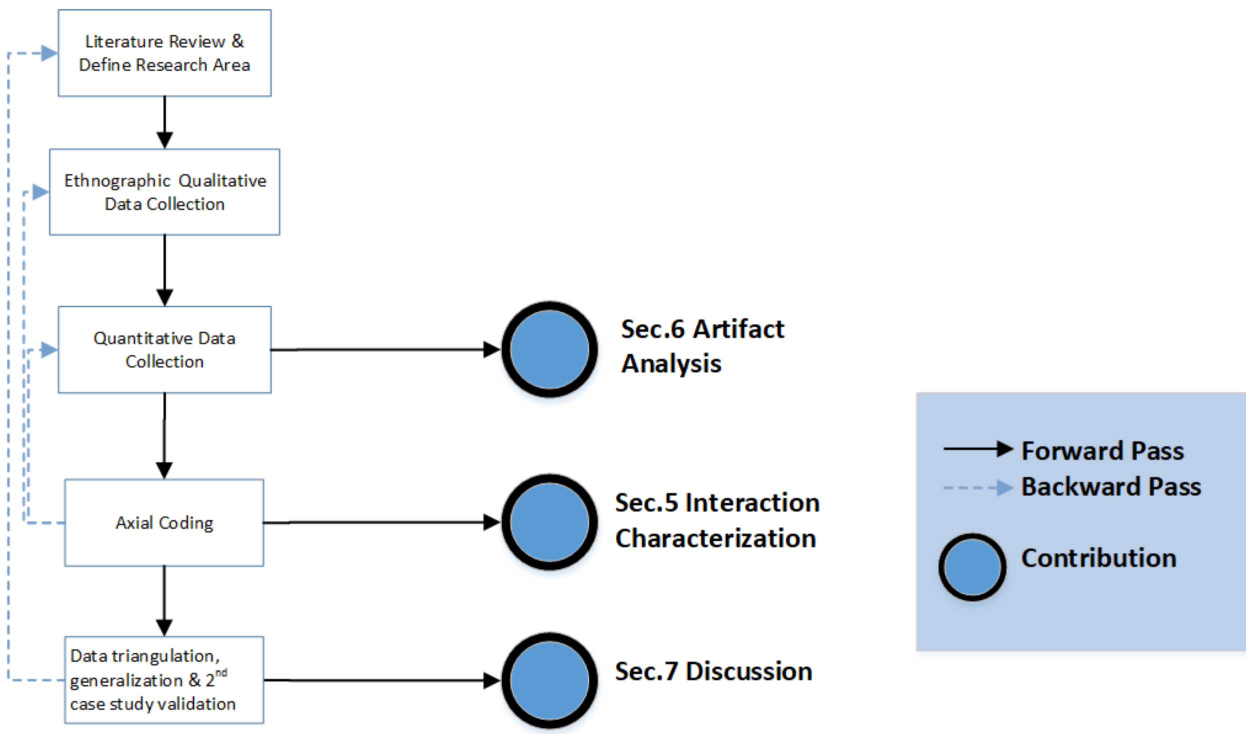


Figure 35: Methods used to drive this research. Black arrows representing forward pass, next steps, and gray broken arrows representing backward pass. Outcome and resulting sections from each research method are shown using blue circles. Section numbers refer to the sections within chapter 3.

3.3.1 Case Study Observation and Qualitative Analysis

Our understanding of the current practice of design issue resolution was developed by observing a building design coordination team during design coordination meetings throughout design and construction stages. An ethnographic approach was chosen to collect the "richest possible data" (Lofland and Lofland, 1995), and to observe meeting participants in their natural setting (Denzin, 2017). We observed and video recorded weekly design coordination meetings from the early stages of design through construction of the building systems. In total, we recorded 44 design coordination meetings, of which 32 meetings were held in our BIM trailer (our own trailer placed in the construction site). The frequency of the meetings varied – in the early design stage, meetings were less frequent (monthly), whereas during construction, meetings occurred more frequently (up to twice a week). Most meetings lasted about 90 to 120 minutes, which resulted in over 70 hours of BIM-based design coordination meetings. We had access to construction documents, BIM files, site progress, design issue spreadsheets and some of the communication between project participants.

We first conducted a qualitative assessment of the meetings in which we looked at 14 whole meetings (90 to 120 minutes each) to layout our initial data collection and analysis model. We selected these meetings based on different stages of design and construction of the building. From the meetings, we selected 5-minute vignettes similar to Figure 25 based on the level of interaction with artifacts, the participation of participants and stage of construction. For instance, we ensured an average number of participants plus one person was present, at least four or more design coordination issues were being discussed, and meetings were picked from all stages of construction. In addition, we investigated how design issues were identified, communicated among BIM and MEP Coordinators, presented and resolved, their documentation approach and their future follow-up regarding each issue. We considered each issue first, and tracked how that issue was identified through checking the BIM files of each meeting, how it was resolved through observing specific segments of the meeting related to that issue and by analyzing participants' notes and issue documentation spreadsheets regarding each issue.

3.3.2 Quantitative Data Collection and Analysis

Once the qualitative study was completed, we employed a quantitative data collection approach. We performed transcription of selected design coordination meetings, selected vignettes, and meetings based on our qualitative observations and their richness of interactions. In total, we coded over 300 minutes of design coordination meetings. During transcription of the meetings, we coded and filtered the discussion, context, and interactions with the design artifacts (2 Interactive displays, paper, and two computers) objectively. For instance, instead of recording "the plumbing subcontractor became frustrated when he could not interact with 3D model and went back to his seat" we recorded "the plumbing subcontractor interacted with the 3D model for X seconds, he was unable to perform view change." This approach helped us examine more aspects of complex coordination moments and obtain a broader, less biased picture of what was going on. Furthermore, we tracked the time spent interacting with each artifact, we interlinked video recordings with the text, and were able to track time spent per interactions and per artifacts. Finally, as per guidelines of prior research (Angrosino, 2007), we went beyond simply recording the conversation by constantly asking questions such as "What are they trying to achieve?", and "What is the context?", while recording interactions with design artifacts. In addition, we coded our transcribed data based on the in-vivo open coding approach. With this approach, code names are assigned based on a section of data, such as an interview transcript, using a word or short phrase taken from that section of the data itself (Phelps and Horman, 2010). The aim of creating an in vivo code is to ensure that concepts stay as close as possible to research participants' own words as they capture a key element of what is being described (Given & Ed., 2008). In total, we captured 108 in-vivo codes, with ten categories and three sub-categories.

3.3.3 Axial Coding

The purpose of axial coding is to reassemble the data that were fractured during open coding. During the process labels produced during open coding, are grouped into core categories by constant comparison (Sabelli et al., 2011). Hence, the groundedness of the codes was analyzed (frequency of how often a code has been applied) as well as their density (number of interlinked codes) (Okendu, 2008). Further, we aligned codes with related contents to form higher level "concepts" using Axial coding (Glaser and Strauss, 1967). The Axial coding method realigned the data based on its properties and dimensions. These "concepts" were later on divided into broader groups, forming "categories" representing interactions, goals, and artifacts. In this process, we constantly searched for and refined the conceptual constructs to explain the relationship between the concepts and categories, as per guidelines of (Glaser, 1978). In essence, we re-coded our transcriptions, codes and renamed our categorization multiple times to reflect our new findings. These findings are reported in section 3.5, where we explain our characterization of interactions with design artifacts in detail and formalize them into a taxonomy.

3.3.4 Data Triangulation, and a Second Case Study Validation

In order to triangulate our findings from prior steps, a variable-centered approach (Hong, Liao, and Gu, 2000) was employed to triangulate the findings of this research based on other domains and technologies (specifically human-computer interaction). The terminology, coding scheme, and categorization were revised again and again during our analysis to ensure they conveyed and reflected all of our observations. In addition, we went back to the literature to ensure our categorization corresponded with findings of prior research (Mahyar, Sarvghad, and

Tory, 2012; Tory et al., 2008). Hence, we revised both our qualitative and quantitative data collection results, multiple times to achieve constancy.

Furthermore, we conducted a rigorous evaluation of our findings by observing a second case study which had used a similar setting and an almost equal number of project participants. In effect, we used the second case study as a replica of the first case study (LeCompte and Goetz, 1982). Since the second case study occurred after data collection of the main case study, and we had access to meeting recordings and project data, we observed select meetings to validate our findings. It is worth acknowledging that because human behavior is never static, no study can be replicated exactly, regardless of the methods and designs employed (LeCompte and Goetz, 1982). We selected short vignettes from the second case study to analyze the interactions and goals and examined them to see if they could have been characterized and classified using our findings. Finally, informal interviews with two BIM Coordinators in the field, including one from the Pharmacy case study were carried out to add an additional layer of rigor to the findings of this study.

In this section, we summarized the research methods we employed that resulted in design artifact interaction analysis, and characterization of interactions with design artifacts, which are presented in the subsequent sections. In the next section, we highlight our case studies, the specifics of the meeting environment, the tools used, and the observed BIM-based building design coordination process.

3.4 Case Studies

While this research bases its findings primarily from one case study, and validates it based on a replica case study, the following case studies represent state of the art public sector projects involving some of the largest general contractors, institutions and most BIM-savvy design consultants, and sub-contractors in western Canada. The general contractor, had substantial prior BIM experience from prior projects and the institutions had prior BIM implementation experience. Generally, it is extremely hard for researchers to gain access full level access to such projects which involve similar level of complexity, scale, significance, and BIM level of development. Hence, in this research the goal was to analyze the case studies in depth, rather than a breadth of numerous smaller scale case studies.

The primary case study for this research was the new Pharmaceutical Sciences Building (Figure 36, left) at the University of British Columbia, Vancouver campus. This is an 18,000 m^2 facility, providing a variety of teaching and learning spaces from lecture halls and seminar rooms, to a pharmacy clinic and three floors of research laboratories. The project had considerably complicated MEP systems along with a unique architectural design, which made design coordination and constructability the key concerns for this fast track project. Over the course of design and construction, BIM was used extensively to coordinate designs from different consultants and sub-trades. The meeting participants (a total of 15 frequent participants) consisted of representatives from the different trades involved in the project, including the owner, the construction manager, architect, engineering consultants and construction sub-trades. The meetings typically had six to nine participants from different disciplines including, general contractor, consultants, subcontractors and owner representatives.

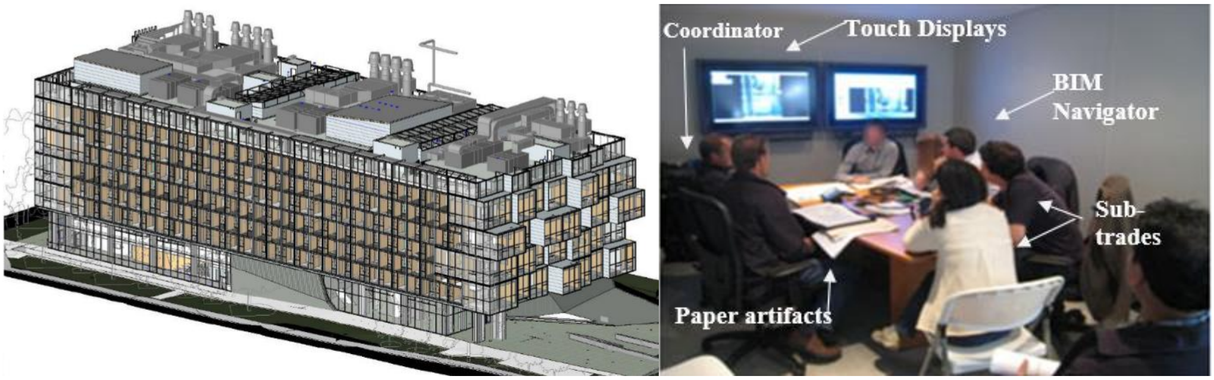


Figure 36: Integrated BIM model of the UBC Pharmaceutical Building (left) (image courtesy of Hughes Condon Marler Architects) (left) and BIM Trailer used during design coordination on site (right).

From the beginning of construction, weekly meetings were held in our BIM Trailer on the construction site. The BIM Trailer (Figure 36, right) was equipped with two large-screen touch displays, connected to separate computers displaying 2D and 3D digital information. In terms of the software used, PDFs were used to display 2D digital information, Autodesk Revit was used to modify 3D digital information, and Autodesk Navisworks Manage was used to navigate through the integrated 3D model. The SMART software and hardware on the Interactive displays enabled the participants to draw on top of design information, in multiple colors, erase, save screenshots, and use panning techniques to navigate through what was on display. Each participant had a display port installed on the table so that they could connect their laptops to the Interactive displays. In addition, the participants often brought their own set of paper drawings to the meetings, these included paper drawing sets, log books, and paper screenshot of 2D digital elements. The main leaders of the meetings were the MEP and BIM Coordinators. The project team utilized our BIM trailer during the meetings, but the research team did not intervene or support the design coordination process.

We also conducted a second case study that involved the construction of a large institutional building project to verify our findings (Figure 37). We remotely participated in the design coordination meetings, recorded and observed participants conducting design coordination, and had access to all construction documentation including BIM files, drawings, and conflict detection reports. We also had access to a series of informal communication between team members (such as circulated emails about design issues) and post meeting design coordination issue documents. Like the first case study, the meetings were often comprised of six to nine participants, and there were two Interactive displays, displaying 2D and 3D digital information.

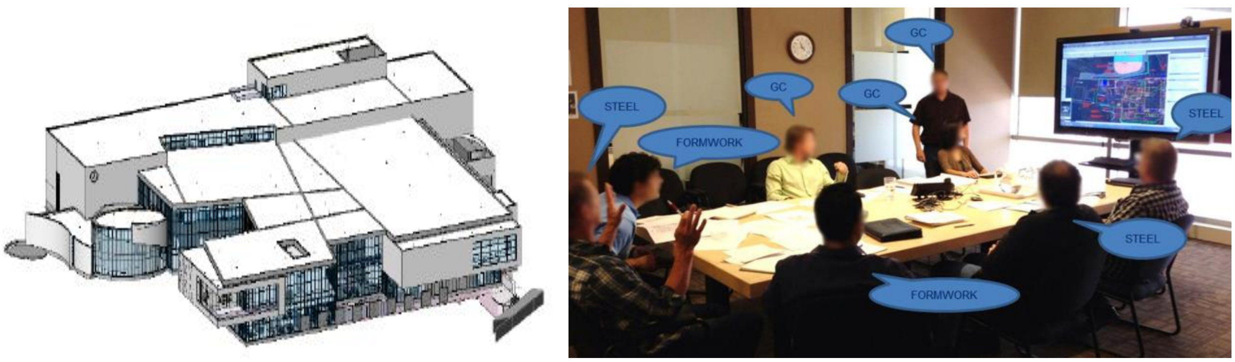


Figure 37: An architectural model of the second case study project that was used to validate the research findings (left) and a snapshot of design coordination meeting environment for case study 2 (right).

3.4.1 Observed BIM-based Design Coordination Process

We have observed BIM-based building design coordination processes in different projects involving various general contractors, owners and sub-trades (e.g., Mehrbod et al. (2015)). We have come to understand the design coordination process as a cycle of three interconnected steps: (1) Issue Identification, (2) Issue Resolution and (3) Issue Documentation. We emphasize that the process outlined in this section reflects the process observed in many BIM-based design coordination projects but we recognize that the process below does not apply to all BIM-based building design coordination and does not represent an optimum or ideal BIM-based design coordination process.

Prior to coordination meetings, a set of activities are performed to prepare the design information to be discussed during the meetings. Once the models are prepared and a meeting agenda is defined, the project team meets to discuss issues raised from the issue preparation stage. During the meetings, participants review progress on previously discussed design issues, describe new design issues, look up design information, inquire about the designs, visualize various design information, and finally document design decisions and notes, through interactions with three design artifacts (2D digital, 3D Digital, and 2D physical). Once the discussion on a certain issue reaches an end (e.g. resolved, requires further input from a different source, or needs follow up in the future), depending on the importance of the issue, the MEP Coordinator documents the details of each issue.

To better elaborate the steps involved in the resolution of a coordination issue, below we describe a 5-minute vignette from a coordination meeting, showing how an issue was presented, discussed and tackled for resolution in the meeting as well as how participants interacted with the design artifacts (as illustrated in Figure 38).

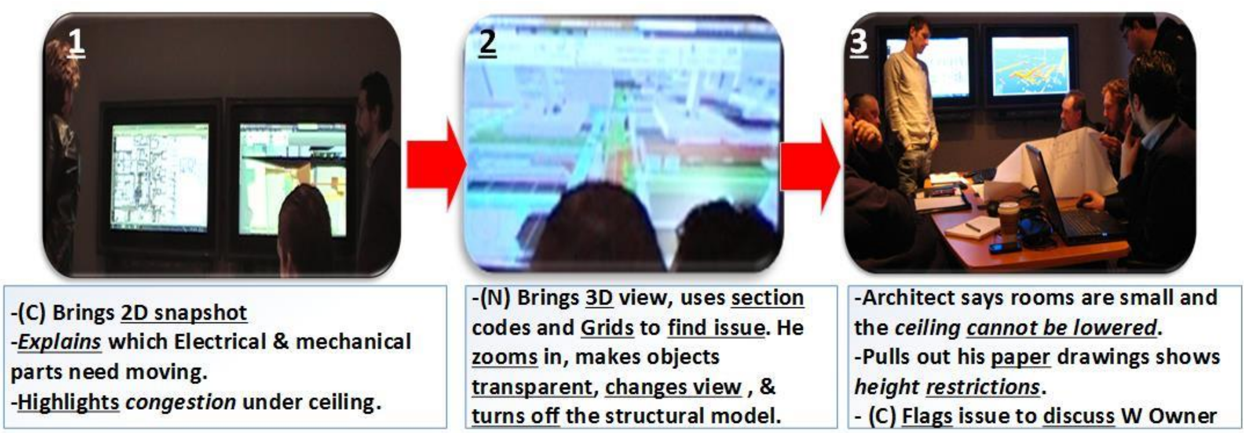


Figure 38: Design issue resolution meeting after all issues were prepared. (C) notes for MEP Coordinator, (N) notes for BIM Coordinator

Participants interacted with digital artifacts (Figure 38 – Image 1) using navigation techniques such as the use of sectioning, boxing, and hiding model views within the 3D digital design information. Finally, in image 3, the architect states that the issue needs to be further discussed as input from other project team members are required. At this stage, the MEP Coordinator determines that the issue needs to be documented for future follow-up. Figure 39-image 2 shows when the BIM Coordinator started explaining the issue on the 3D display, but the focus then shifted to paper drawings for architectural drawings. The MEP Coordinator then showed the electrical model on the 2D display, and afterward the BIM Coordinator brought up the 3D view up for further explanation. On another occasion from the same meeting (Figure 39), while discussing an issue on paper, they transitioned to 3D digital, then to 2D digital, and back to 3D digital views to gain a better understanding of the issue. The transition process happened multiple times through discussions of each design issue, and often was error prone, since the exact location of design information could not be accessed immediately and often there were inconsistencies between different representations of the design.

- The BIM Coordinator (N) shows view of the issue in 3D. (Pic 1)
- N loads another view of the elements in 3D (pic 1).
- Architect takes his paper drawing out and takes dimensions (pic 2).
- MEP Coordinator loads the 2D east elevation Screenshot on 2nd display to check levels (pic 3).
- N changes his view in 3D and walks along cable tray to find another view of section (pic 4).

Figure 39: Two displays showing transitions from 3D to 2D, and 2D to 3D digital information.

In this section, we highlighted the current practice during BIM-based design coordination meetings. While we recognize the connection between design meetings, issue preparation, and issue documentation, this research primarily focuses on the issue resolution step in coordination meetings. In the next section, we describe our analysis of project team interactions with design artifacts

3.5 Characterization of Interactions with Design Artifacts

In this section, we present our findings regarding the characterization of the relationship between design artifacts, interactions, transitions and goals participants made during the observed meetings. Our findings are presented in the form of a taxonomy, laying out the relationship and the flow. By definition, a taxonomy is defined as a systematic set of relationships or a conceptual scheme, structure, or system (Gove, 1961). Similar to Jung and Joo (2011) our purpose of creating a taxonomy is to guide research efforts and enhance communications with shared understanding, and to integrate relevant concepts into a descriptive or predictive model.

Figure 40 summarizes our taxonomy of interactions with design artifacts within the design issue resolution stage. These findings have emerged from our qualitative data collection analysis as well as enrichment of our quantitative analysis. Interactions with various design artifacts were a means of achieving participants' goals. We observed that a series of interactions are often required to perform all activities necessary for a goal. Specifically, we found that participants mainly had six high-level goals (prepare, grab attention, inspect, visualize, document, query) while interacting with design artifacts, along with their four major types of interactions (prepare, navigate, annotate, record) with the three types of design artifacts (3D, 2D, and paper). Transitions, occurred when there was a bottleneck interacting with design artifacts and the required design information was available on a different design artifact.

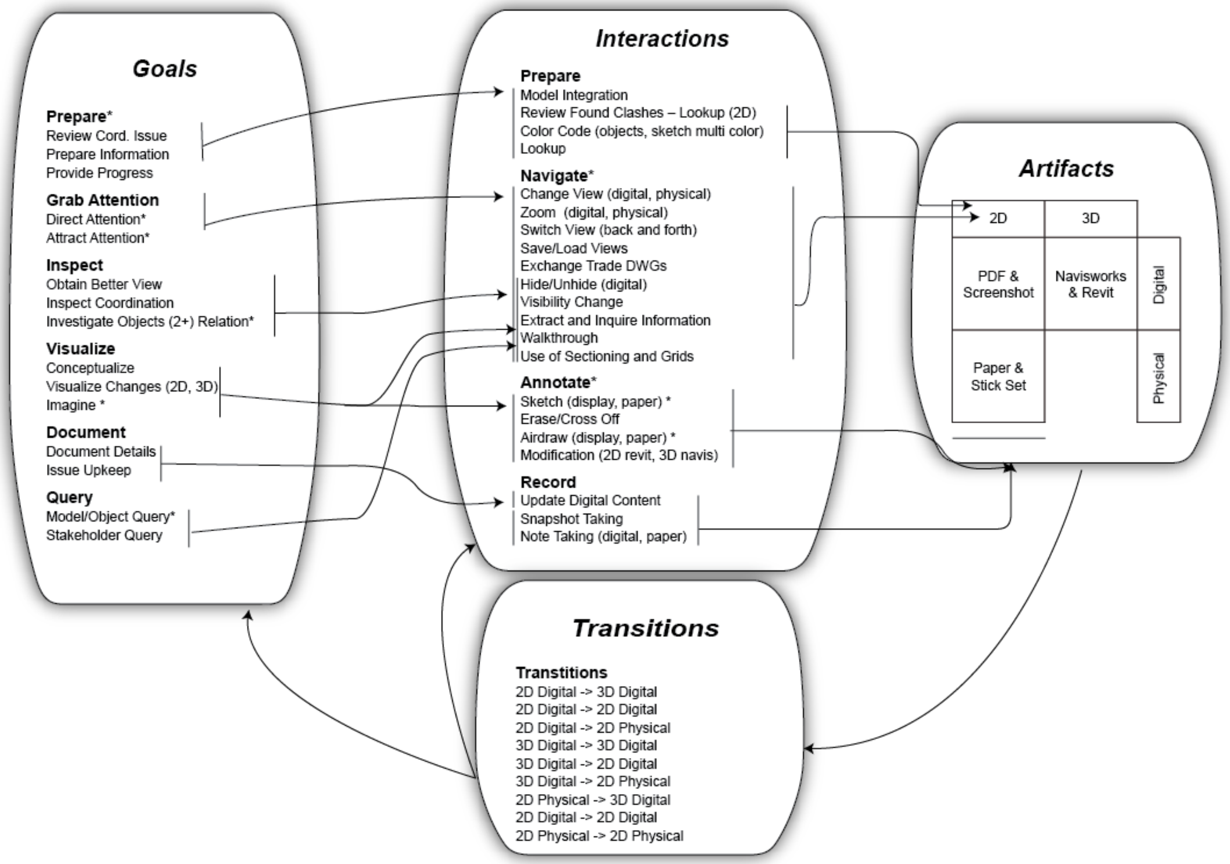


Figure 40: Taxonomy of interaction with design artifacts, outlining the relationship between interactions, goals, and artifacts.

The remainder of this section describes our characterization of BIM-based design coordination issue resolution using the taxonomy components, along with examples and descriptions.

3.5.1 Goals and Sub-Goals

We found that issue resolution is comprised of both high-level and low-level goals. While we acknowledge that the ultimate goal of design coordination meetings to resolve design issues, our focus was on understanding the ways in which design information was used to support these higher-level goals. Sub-goals involving design information could be organized in a few simple categories. These categories share similarities with existing taxonomies of data analysis tasks (e.g., Tory et al. (2008); and Wehrend and Lewis (1990)).

Table 7 shows our categorization of goals and sub-goals, which has benefited from previous literature (Wehrend and Lewis, 1990) and builds on the sub-goal characterization (Tory et al., 2008) and (Mahyar et al., 2012). The terms used from their characterizations are marked with an asterisk (*). While previous literature has provided a rich categorization of goals and sub-goals behind interactions with design artifacts, we developed our goals and sub-goal classification to better capture the details of how goals influenced interactions with design artifacts. The sub-goals were specifically defined to capture the lowest detail possible. We believe both goals and sub-goals are essential parts of issue resolution. We define goals as preliminary objectives when participants interact with an artifact and sub goals as elements of those objectives. Following the same philosophy, interactions become the mechanics of how participants achieve their goals.

Table 7: Types of goals and sub-goals along with a brief description and an example. Note that items labeled with an * are used from (Tory et al., 2008)

Goals	Description	Example
Prepare*		
Review coordination issue	Outlining design coordination issue being resolved using artifacts and viewpoints.	MEP Coordinator explains the issue regarding congested area near columns using 2D highlighted PDFs.
Prepare Information	Information is being prepared for interactions with design artifacts.	BIM Coordinator integrates updated 3D models in Navisworks.
Review progress	Describe previous progress on resolving an issue using viewpoints, agenda and issue spreadsheet.	MEP Coordinator explains progress using spreadsheet, screenshots, viewpoints and navigation.
Grab Attention		
Direct Attention*	Invite the group or individual using an artifact to ensure they are prepared to listen.	Plumbing subcontractor asks group to look at pipe details on 3D model.
Attract Attention*	Bend attention of the group or individuals to a particular artifact or view being discussed.	Architect highlights the door size change in the labs using sketch, air draw, and gestures.
Inspect		
Obtain Better View	Obtain a different/detailed view of the element being discussed within one design artifact.	BIM Coordinator walk through the duct to show surrounding elements and their length.

Inspect Coordination	Inspect an object in detail, look around it, to understand its coordination in the model and relation to other components.	BIM Coordinator changes view around sprinklers in 3D to see its surrounding objects and limitations.
Investigate Objects (2+) Relation*	Understand relationship between the information in two or more design artifacts.	MEP Coordinator compares electrical and mechanical PDF to understand the relationship between duct and lighting.
Visualize		
Conceptualize	Use drawing, annotation, or other interactions with a design artifact to express a design concept as a solution.	Architect sketched the change to a door opening as a possible solution to an installation problem.
Visualize Changes (2D, 3D)	Show the group real time changes after they are finalized.	After updating ceiling high in the meeting, BIM Coordinator imports new architectural model into Navisworks.
Imagine*	Visualize or imagine elements that are not present in the artifact, and are necessary for decision making.	Fire model is missing, BIM Coordinator asks the group to imagine the space missing components take.
Document		
Document Details	Recording detailed items regarding discussion in the meeting.	MEP Coordinator records the new door size in his logbook, as well as other reminders.
Issue Upkeep	Updating/ recording issue outcomes in the spreadsheet (new and existing issues).	MEP Coordinator updates the decision regarding issue along with snapshot and the trade responsible.
Query		
Model/Object Query*	Ask a question about the design information shown in an artifact.	Mechanical sub-trade asks if there is enough room between electrical tray and gas pipes.
Stakeholder Query	Ask a question about requirements, guidelines, etc. from project stakeholders.	MEP Coordinator to check with project owner to see if new ceiling height works.

To elaborate further on the labeling of categories and subcategories of goals, under ‘prepare’, ‘review coordination issue’ involves a detailed explanation of the issue for the first time, showing the issue in various forms of design representations. Compared with ‘review coordination issue’, ‘review progress issue’ refers to follow up on previously discussed issues, taking significantly less time, kept to a brief update and does not involve detailed outlining of the issue on the design artifacts. Under ‘inspect’, ‘obtain better view’ refers to obtaining view of surrounding objects within the same artifact, while ‘investigate objects (2+) relation’ refers to seeking better understanding of multi-disciplinary components involving transitioning between two or more artifacts. Under ‘visualize’, ‘conceptualize’ describes interactions with design artifacts to express a design concept, mainly to propose a solution to the design issue, whereas ‘imagine’ describes, imagining elements that are not present in the artifact (mostly non-modelled BIM components), and are necessary for decision making.

In addition, under ‘document’, ‘document details’ outlines recording detailed items regarding discussion in the meeting throughout issue resolution. However, ‘issue upkeep’ refers to updating/ recording design coordination issue outcomes in the spreadsheet (new and existing issues). In other words, the first term refers to the details of micro components of the discussion of issue resolution, whereas the second one refers to the outcome of design coordination issue. Moreover, under ‘query’, ‘model query’ is to enquire about the design information shown in an artifact, and needs action of BIM or MEP coordinator. ‘Stakeholder query’ is enquiring about requirements, guidelines, etc. from other project stakeholders which the data is not present in the model and requires a discussion. In fact, the main difference is where the knowledge resides. On model based queries, the knowledge resides on the design information, on stakeholder enquiry the knowledge resides in stakeholders’ minds.

3.5.2 Interactions

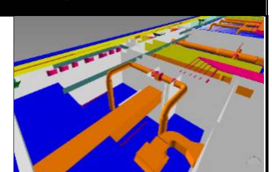
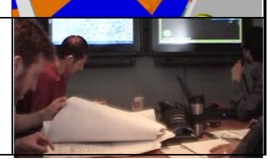
Similar to Tory et al. (2008), we define interactions as “cognitive or physical engagement with artifacts”, or simply utilization of artifacts. To better illustrate some of the more frequent interactions, we present a 5-minute vignette from a meeting, showing how an issue was presented, discussed and resolved in the coordination meeting, as well as how participants interacted with the design artifacts. We then characterize these interactions in the following sub-sections. We categorized interactions with artifacts into four categories of navigation, annotate, record and prepare. These interaction types are explained in detail below.

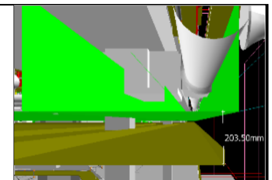
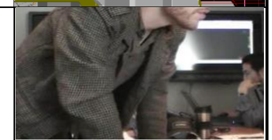
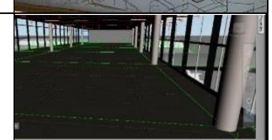
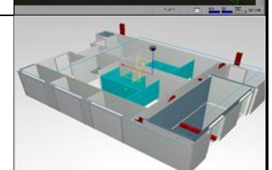
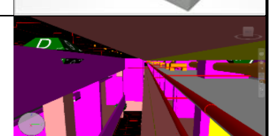
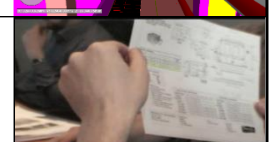
3.5.2.1 Navigation

The most common type of interactions we observed was navigation of design information. These interactions mostly included interactions with 3D and 2D displays. Although most of these interactions were performed by the participant driving the models, often other team participants took control of the navigation. Other meeting participants normally walked to the laptops or displays in order to navigate design information. On multiple occasions, the participants directed the MEP and BIM Coordinators to perform navigational interactions for them. The navigational interactions that we observed are explained in detail in Table 8, showing the interaction categories, description of each interaction, and examples of how interactions were performed. To simplify our findings, we have noted the primary artifact related to each interaction. In the case of interactions that applied to all design artifacts, no specific notes are provided. We found participants navigating with paper drawings mostly, when they required information from their own drawing sets, or when another participant was already interacting with paper.

Unlike Tory et al. (2008), we did not observe preparatory navigational activities in advance in order to prepare design artifacts for subsequent use of design artifacts. We instead report this type of interaction as a separate category of "prepare" interactions in a subsequent section.

Table 8: Navigational interaction categories.

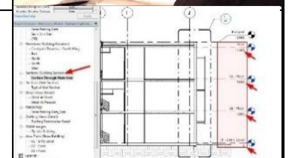
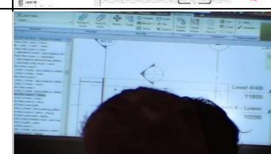
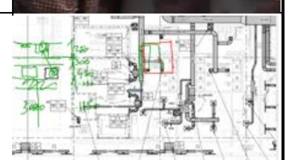
Sub-Category	Description	Example	Snapshot
Change viewpoint (3D&2D)	Adjust the viewpoint in 3D and 2D digital to see surrounding objects.	Change the steering wheel (travel with the curser) to surrounding objects.	
Change view (paper)	Change pages on the drawing set.	Mech Rep keeps changing papers to find the right drawing.	

Zoom (3D&2D)	Zooming in, and out of visualizations.	Zooming into the HVAC unit to see connection details.	
Physical zoom (paper)	Getting closer or moving objects closer for a better look.	The subcontractor leans over the architectural drawings to find the measurement details.	
Save/load views (3D)	Bookmarking and recalling specific 3D views for easier navigation.	BIM Coordinator saves snapshot of tight space between ducts.	
Switch view back and forth (2D)	Going between different trade drawings to compare information.	MEP Coordinator, Mechanical rep and architect switch between electrical/ mechanical dwgs.	
Hide/Unhide models (3D and 2D)	Turn off/on models and objects.	Ducts clashing with the structural floor, BIM Coordinator turns off other models.	
Visibility (make transparent)	Make objects see-through.	BIM Coordinator makes other building elements see-through so he can better see electrical routes.	
Use Grids (3D)	Use of Grids for easier navigation.	Look up grids to load previously found clashes.	
Sectioning (3D)	Insert sections in BIM for easier navigation.	BIM Coordinator places and reuses section points in the 4-D model in addition to grids.	
Walk-thru (3D)	Walking through the BIM along a path.	Mechanical sub-trade asks BIM Coordinator to walk along the duct to see objects in its way.	
Extract Information (paper)	Find out the required information from guidelines/requirements.	Electrical sub-trade looks at the requirement of the system before advising about cable tray route.	
Inquire dimensions (paper)	Use of ruler/ identifiers to find dimensions of objects.	BIM Coordinator asks architect to measure current ceiling height.	

3.5.2.2 Annotate

We observed participants frequently annotate design information during the meetings. We observed that most annotations were with 2D digital design information on top of PDFs. The Interactive display features played a major role in how participants used the displays for annotating design information. We also found there was a learning curve that affected how frequently participants interacted with design information in this way. For instance, in earlier meetings, only the meeting MEP Coordinator frequently used annotation tools, whereas, in the final meetings, we observed more participants walking to the boards and simultaneously utilizing the pens. Unlike Tory et al. (2008), we rarely found practitioners performing a side-sketch (sketching on a blank page/paper) to conceptualize or Air-draw (drawing-like actions over the design information). These annotation techniques are explained in detail in Table 9.

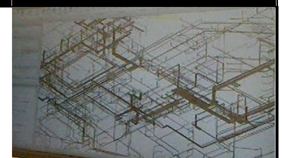
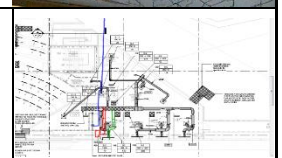
Table 9: Categories of annotation interactions. Note that items labeled with an * are used from (Tory et al., 2008)**.**

Sub-Category	Description	Example	Snapshot
Sketch on display (2D)	Sketching on top of PDFs with Interactive display tools.	Electrical Rep draws an alternate path for cable trays on the display.	
Sketch * (Paper)	Use pen or pencil to draw on top of the paper.	Mech Rep asks if the duct 90, will clash with slab bands.	
Modify (3D)	Modify objects in real-time.	The BIM Coordinator adjusts the ceiling to show the correct height.	
Update (3D)	Export updated 3D model for Clash detection.	BIM Coordinator updates the ceiling height to 250 mm in Revit to update in 3D.	
Erase (2D)	Removing the sketch already drawn on top of Interactive display.	The MEP Coordinator removes previous hand sketch of the ducts and proposes a new route.	
Cross off (2D, paper)	Draw lines through previous details on (printed screenshot or sketch on Interactive display).	MEP Coordinator crosses off what architect drew as it did not have correct dimensions on it.	
Air Draw * (2D, paper)	Use of hands/marker on top of the Interactive display without sketching.	BIM Coordinator uses both hands to draw a schematic design on air before sketching.	

3.5.2.3 Record

We found recording or record-keeping was an important interaction with design artifacts. The recording interactions played a vital role in issue tracking, documentation and eventually resolution of issues, as well as when participants required follow up with queries, decision outcomes, and subsequent activities. Although research has established the advantages of note-taking and documentation in group work studies (Mahyar et al., 2012), our findings indicate few previous studies addressed recording interactions in the design coordination domain. Our findings are summarized in Table 10, showing the interaction categories, description of each interaction, and examples of how these interactions were performed.

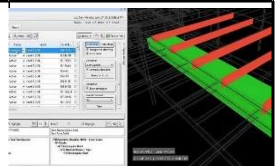
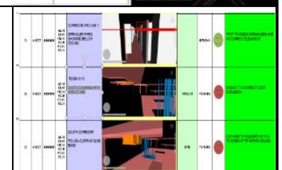
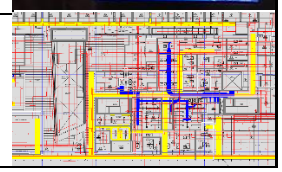
Table 10: Recording interaction categories.

Sub-Category	Description	Example	Snapshot
Save Screenshot (3D)	Capture the current view of BIM, or sketch form Interactive display.	Mech Rep sketches a change on ducts' path. The MEP Coordinator then takes a snapshot of his concept.	
Save Screenshot (2D)	Taking a snapshot of changes on top of PDFs on Interactive displays.	Ducting subcontractor shows his solution and MEP Coordinator takes a snapshot.	
Take notes (Paper)	Taking notes for personal, or team use.	MEP Coordinator records on his logbook the changes discussed with Mechanical Rep.	
Take notes (2D)	Taking notes for later follow-ups on Excel.	MEP Coordinator documents a new design issue along with its snapshot and trade responsibility.	

3.5.2.4 Prepare

During the meetings, often one or more participants (usually the BIM and MEP Coordinators) interacted with design information to prepare the view and/or information for future use. Although previous research briefly reported preparation activities (Tory et al., 2008), we observed a wider range of interactions with design artifacts that were related to the preparation of design information. These interactions were mostly done on 3D digital design information as often specific goals (e.g. clash or view finding) required a longer time to find and load. In addition, we found some interactions were used later to help participants better understand or differentiate between different disciplines, such as color coding different system components and sketching on displays using multiple colors. For instance, during conceptualizations and providing solution participants used different colors to make sure they can distinguish systems being discussed. Our findings are summarized in Table 11.

Table 11: Preparation interaction categories, descriptions and examples.

Sub-Category	Description	Example	Snapshot
Model integration (3D)	Integration of models and review.	BIM Coordinator integrates all models and goes through the design issues.	
Review Clash Detection (3D)	Locate previously found clashes.	Go through documentation to retrieve previous clashes.	
Lookup (3D, 2D)	Navigating in the PDF to find the right information or a more detailed view.	BIM Coordinator looks for the exact view of a floor opening, he zooms, and changes view to find it.	
Color Code (3D, 2D)	Use of different colors for each trade model.	MEP Coordinator highlights colliding cable tray and duct with different colors.	

3.5.2.5 Transitions

Frequent transitions occurred between design artifacts this interfered with participants' goals, particularly when interactions were performed to obtain a better view or to better understand coordination and investigate objects relationships. Although these transitions were necessary, it typically took several minutes to complete a set of transitions and participants had difficulty finding the exact required view, before getting back to the main discussion topic. We have found that there are nine main categories of transitions, which include the 27 subcategories shown in Table 12. As an example, during one meeting (90 minutes) we captured over 50 transitions between various views and design artifacts.

Table 12: Transitions categories, descriptions and examples

Artfiacts	Description	Example
2D digital -> 3D digital	Transition from 2D PDFs, or screenshots, to Navisworks, or Revit.	while viewing mechanical info in PDF, BIM Coordinator brings the view in Navisworks.
2D digital -> 2D digital	Transition from 2D PDFs, or screenshots, to 2D PDFs, or screenshots .	MEP Coordinator switches back and forth between mechanical and electrical design details to understand Coordination.
2D digital -> 2D Physical	Transition from 2D PDFs, or screenshots, to paper drawings, printed screenshots, or logbook.	While mechanical 2D is discussed, electrical subtrades takes paper drawings out and grabs attention of participants
3D digital -> 3D digital	Transition from Navisworks, or Revit, to Navisworks, or Revit.	While editing ceiling height in Revit, BIM Coordinator brings integrated model in Navisworks to see changes.
3D digital -> 2D digital	Transition from Navisworks, or Revit, to 2D PDFs, or screenshots.	While discussing elements colliding in a condensed space, MEP Coordinator brings 2D electrical plan view.
3D digital -> 2D physical	Transition from Navisworks, or Revit, to paper drawings, printed screenshots, or logbook.	While discussing design details in tight ceiling space, Architect takes paper drawings out and looks for element sizes.
2D physical -> 3D digital	Transition from paper drawings, printed screenshots, or logbook, to Navisworks, or Revit.	To show surrounding elements regarding a duct being discussed on paper, BIM Coordinator brings 3D view if the area.
2D digital -> 2D digital	Transition from 2D PDFs, or screenshots, to 2D PDFs, or screenshots .	MEP Coordinator minimized and switched between trade PDFs to gain a better understanding of each trade component.
2D physical -> 2D physical	Transition from paper drawings, printed screenshots, or logbook, to paper drawings, printed screenshots.	Fire protection consultant compared a printed 3D screenshot with his paper drawings 2D elevation views.

In this section, we have described the four major categories of interactions with design artifacts, along with the four major categories of goals motivating the interactions. We also characterized our understanding of the correlation of design artifacts, interactions and goals through the taxonomy presented in this section. The next section builds on this characterization and presents analysis of different interactions participants had with design artifacts.

3.6 Design Artifact Interaction Analysis

We investigated project team interactions with design artifacts in design coordination meetings with a particular focus on better understanding what artifacts were utilized, how frequently artifacts were used, why artifacts were used and when participants transitioned between artifacts. We first demonstrate the different types of design artifacts used by the participants during meetings. As Table 13 shows, Navisworks, Revit, and 2D drawings were the primary navigational artifacts for 3D digital, 2D digital and 2D physical design information respectively. Other artifacts in each design information representation category were utilized to perform other interactions, such as editing, issue tracking, and recording.

Table 13: Design artifacts and their role in the meetings.

Representation	Artifact	Primary role in meetings	Location
3D Digital	Navisworks	Review Issues, Direct Attention, Obtain View, Understand Coordination, Investigate Relations, and Model Query, Imagine	Right Interactive display
3D Digital	Revit (object editing)	Visualize Changes, Conceptualize, Information preparation, Document Discussion.	Right Interactive display
2D Digital	2D PDF	Obtain view, understand coordination, conceptualize, attract attention, stakeholder query, visualize changes	Left Interactive display
2D Digital	2D Revit screenshot	Document discussion, understand coordination, visualize changes	Left Interactive display
2D Digital	2D Navisworks screenshot	Issue Tracking, Document Discussion, Stakeholder Query, Review progress report.	Left Interactive display
2D Physical	Paper Drawing set	Obtain view, understand coordination, conceptualize, attract attention, direct attention, stakeholder query	Table
2D Physical	Printed Screenshot	Understand coordination, visualize changes, imagine.	Exchanged by hand
2D Physical	Logbook	Issue tracking, document discussion, stakeholder query	Next to MEP Coordinator

3.6.1 Frequency of Interactions with Design Artifacts

Figure 41 represents our analysis of the percentage of time participants interacted with each design artifact during the meetings. As shown, the participants utilized all design artifacts, relatively similar amounts of time and each category of artifacts was in use for an almost equivalent portion of the time. We believe this highlights the importance of the application of each design information representation throughout the meetings. Though it also highlights that BIM is only used 30% of the time. The most favorable platform for 3D digital design information was Navisworks, followed by Revit. For 2D digital design information, the most favorable platform was PDF bundled drawings, and 2D Revit screenshots. And finally, the most favorable form of 2D physical artifacts were paper drawings and printed screenshots of design information.

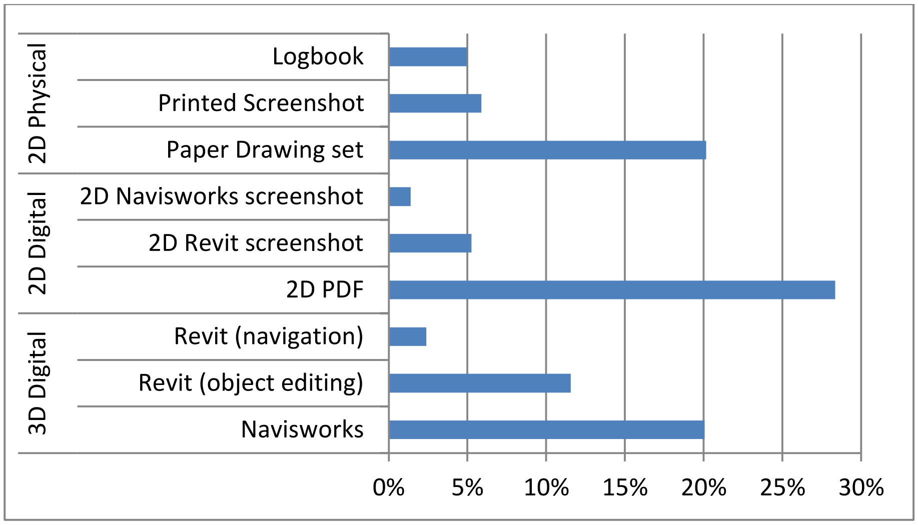


Figure 41: Design artifacts utilization during meetings (% of the time).

Figure 42 shows the four major categories of participants' interactions with design artifacts. These include navigation, annotation, recording and preparation. Overall navigation accounted for the majority of interaction across all artifacts (62%), followed by preparation interactions. These interactions are broken down in detail in the subsequent sections.

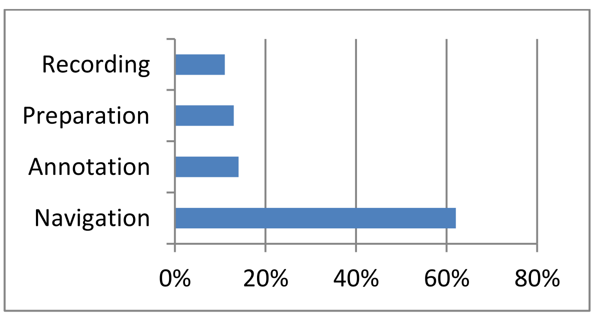


Figure 42: Interaction types and their frequency (Percentage of all interactions).

We also investigated the interactions in terms of their frequency, determining the total instances of interactions with design artifacts per total number of observed interactions. In Figure 43, we illustrate our findings using different colors for different design artifact representations (Blue: 3D digital, Green: 2D digital, and Orange: 2D physical). As the figure shows, changing viewpoint, information take-off and saving/loading views were among the highest frequency navigational interactions. On the other hand, hiding components in 2D were among the least frequent interactions. In addition, the most frequent annotation interaction we observed was sketching on the Interactive display used for displaying 2D PDF design information, followed by sketching on paper and erasing digital sketches. The ‘preparation’ and ‘recording’ types of interactions, which have been rarely reported in prior studies, accounted for roughly a quarter of all interactions with design artifacts. The nature of these interactions often required the participant to perform them simultaneously with the discussion between participants while using other artifacts. All preparation interactions we captured were with 3D digital information except sketching in multi-color which was done with 2D design information as well. The most frequent preparation interaction was look up, followed by reviewing clash detection, BIM color coding, and model integration.

In terms of interactions per each design artifact, the most frequent interaction with 2D digital design information was sketching on Interactive display overlays, and the most frequent interactions with 3D digital information were zooming and changing viewpoint, and finally the most frequent interaction with 2D physical information was information take off. We also observed rare interactions of air-drawing (drawing on top of the paper) and crossing of design information across all design artifacts. Although Interactive display overlays provided a wide range of functionalities, including panning, zooming, and sketching, practitioners primarily used the sketch, erase and screenshot functionalities.

In addition, we found that 2D digital design information was most frequently used to annotate and navigate design information, 3D digital design information was most frequently used to prepare and navigate design information, and paper was most frequently used to record decisions and details and navigate design information.

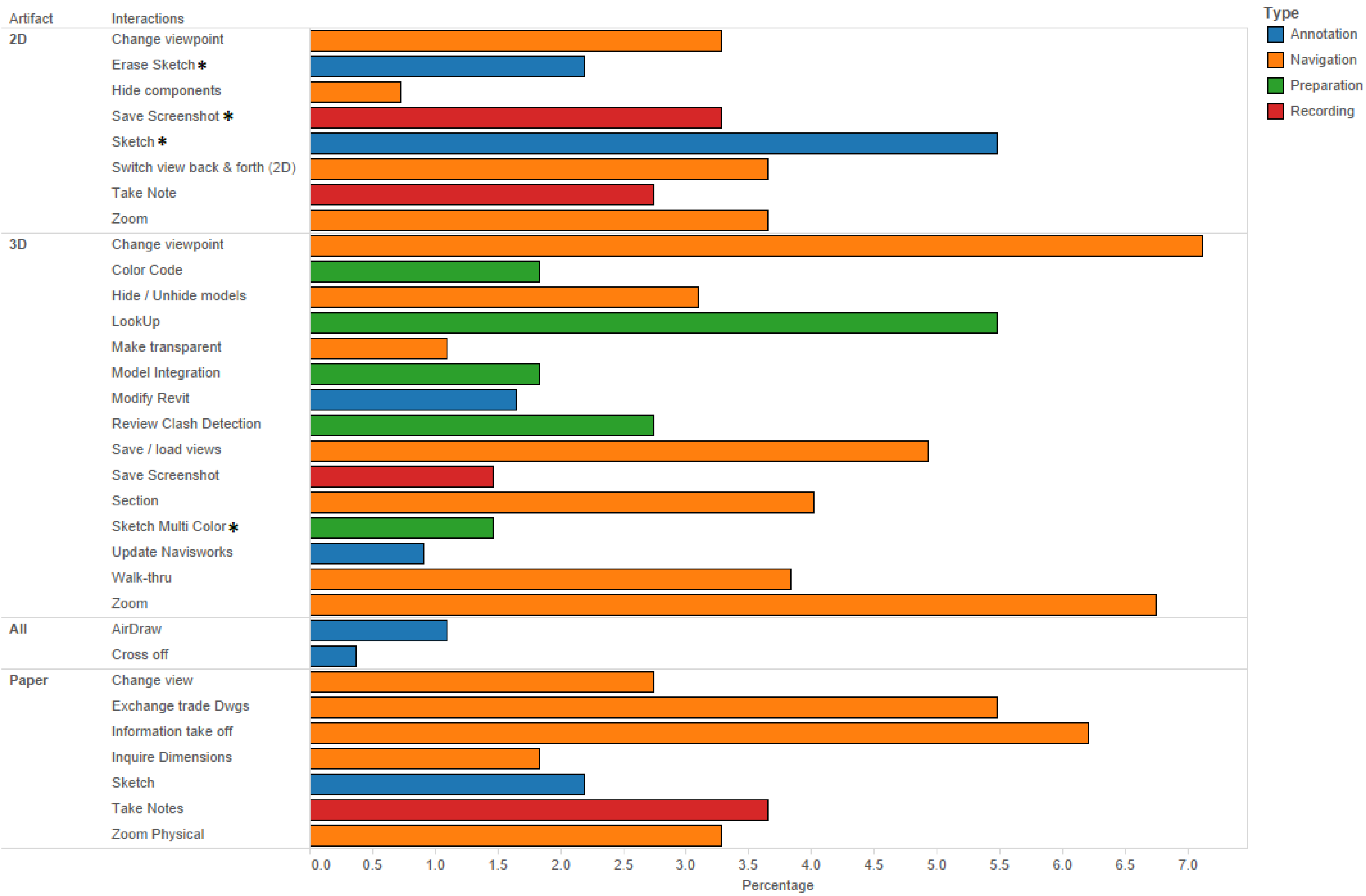


Figure 43: Frequency of interactions with design artifacts (Percentage of all interactions) by artifact type. blue: annotation interactions, orange: navigational interactions, green: preparation interactions, and, red: recording interactions. *indicates functionality related to interactive display use.

3.6.2 Transitions

This section describes our analysis of the transitions made between different design artifacts during the design coordination meetings. Although it is reasonable for practitioners to require multiple views when reviewing design information (Korman, 2009), our observations and prior studies confirm that a large portion of transitions occur when there is limited information about the design issue available (Tommelein and Gholami, 2012), design information is not accessible or available (Liston, 2009), or difficult to interact with (Tory et al., 2008). Figure 44 shows the types and frequency of transitions during all analyzed meetings. Transitions from PDF views to other design artifacts and from other design artifacts to PDFs were the most frequent transitions during the meetings. Our findings indicate that 47% of the transitions were made from 2D digital information (PDF), 30% of the transitions were made from 3D digital information, and 27% of the transitions were made from paper based artifacts to other design artifacts. Our findings also demonstrate that almost half of the transitions were initiated when participants were interacting with 2D digital information during the meetings. In other words, one could argue that 2D digital design information acted as the main gateway for transitions to other design artifacts. In addition, practitioners were less likely to transition to other design artifacts when interacting with printed screen shots of digital design information.

Furthermore, transitions between 3D digital artifacts were rare, but transitions between 2D digital design artifacts were very frequent. Team members constantly compared the two design artifacts to come up with a solution. This approach, however, appeared to slow down the issue resolution process, since each time the main drawing being discussed moved to other segments (e.g. going to the next level to follow the duct routing), other trades' drawings had to be changed too. This especially became problematic when trade drawings did not have the same reference points, page directions, or levels of detail. We elaborate more on this issue on section 3.7.

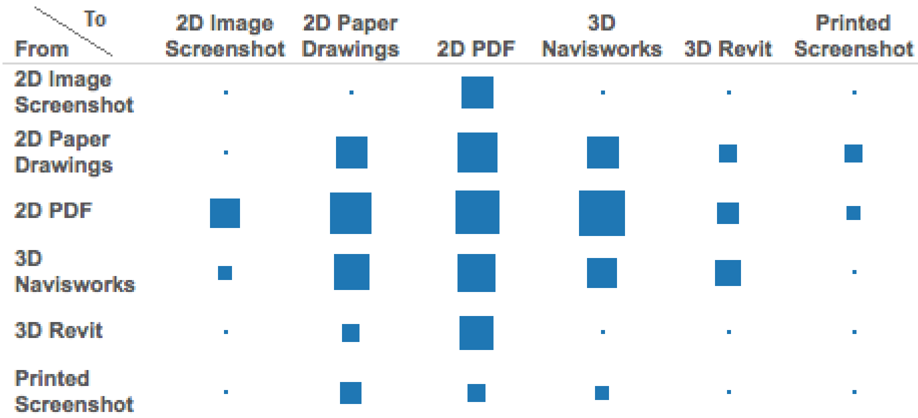


Figure 44: Types and frequency of transitions between different design artifacts and views.

In addition, we investigated the motivation behind why participants transitioned between different views and artifacts. We investigated different goals motivating the transitions and their frequency. These goals are defined further in Section 3.5.1. Figure 45 presents the goals along with the frequency percentage of how often goals influenced transitions. We found that most transitions occurred when participants required a better view, followed by when they were trying to attract the attention of others, and finally when they wanted to make an inquiry to the design information, such as taking dimensions.

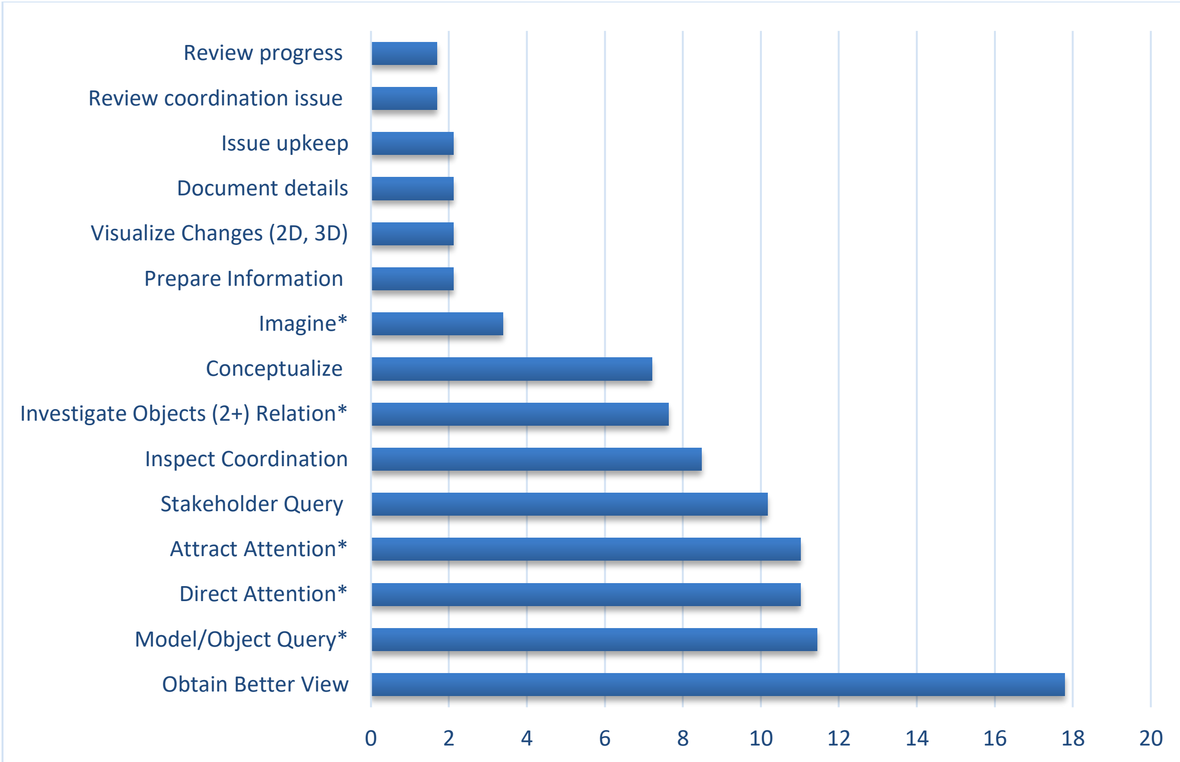


Figure 45: Types and frequency of goals, influencing transitions between different design artifacts and views. Numbers shown are percentages out of all.

In this section, we have described observations of how participants utilized design artifacts, the interactions with design artifacts, the transitions between design artifacts and views, as well as transition categories and frequency of goals influencing these transitions. We found that paper, 2D digital and 3D digital design information were utilized almost equally throughout the meetings, transitions were frequently made between views and design artifacts that were error prone and inefficient. We also found that the most common reason for transitioning was to obtain a better view, and that the most common interactions with 3D digital information were zooming and changing viewpoints. The most common interactions with 2D digital artifacts were sketching on Interactive display and switching back and forth between views, and the most common interaction with paper drawings were information take-off and exchanging trade drawings. In the next section, we further elaborate on the findings.

3.7 Discussion

In this section we further elaborate on the findings of the prior sections. Specially, we discuss the transitions across design artifacts, availability and accessibility of design information, inconsistency of design information across different artifacts, and unfit navigation tools for fast-paced BIM coordination environment.

3.7.1 Design Artifact Utilization

The fact that 2D digital, 2D physical and 3D digital design information were utilized almost equivalently is an important outcome and surprising given that many prior research efforts (e.g. Adamu, et al. (2015)) emphasize BIM utilization in the delivery of BIM projects. We acknowledge that this finding is unexpected, and as one of the key initial findings of this research, this motivated us to conduct more detailed analysis of participant interactions with design artifacts in design coordination meetings. As discussed in the related work section, previous research and our own observations found that each design information representation played a key role in information delivery. The use of both 3D and 2D design artifacts was advantageous. We found 3D information was useful for providing an overview of the object and conveyed the 3D shape while similar to findings of Tory (2004), 2D information was better for displaying interior details, and making precise measurements. In addition, we believe that the interaction level with artifacts could be affected by the fact that the displays were in a public setting. Various points of departure have examined the extent of private versus shared media use of practitioners while interacting with design artifacts (Liston, 2009; Tang and Leifer, 1988). We believe the collaboration tool settings could affect the interaction level with various design artifacts, similar to Hawkey et al. (2005), and we found that participants are less likely to interact or participate if the artifact was not easily accessible. As the team moved its focus from one artifact to another artifact, changes in accessibility did occur. Although, we acknowledge participation among team participants can impact interaction level with design artifacts (Weisband et al., 1995), the limited resources and time did not allow for measurement of participants participation during the meetings.

Furthermore, during informal interviews with BIM experts, interviewees believed the high interaction with the paper drawing set was due to its accessibility in the center of the table, as well as the general familiarity of construction practitioners with the printed design information. In addition, the interviews stated that project participants had difficulty interacting with the displays showing 2D and 3D digital information remotely, or at the same time (more than one user) as the MEP and BIM Coordinators who were primarily in control of the displays. Furthermore, while practitioners were familiar with model creation, a different tool was used for model navigation. In this situation, participants used Autodesk Revit to create the models but used Autodesk Navisworks for navigation.

The interviewees also revealed other factors that could have played a role on high artifact utilization, including the fact that design information was often prepared and conveyed to practitioners in 2D digital format (PDF bundles). Similar to Volk et al. (2014) we found that bidding documents, RFIs and construction documents were only conveyed in 2D digital format during the project. Most of the BIM was created for the purpose of design coordination by practitioners related to each building system. Practitioners found 2D digital design information easier for on-screen annotation since they did not have to show perspective points in 3D and found 2D digital artifacts easier for "big picture" navigation, whereas 3D appeared to work easier for capturing and discussing building systems in detail. It is worth noting that, we do not claim that '3D digital information is more effective,' or superior to other forms of design representation. Although some of the state of the art BIM tools support multi representation of design information, most tools are designed to support not only a single form of design information representation, but also a unique application. For instance, Autodesk Revit, supports creation of 3D digital design information, but it is not deemed suitable for 2D or 3D digital navigation. In addition, none of the tools examined, supported efficient transitions between design representations.

Unlike Tory et al. (2008), we did not find the richest navigation interactions with 2D paper drawings. We found that 3D digital design information was utilized the most when practitioners navigated design information. Furthermore, although earlier studies (e.g. Jordan and Henderson (1995) and Tory et al. (2008)) found sketching on top of design information rare, we found frequent sketch interactions on top of 2D digital design information, which was facilitated by the SMART Overlay. We rarely observed sketch interactions on top of paper (mostly on printed screenshots of digital design information). When we compared our observation of meetings at the architect's office, (where there was only a single projector available) with meetings at our BIM trailer, we found more frequent annotation interaction, instead of grabbing attention of practitioners. We believe practitioners ability to undo mistakes, building on top of existing displayed information, ease of use of interactive overlay and having the knowledge of changes being temporary, are among potential contributing reasons or increased annotation interactions. The fact that, we rarely found practitioners performing a side-sketch (sketching on a blank page/paper) to conceptualize or Air-draw (drawing-like actions over the design information) compared to (Tory et al., 2008) contributes towards this assumption.

3.7.2 Transitions

Example 8 on Table 12 illustrates how and when transitions within the same design artifact became a burden and impeded the efficiency and efficacy of interactions with design artifacts. In this example, we observed that when participants interacted with 2D PDF, they frequently switched between discipline-specific views (e.g. mechanical and electrical). Although we categorize this interaction as a transition, we believe this type of transition within the same design artifact caused more delays compared with other transitions. When measured how long participants spent per transition, participants spent 24% more time compared with other transition types, when they transitioned from 2D digital to 2D digital design representation.

During the interviews with domain experts, interviewees believed their peers have mostly transitioned to reach goals of showing changes, tracking issues, and to do record keeping. However, our quantitative analysis found these goals least likely to influence practitioners to transition to a different design artifact. In addition, interviewees stated that they believed the top goals leading to transitions were investigating the relationship and better understanding the coordination of building components, whereas our quantitative analysis revealed these goals ranked as the 5th and 6th reason leading to transitions.

3.7.3 Consistency of Information, Organization and Navigation

Issued for construction drawings were often comprised of very large PDF files containing all the trades' design information, making navigation time-consuming and error-prone. This was mainly caused by participants having difficulty finding the right information. For instance, going to the same view but in a different trade's drawing required significant knowledge of various buildings systems and even then it took a significant time to find it manually. This challenge was often addressed by the MEP Coordinator (usually the person in charge of 2D digital information) frequently slicing the digital files into smaller discipline-specific chunks, to be able to navigate back and forth between design information. We believe this also emphasizes on the fact that accessing both 2D and 3D digital design information are required during building design coordination.

In terms of availability and the effect of location of design artifacts and their settings, we found that accessibility was dynamic, as the team moved its focus from one medium to another, and changes in accessibility did occur. When we compared our observation of meetings at the architect's office, (where there was only a single projector available) with meetings at our BIM trailer, we found increased interaction level of project participants with digital design artifacts, and a decrease in gestures in the BIM trailer. Moreover, when interacting with digital design information, we found participants were more likely to interact with publicly available design information within the primary design artifacts, than their own computer or other portable devices. For instance, on one occasion, while the architect was interacting with the paper drawings in front of him, he walked to the Interactive display showing the same design information to refer to the objects. On the other hand, participants interacted more on their own when using paper design artifacts. In addition, we rarely saw meeting participants utilize the available display ports on the central desk that they could easily plug their laptops into, which could be partly explained by the fact that the left Interactive display was frequently in use by the MEP Coordinator and the right Interactive display was primarily used by the BIM Coordinator.

In terms of design inconsistencies, we frequently observed instances where meeting participants did not have the right BIM component modeled or an entire section of the model was missing. The inconsistencies between design information mainly impacted interactions when participants wanted to review coordination issues, make object or model-based queries, obtain a better view, better understand coordination and investigate objects relationships. These situations occurred more frequently when a trade forgot to merge in their BIM components or had not yet modeled them. For instance, in one case, the electrical subcontractor had to recalculate his solution as the missing component was not present. In addition, we often observed discrepancies between design information in artifacts present in the meeting room. This included discrepancy of information between paper and PDF information, 2D versus 3D digital, and paper versus 3D digital.

Finally in terms of navigation tools, although participants had sufficient prior experience using BIM tools, the tools were often not fully utilized. Participant's interactions were most affected by these limitations when they needed to review coordination issues, prepare information, and visualize changes. In some cases, the participants who created the BIM often asked the BIM and MEP Coordinators to perform navigational interactions for them. as a result, participants did not further interact with the tools and only directed others to perform the interactions for them, when their interaction with BIM tools were not satisfactory. We found these instances disruptive both for the person doing the interactions and the other participants.

3.7.4 Limitations

In terms of analyzed contents within each artifact, we acknowledge that specific contents of the artifacts could play a role in how frequent practitioners transition between design representations. Although Table 12 attempts to reflect the content and representation of information within the artifacts in Table 12, further investigation into specific contents within design artifacts during the meeting (e.g. specific design information, and guidelines) could be beneficial. It is worth noting that drawing conclusions, or correlations from such investigation may prove difficult.

3.8 Validation

As the first test for validation of the findings, we performed a non-intrusive ethnographic case study of a design team on a replica case study consistent with (LeCompte and Goetz, 1982). Specifically, we sought to prospectively validate the characterization of interactions and goals observed. Similar to the qualitative analysis of the primary case study, short vignettes from the second case study were selected to verify whether the interactions and goals could have been classified using the taxonomy presented in Figure 40. The second case study project had a similar setting and almost equal number of project participants. We acknowledge that because human behavior is never static, no study can be replicated exactly, regardless of the methods and designs employed (LeCompte and Goetz, 1982). We found all interactions and goals repeatedly occurring in the second case study, however, since the meeting environment and design artifact settings were different, we saw less direct interactions with digital design information by project participants other than the BIM Coordinator. As Figure 64 illustrates, the success rate initially was low, but as more vignettes were coded, and as the categories were revised, the success rate improved significantly. Specifically, the first 5 vignettes showed that the categories initially developed, could not contain a significant portion of interactions and goals. Hence, revision to the terminology and description of categories were made. Although encoding the initial vignettes was unsatisfactory, with numerous revisions to the taxonomy, the average success rate using the taxonomy increased to 83%.

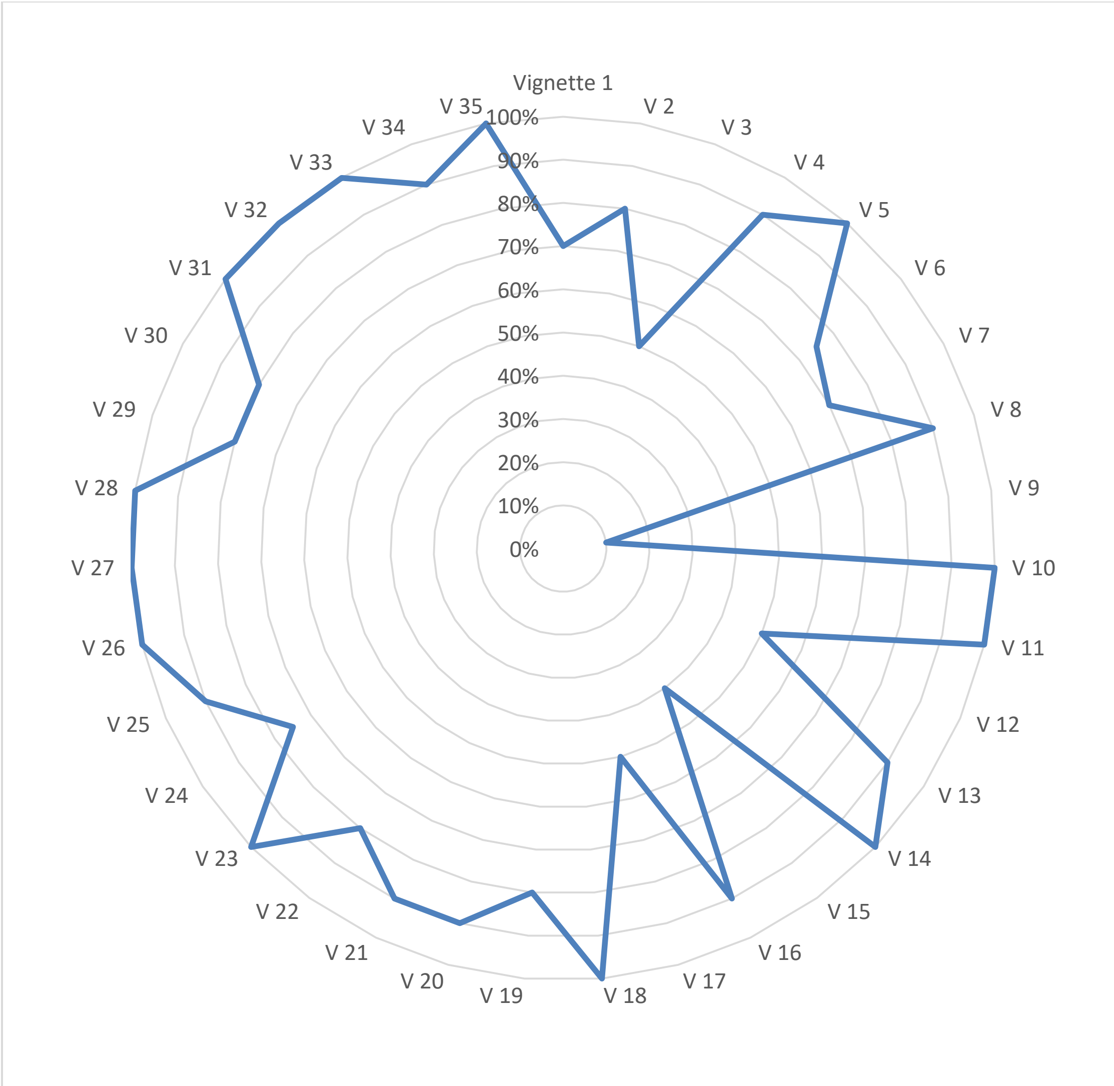


Figure 46: Average success rate for encoding video catalogs by interviewees. V: Vignette #

We also performed an informal interview with two BIM experts in the field, including one from the Pharmacy case study. Similar to others (Howard and Bjork, 2007; Kreider et al., 2010; Wang and Leite, 2016), we asked the BIM experts to comment on the interaction taxonomy presented in Section 3.5 and compare their own experience with the findings of this research. We then asked them to capture word by word (encode using our taxonomy codes) three 5-minute vignettes from the case studies using the taxonomy. The feedback of the experts was rigorously analyzed and the wording of the taxonomy was later revised to improve clarity. During this process, we constantly sought interviewee's opinions as to the interaction and artifact utilization analysis of this research and attempted to capture their thoughts regarding the results presented in Section 3.5. Furthermore, we specifically sought feedback of interviewees to better understand and confirm the utilization rates of 2D digital, paper and 3D design information found in this study.

3.9 **Conclusions and Future Work**

This paper presents the results of a two-year ethnographic field study of the design coordination process of a new multi-purpose building project. The goal of this research was to better understand how and why participants interacted with different design artifacts during the coordination process, with a particular emphasis on interactions with BIM tools. We identified the low-level interactions participants had with design artifacts, analyzed the frequency of their interactions, and evaluated the artifact utilization rates.

This research builds on and extends the previous work (Tory et al., 2008) by analyzing the frequency of interactions with different design artifacts, characterizing interactions with state of the art BIM tools, and identifying the motivation behind interactions with design artifacts. An important contribution of this research is the identification and characterization of the transitions participants had between design artifacts and views, which has previously not been studied in depth. We also characterized the reasoning behind participants' transitions between design artifacts and the frequency of their occurrence. We developed a taxonomy that characterized the interactions participants had with design artifacts, the transitions between design artifacts, and the short and long term goals of these interactions. We characterized interactions into four major categories of preparation, annotation, navigation, and recording, and the goals into six categories of prepare, grab attention, visualize, inspect, document, and, query. In terms of detailed analysis of participants' interactions with design artifacts, we found:

- 2D paper drawings, 2D digital PDFs and 3D digital models were utilized almost equally during coordinating meetings.
- The most frequent navigation interactions occurred with 3D digital design information, unlike prior studies that found 2D paper drawings utilized the most when navigating design information.
- When interactive digital tools were provided (e.g., Interactive displays), practitioners performed more frequent sketch interactions compared with paper-based design coordination meetings. Practitioners mostly sketched on top of 2D digital design information, and rarely sketched on paper and 3D digital design artifacts.
- The 2D digital design information was used most frequently to annotate and navigate design information, 3D digital design information was used most frequently to prepare and navigate design information, and paper was used most frequently to record decisions and details and navigate through design information.
- Practitioners transitioned the most when interacting with 2D digital design information and transitioned the least when interacting with printed screen shots of digital design information.

We found that participants interacted equally with BIM, 2D digital and 2D paper-based representations of design artifacts, demonstrating that the practitioners in our study preferred 2D over 3D representations the majority of the time. We also found that practitioners transitioned frequently between design artifacts, preferring 3D to get alternative viewpoints of a particular situation, 2D digital PDF’s to sketch and easily switch between views, and 2D paper to conduct information takeoffs and exchange trade drawings.

We believe these findings can better inform the software development community to better align state of the art BIM tools with how the tools are being utilized, as well as informing future BIM-based building design coordination projects to better adopt BIM-based design coordination and modelling strategies.

Further research is necessary to further explore the impact of new collaborative technologies, such as cloud-based BIM tools and AR/VR, on design coordination processes and outcomes. Incorporation of such tools will presumably change the way practitioners interact with design artifacts, as well the accessibility and availability of design information. In addition, we believe the taxonomy of interactions with design artifacts developed in this study could improve design coordination settings, BIM tool selection and technology development. Our next steps will be to conduct additional ethnographic case studies of teams performing design coordination with a particular emphasis on alternative environments and tools, such as cloud-based BIM platforms, big room settings, and cross-case analysis. We plan to work with computer scientists to implement and test new transition mechanisms between design information representations and views to better support fluid and timely access to relevant design representations that best suit the goal of the interaction.

Chapter 4: Beyond the Clash: Investigating BIM-Based Building Design Coordination Issue Representation and Resolution

4.1 Introduction

Design coordination is a critical and challenging task that ensures building designs meet the functional, aesthetic, and economic requirements of project stakeholders. During the process the components of building systems are defined and routed to avoid interferences and to comply with diverse design and operations criteria (Barton et al., 1983). The coordination process requires extensive knowledge of building systems, such as checking that water lines are not routed above electrical equipment and assuring there is adequate access for cleaning reheat coils located in ductwork (Tatum and Korman, 2000). The level of complexity and number of building systems in a facility impacts the difficulty of the design coordination process, and construction industry professionals cite mechanical, electrical, and plumbing (MEP) coordination as one of the most challenging tasks encountered in the delivery of construction projects (Korman et al., 2003). Prior studies estimate that 57% of design coordination errors have a potentially direct impact on construction costs, with some costing over 26,000 USD per design error (Lee et al., 2012). Hence, successful management of the design coordination process is critical to the efficient delivery of cost-effective and quality projects (Chua et al., 2003).

Recent advancements in Building Information Modeling (BIM) tools have had a significant impact on the efficiency and efficacy of the design coordination process. Studies have shown that design coordination and conflict detection are the most frequent and valued uses of BIM in the construction sector (Bernstein and Jones, 2012). For instance, BIM-based design coordination enabled project stakeholders on a large hospital project to identify over 3 million clashes and resolve over 2.4 million clashes prior to construction (Khanzode, 2010). Despite numerous advantages of BIM for evaluation of building system designs, similar to Lee et al. (2012), we have found that many design coordination issues still go undetected using state of the art BIM tools, often leading to on-site fixes with additional costs and delays to the project (Assaf and Al-Hejji, 2006). Frequently, the low-level details regarding the complexity, priority and severity of design issues are not sufficiently documented during and after meetings, making it difficult for practitioners to understand and revert back to these issues from prior meetings. Furthermore, management of design coordination issues remains a challenge for practitioners, with design coordination issues often being comprised of process-based and model-based conflicts. These types of design coordination issues are resource intensive, time-consuming, involve multiple building systems and go beyond the traditional definition of a 'clash'.

The goal of this research is to better understand and formalize design coordination issue representation, resolution and documentation. Specifically, we developed a taxonomy of design coordination issues and an ontology that defines the relationships between physical, process, and model-based design issues. We then apply the taxonomy to two case studies to develop insights into the frequency of issue types, the distribution of issue types across disciplines, and the resolution rates of issue types. We employed a mixed-method approach based on observation and analysis of two case studies through the entire design coordination process. We transcribed our observations and enriched our collected data using axial coding, and then verified our findings against current literature. To gain a better understanding of the design issue identification process, we conducted think-aloud observation of practitioners performing coordination analysis. The coding process was validated through inter-coder reliability testing and the findings of this study were validated by conducting expert interviews among practitioners.

Throughout this paper, we refer to 'clashes' as conflicts that are detected through an automated clash detection function of BIM tools when two or more building elements occupy the same space (Eastman et al., 2011). We refer to 'process-based' design issues when they are caused by the process of BIM creation, and 'model-based' design issues when they are caused by deficiencies in the BIM. We define 'design coordination issues' as more complex conflicts between systems that are either not detected through automated clash detection or require further examination. We refer to the 'MEP Coordinator' as the person(s) in charge of overall design coordination and the 'BIM Coordinator' as the person(s) in charge of model integration, examination of clashes, and documentation of design coordination issues. We found that many process-based and model-based design coordination issues are the results of further examination of actual physical 'clashes,' and that 28% of design issues remained unresolved by the end of the design coordination stage.

On both projects we studied, *design discrepancy, design error, clashes* and *missing items* were respectively the most common, and *as-built inconsistency, functional,* and *clearance* least common design coordination issues types. In total, 46% of the design issues were comprised of process-based, 21% were model-based, and 33% were physical design coordination issues. The case study that was delivered using a Construction Management method had more *missing information, as-built inconsistency*, and *design error* issues, but less *temporal, functional* and *clearance* issues, compared with the case study that used a Design-Build delivery method. The *temporal and functional design issues* took the longest time to resolve and *missing information* took the least amount of time. *Design discrepancies* were least likely to be resolved by the end of design coordination. We found little correlation between the complexity of design issues and their resolution time. Design coordination issues occurred the most at mechanical rooms, their adjacent spaces and within condensed spaces between architectural ceilings and structural floors. The experts we interviewed attributed unresolved design issues with unexpected additional costs and delays, and confirmed that the potential integration of the developed taxonomy along with maintaining sufficient LOD across key project stakeholders could improve identification, documentation and communication of design coordination issues in practice.

In the subsequent sections, we describe the related literature in Section 4.2, our research methodology in Section 4.3, and our analysis of the BIM coordination process in section 4.4. Next, we describe the BIM-based design coordination representation taxonomy we formalized in Section 4.5, the application and analysis of the taxonomy to the two case studies in Section 4.6, and Validation of our findings in Section 4.7. Finally, we discuss our analysis in detail in section 4.8, and then finally, describe our conclusions and recommendations for future work.

4.2 Related Work

In this section, we discuss relevant literature in the fields related to design coordination issue characterization and knowledge-capture strategies for design coordination. We address the progress in relation to each field and subsequently highlight the theoretical gaps.

4.2.1 BIM-based Design Coordination Issue Characterization

In an early attempt, Korman et al. (2003) classified design issues into three main categories of design criteria, construction, and operations issues. They also identified design issue attributes as geometric characteristics (component dimensions) and topological characteristics (spatial relationships). Their work later became a foundation on which Tabesh and Staub-French (2006) built to further classify design issues as tasks of conceptual reasoning (i.e., design validation, detailing, and sequencing), spatial reasoning (i.e., layout, routing, and positioning), and underlying reasons behind the constraints identified in each discipline (i.e., tolerance, productivity, space, performance, access, safety, and aesthetics). Other researchers, such as Wang and Leite (2016), studied design issue resolution and knowledge capturing and provided a formalized representation schema for MEP coordination to help in clash analysis, clash resolution, and management. Furthermore, while proposing a structured method for analyzing BIM's return on investment, other researchers such as Lee et al. (2012) classified design issues in terms of their cause, the likelihood of identification, and the impact on schedule, quality, direct cost; they classified design errors into three categories of illogical design, discrepancies between two drawings, and missing items.

While the prior studies above have provided a good understanding of geometrically identifiable conflicts, or what are generally known as "clashes" in BIM-based building design coordination, our findings indicate that the current literature has yet to address the broader concept of what we call in this study "design coordination issues." These design coordination issues are often comprised of clashes, thus demanding more expertise and knowledge, and are often non-detectable using state of the art BIM tools while sometimes taking months to resolve. Although some researchers, (e.g. Lee et al. (2012) have explored beyond clashes, little research has been done on the process of identifying complex design issues or provided a classification which could contain the design issues we observed. Also, often the complexity, priority and severity of design coordination issues could not be identified using existing knowledge in the field.

4.2.2 Design Coordination Knowledge Capture Strategies

Most construction knowledge is tacit and resides in the minds of domain experts (Khalfan, Bouchlaghem, Anumba, and Carrillo, 2002). A great portion of construction knowledge is both generated and used in the coordination process, and though it is usually lost afterward, it can be utilized if systematically documented (Wang and Leite, 2012). Khalfan et al. (2002) argue that there is a lack of organized processes to capture lessons learned and disseminate useful knowledge to other projects. In the Architecture Engineering Construction (AEC) industry, there is a strong reliance on informal networks, collaboration, and 'know-how' to locate the repository of knowledge (Kamara, Augenbroe, Anumba, and Carrillo, 2002). And considering the intense environment of design coordination meetings, there is little time available to document the causes of clashes due to time pressure (Tommelein and Gholami, 2012).

Previous research has employed different research approaches to capture this tacit knowledge. These include conducting expert interviews to produce a record of knowledge (Lindlof and Taylor, 2010), conducting observational techniques (without interruption) to capture the spontaneous nature of a particular process or procedure (Awad and Ghaziri, 2007), and asking practitioners to perform a think-aloud approach and verbalize their thoughts and considerations while going through a task (Ericsson and Simon, 1984). Finally, some propose using a repertory grid technique, with a table-based format, to represent practitioners' reasoning about a particular problem (Liou, 1992). Despite the wide range of benefits each method provides, they generally fail to capture the knowledge created during the execution of a project as they fail to integrate knowledge capturing strategies with the current tools practitioners use in a "live" setting (Korman et al., 2003; Wang and Liete, 2014). In addition, some (Wang and Liete, 2014) attempt to provide a repository platform for storing physical design issues identified during clash detection, creating different tags and storing various 3D viewpoints relating to each clash. However, their approach fails to address more complex design coordination issues that go beyond clashes, which often comprises most of the issues being discussed in the coordination process. Additionally, and their tools do not incorporate the current tools teams use to capture design coordination knowledge and details regarding each design issue.

4.3 Methods

Our research approach involved two steps: (1) design coordination issue taxonomy construction, and (2) evaluation and validation of findings (Figure 47). We employed a mixed-method contextualist research approach that involved iterative grounded theory and coproduction of knowledge within research cases (Green et al., 2010). We conducted an ethnographic case study of two building projects that included observation of design coordination meetings throughout the design process. We continuously compared collected data and searched for resonance with conceptual ideas derived from ongoing literature searches. Specifically, the research involved observation of design coordination meetings, construction document tracking, BIM analysis, and in-depth qualitative analysis of meeting segments. We analysed the collected data, labeled our findings and performed axial coding and data enrichment. In terms of evaluation and validation, a think-aloud observation of practitioners preparing design issues (Lewis and Mack, 1981), inter-coder reliability testing, and expert reviews were employed.

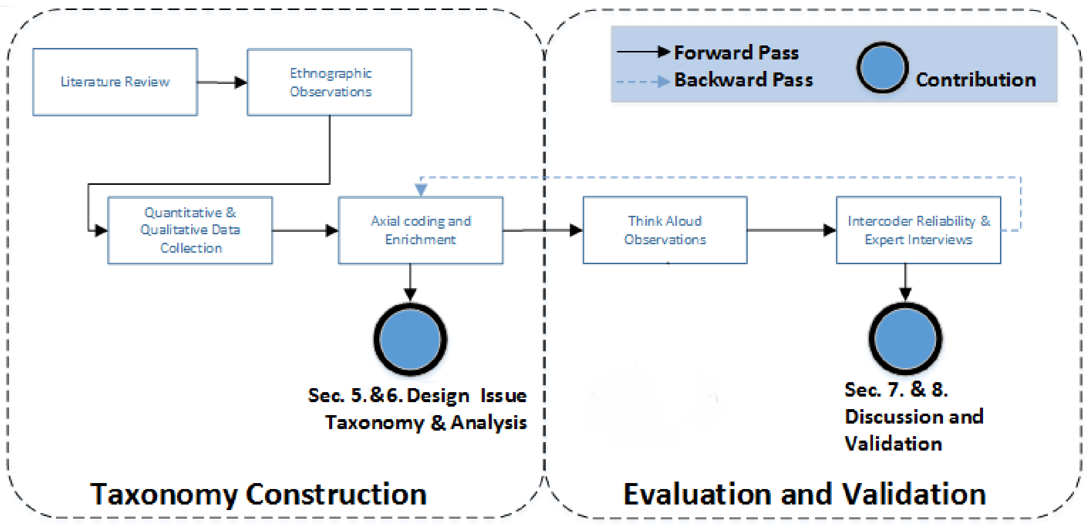


Figure 47: Methodology implemented in this research included two phases: (1) taxonomy construction and (2) evaluation and validation. Section numbers refer to the sections within chapter 4.

4.3.1 Case Studies

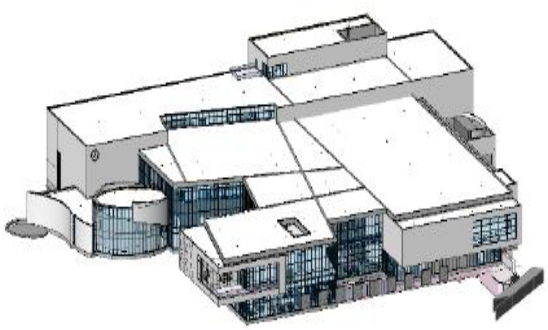
In this sub-section, we introduce the two case studies we observed, including the specifics of the design coordination process, the meeting environment, the tools used, and our involvement in each case. The projects had considerably complicated MEP systems along with unique architectural designs that made design coordination and constructability key concerns on these fast track projects. Over the course of design and construction, BIM was used extensively to coordinate designs from different consultants and sub-trades. In both case studies, the meetings typically had 6 to 9 participants from different disciplines, including the general contractor, consultants, and subcontractors. In terms of leadership of the meetings, the MEP Coordinator was in charge of overall coordination of building design issues, and the BIM Coordinator was in charge of integrating the BIMs, clash detection, and navigating the 3D and 4D models during meetings.

The case studies focused on different stages with one case study focusing on the design to mid-construction stage, and the other from mid-construction stage to end of construction stage.

These case studies were chosen to capture the breadth of design issues practitioners encounter at different stages of design coordination. On both projects, there was early engagement from construction trades and the expectation was that trades would implement BIM to fabrication level (LOD of 350 to 400).

4.3.1.1 A - Royal Alberta Museum

The newly constructed Royal Alberta Museum (RAM) building project is a 25,349 m^2 building located in downtown Edmonton, Alberta, on a site measuring 20,024 m^2, which will be the largest museum in western Canada (Figure 48). The project was a design build delivery and involved early and active engagement from most of the key trades. We remotely participated in the design coordination meetings, recorded and observed participants conducting design coordination, and analyzed relevant project documentation, construction drawings, and BIM files. We were involved from the planning phase through completion of building structure but prior to enclosure of structure and finishing stage of the building.



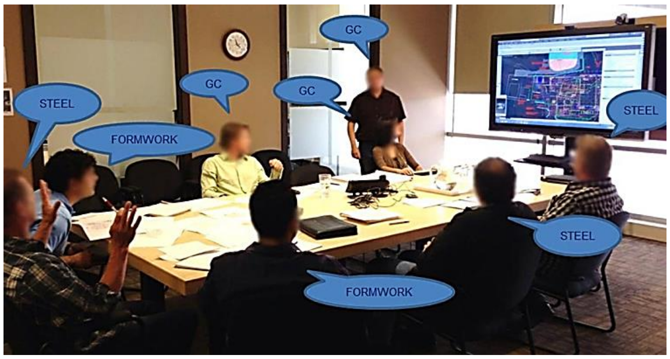


Figure 48: The Royal Alberta Museum - an architectural model of the RAM project that was used to validate the research findings (left) and a snapshot of design coordination meeting environment for the RAM case study (right) (GC indicates general contractor).

4.3.1.2 Case study B - UBC Pharmaceutical Building

The second project was the Pharmaceutical Sciences Building on the campus of the University of British Columbia. The 18,000 m^2 facility provies a variety of teaching and learning spaces from lecture halls and seminar rooms to a pharmacy clinic and three floors of research laboratories (Figure 49). The project was a construction management delivery and the MEP trades were engaged early in the design process. We observed meetings in-person and remotely, recorded and observed participants during design coordination, and analyzed relevant project documentation, construction drawings, and BIM files.

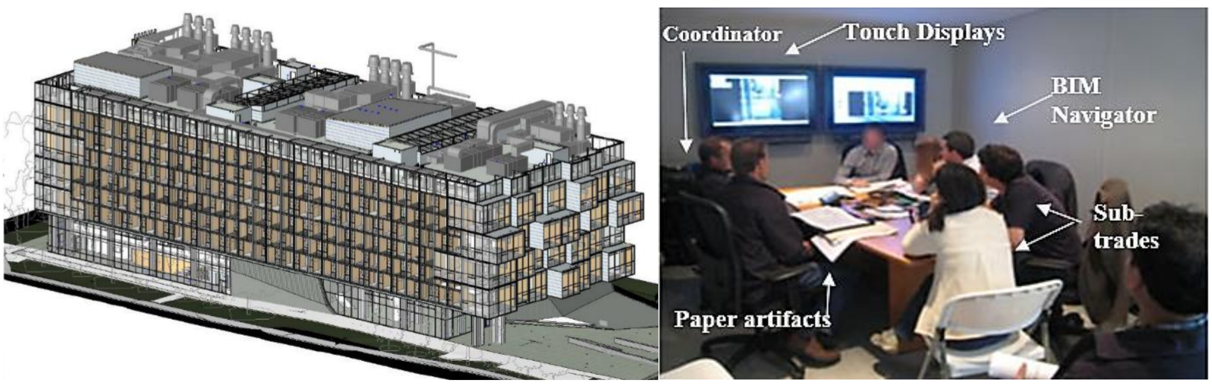


Figure 49: Integrated BIM model of the UBC Pharmaceutical Building (left) (image courtesy of Hughes Condon Marler Architects) and BIM Trailer used during design coordination on site (right).

4.3.2 Ethnographic Observations

Our understanding of the current practice of design issue resolution was based on observations of the building design coordination team during their coordination meetings throughout the design and construction stages for both case study projects. We investigated how coordination issues were identified and communicated among the project team and how the team presented and resolved issues. We also investigated the team's documentation approach and follow-up regarding each issue. We considered each issue first and tracked how that issue was identified through analysis of the BIM files of each meeting, how the issue was resolved through observation of specific segments of the meeting related to that issue, and by analyzing participants' notes and issue documentation spreadsheets regarding each issue.

4.3.3 Data Collection and Analysis

An ethnographic approach was chosen to collect the "richest possible data" (John and Lofland Lyn, 1984) and to observe meeting participants in their natural setting (Denzin, 1970). In both case studies, we rigorously analyzed BIM files, construction communications, RFIs, meeting minutes, and other communications among project participants. Once we observed the meetings (remotely, recorded, or in-person), we went back to prior communications among project participants and tracked how design issues were communicated among the teams. In addition, we tracked BIM changes, design issue spreadsheets, emails, and internal memos. We took detailed field notes on BIM utilization, as well as on the interaction among participants. We observed and video recorded over 90 weekly design coordination meetings, with a typical length of 100 to 140 minutes long, from the early stages of design through construction of the building systems. We had access to construction documents, BIM files, site progresses, design issue spreadsheets, and internal emails distributed among project participants. We also collected and analyzed all information that circulated among meeting participants such as logs of design coordination issues, clash detection logs, e-mails about the coordination schedule, and digital snapshots of the digital model showing clashes between different building systems. In addition, with access to BIMs, internal communications, post meeting notes, and informal interviews of participants on both projects, we were able to gain a deeper understanding of detailed interactions with design artifacts and the low-level mechanics of design coordination processes. In terms of an analysis of project documents, we tracked integrated BIM from each of the design coordination meetings to identify the changes made, analyzed the memos and communications among stake holders through word by word scanning, and pin-pointed documented design coordination issues to BIMs and meeting segments. In total, we analyzed 98 issues from case study Pharmacy, which was at a later stage, and 120 issues from case study RAM which at an earlier project stage.

Once we tracked our case study observations, we transcribed them through verbatim recordings of all actions, dialogues, and details regarding design issues. We later labelled each design issue based on in vivo open coding, using a word or short phrase taken from that section of the data itself (Phelps et al., 2010). The aim of creating an in vivo code (label) was to ensure that concepts stay as close as possible to the research participants' own words as the labels can capture a key element of what is being described (Given, 2008). Table 14 demonstrates how design issues were documented, shortened, and analyzed during the final stages of data collection.

Table 14: How this study encoded design issue labels, solutions, and status from the design coordination issues observed in the case studies

Issue:	Issue Label	Solution	Solution Label	Issue Status
Multiple electrical trays and mechanical services clash	Repeated Patterns	Lower cable tray	Repositioned	Resolved
Duct overlap, lower cable tray	Occupying Same Space	Remove cooling ducts	Removed Item	Resolved
Multiple sprinklers clash with duct and pipe	Repeated Patterns	Lowered sprinkler but still clashes	Repositioned	Unresolved
Electrical tray clashes with mechanical ducts	2 Objects Clash	Make the tray higher	Repositioned	Resolved
As built required / what is heating pipe size?	As Built Inconsistency	Lower the ceiling, still clashes	Repositioned	Unresolved
Multiple clashes B duct, cable tray, grills	Repeated Patterns, Un-coordinated Designs	Ceiling type to be reviewed - tray to be stopped	Removed Item, Re-Routing	Unresolved

4.3.4 Axial Coding and Data Enrichment

As the first step for enriching our coded data, we analyzed the frequency of how often a code (label) had been applied (Okendu, 2008). Further, we aligned codes with related contents to form higher level "concepts" using axial coding (Glaser and Strauss, 2009). This process yielded more than 40 label categories for design coordination issues and resolution solutions. By constant comparison of labels, and by using axial coding, we were able to merge similar categories and reduce the total number of label categories down to 15 codes. Later, by iteratively refining our data, consulting prior literature, and conducting expert interviews, we further reduced the total classification categories to 11. These classifications are shown in section 4.5.

4.3.5 Think-aloud Observations

Although the non-intrusive ethnographic data collection and analysis of design coordination meetings provided a rich understanding of how design coordination issues are resolved and documented throughout the meetings, the process prior to the meetings remained unclear. In order to gain deeper insights as to how pre-meeting issue identification and communications are handled, we conducted a think-aloud observation (Lewis and Mack, 1981). While a BIM Coordinator performed issue identifications on a high-rise multi propose facility in Vancouver (Figure 50), we asked the BIM Coordinator to tell us whatever he was observing, thinking, doing, and feeling as he performed the task. We observed how the BIM Coordinator performed 3D model integrations and clash detection, distinguished between true and false clashes, communicated with the project Coordinator to discuss each issue, and prepared the coordination meeting agenda. As the figure below shows, the BIM Coordinator went through issues one-by-one on the left screen and viewed them on the right to inspect the computer-identified *clashes* and identify larger scale *issues* that required further investigation and discussion at the meeting.

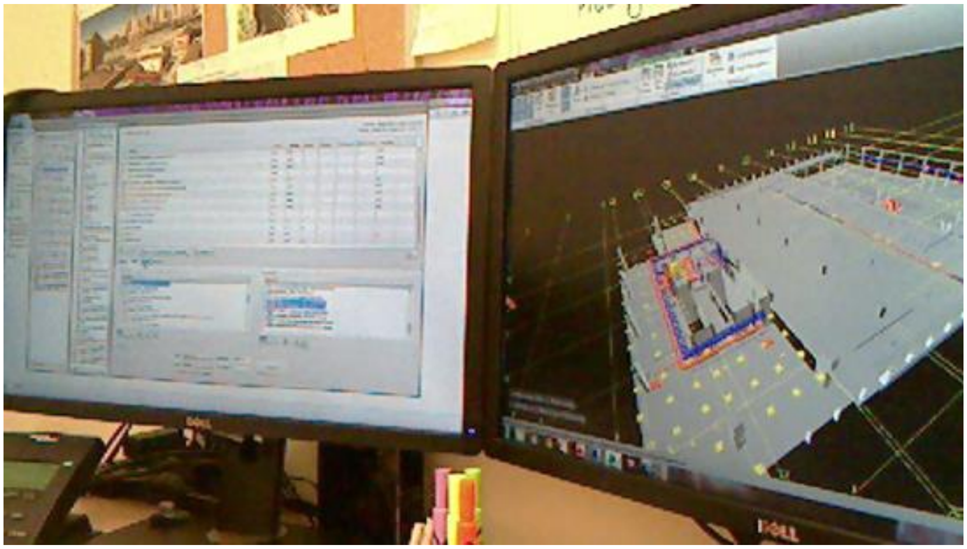


Figure 50: Observing a BIM Coordinator conducting issue identification. Reviewing the automatically identified clashes on the left and analyzing them on the right.

4.3.6 Inter-coder Reliability Testing and Expert Interviews

As further elaborated in section 4.3 of this study, we employed two user testing and validation strategies in order to ensure that our taxonomy can be applied by other coders and industry experts. For the first attempt for reliability testing, we coded 50% of the Pharmacy case study transcriptions with the categories that emerged from the RAM case study. In addition, we employed inter-coder reliability testing (Tinsley and Weiss, 2000) on 10% of the issues in the Pharmacy case study. During this process, we asked a mechanical engineer, who had sufficient BIM expertise, to code the BIM building design coordination issues based on our classification. Furthermore, we carried out 5 interviews with BIM and trade experts in the field and 3 interviews with other research members. The duration of interviews was between 50 to 90 minutes. Many prior researchers in the field have adopted this approach to ensure validity

(Howard and Bjork, 2007; Kreider et al., 2010; Wang and Leite, 2016). The details of our expert interviews and inter-coder reliability testing can be found in section 4.7.

In this section, we summarized our research methods that resulted in our design coordination issue representation, as well as analysis of design coordination issues (sec. 6), presented in the subsequent sections.

4.4 BIM-Based Design Coordination Process and Challenges

The design coordination process typically consisted of a cycle of three interconnected steps, as shown in Figure 51:

- **Issue Identification:** In a typical coordination process, the BIM Coordinator received 2D and 3D digital information, project requirements, and design specifications (e.g. the minimum ceiling height, clearance required to access and service equipment) to initiate the coordination process. They then integrated the models in Navisworks Clash Detector and the system automatically identified conflicts. Then, the BIM Coordinator then reviewed the relied on their own knowledge of design coordination issue the automatically detected conflicts and identify true physical conflicts as well as process and model-based design issues.
- **Issue Resolution**: In the second step, project stakeholders meet to review, discuss and develop solutions to resolve the identified coordination issues. Once the models are prepared and issues are identified, the project team discuss issues raised from the issue identification stage. Participants interact with three major design information representations, 2D digital, 3D Digital, and 2D physical (artifacts), and use their rationale to discuss and make decisions about each design issue, while interacting with state of the art tools to navigate and transition between different views.

- **Issue Documentation**: Finally, once the discussion on the issue reached an end, the BIM Coordinator documented the issues. At this point, based on their understanding and documentation strategy, they filtered the necessary information as to which issue to capture, what details to record, and who to hold accountable. They also tracked each design issue separately and prepared them for the subsequent issue identification stage.

Figure 51: Three critical steps in the BIM-based design coordination process. Design coordination issue identification, resolution, and issue documentation.

The current approach to identify design coordination issues using the automated clash detection function often results in thousands of conflicts between building and system components as (Figure 52) shows, only a small fraction of these represent actual conflicts between different systems, and the reminder contain many repeated or erroneous detections known as 'false positives' (Leite et al., 2011). Project Coordinators and BIM Coordinators eliminate these false positives and investigate actual clashes one by one to determine which design conflicts lead to potentially bigger design issues between building systems. We refer to these issues as 'process-based' design issues when they are caused by the process of BIM creation, and 'model-based' design issues when they are caused by deficiencies in the BIM. We have found that many process-based and model-based design coordination issues are the results of further examination of actual clashes.

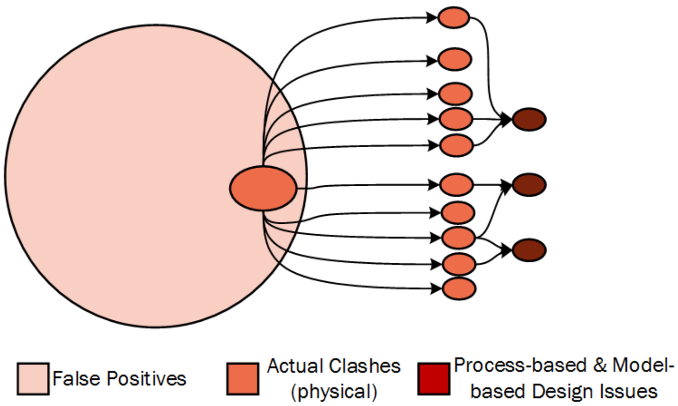


Figure 52: Graphical illustration of how design coordination issues evolve by filtering out 'false positives', identifying 'actual clashes' and then, in some cases, leading to more complex 'process' and 'model' based design coordination issues

Figure 53 provides a specific example illustrating how issues evolve from a clash into a process or model-based design issue. Image 1 on the left shows a 'clash' between the duct and cable tray. The BIM Coordinator examined it in detail and found that the duct could not be moved as it collides with other building systems. Further examination revealed that the building systems were congested near the column cap and the BIM Coordinator communicated the issue to the MEP Coordinator (Image 2). The MEP Coordinator inspected the issue, and then communicated the issue by sending a snapshot of the relevant systems (Image 3) to the different disciplines with a request for a group discussion. This particular design issue took over 3 weeks to resolve. This example demonstrates how a physical clash of two building components often leads to a more complex process-based design coordination issue.

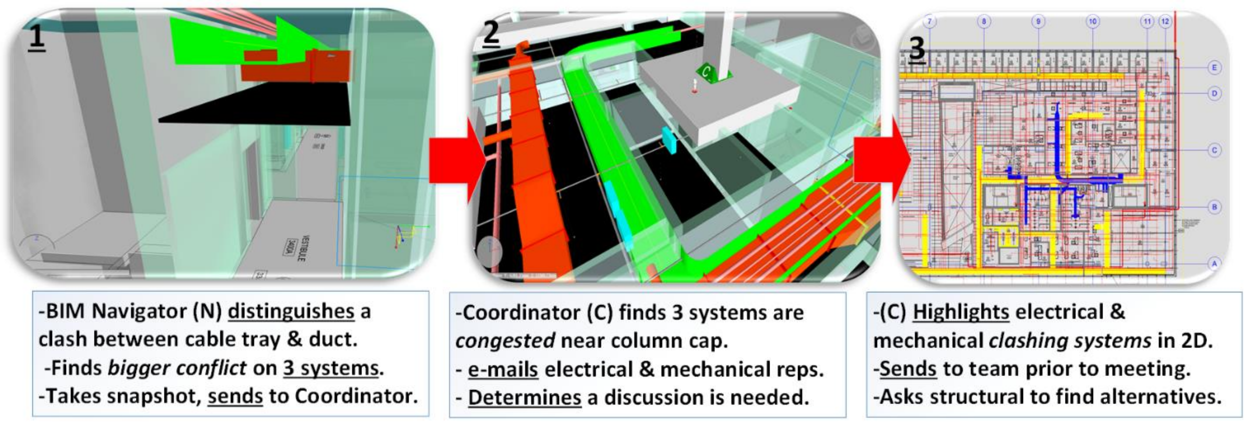


Figure 53: Example of how a simple coordination clash leads to a more complex design issue. Underline indicates actions taken, italics indicates more complex design coordination issues resolution

As described above, despite numerous advantages of BIM for design coordination, our observations of case studies have revealed that practitioners still face notable challenges in the current process of BIM building design coordination, including:

- *Unclear characterization of design coordination issues*: Coordination issues vary by complexity, priority and severity, and result from physical, process, and model based design coordination issues. We found that the scope, priority, and rationale of design issues were rarely defined. Practitioners often had difficulty relating to the design issues. They initially needed help understanding the relationship between the initial 'clash' to the more complex process-based and model-based issue context. There also were many instances where terminology and inability to categorize design coordination issues caused time-consuming errors.
- *Inefficient design coordination issue resolution*: Our observations reveal inefficiencies in how practitioners follow up on previously discussed design coordination issues. As Figure 54 demonstrates, a design issue was recorded regarding a confined space under slab bands and dropped ceilings that involved the ductwork and electrical contractors.

Initially, the snapshot with a description of the issue was recorded (shown as documented) on the first meeting (number n). One week later, the electrical trade asked for the reason why this issue was flagged; on meeting (n+2), the mechanical contractor stated they could not find the viewpoint and whereabouts of the design issue; eight meetings later (n+10), the Coordinator proposed a solution to help with resolution of the design issue. This design issue was never documented as resolved.

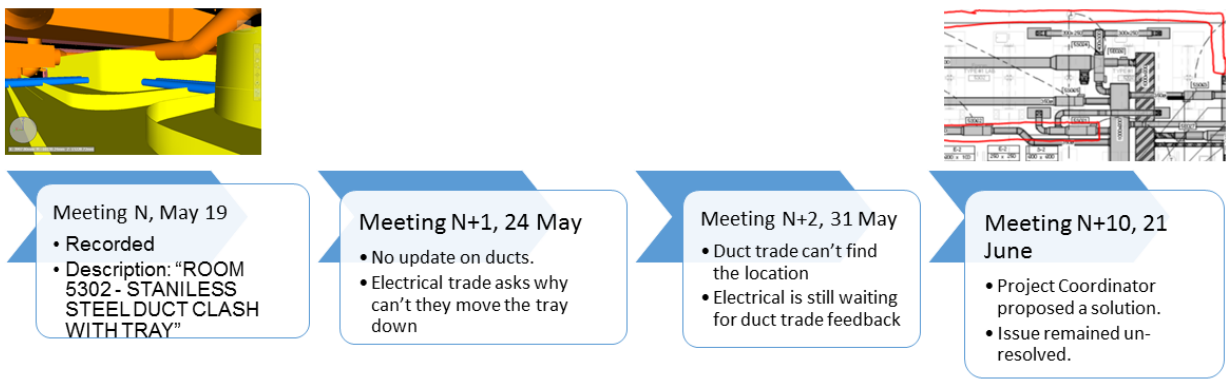
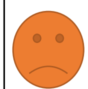


Figure 54: Example illustrating the slow progress of a design coordination issue resolved over many meetings.

- *Insufficient issue documentation*: We found participants' knowledge of how different systems work together and the protocol and tools for documentation affected how design issues were noted, followed up on, and resolved prior to construction. In addition, when design coordination meetings were poorly documented, the result had a direct impact on issue identification at the next meeting. When meeting participants were asked to comment on the spreadsheet of documented design issues, they stated that they did not have sufficient understanding about what the document represented. As one interviewee stated, *"this spreadsheet is really ambiguous. I do not understand most of the design issue scopes. They really need more detail in description"*. Table 15 highlights the details captured by the BIM Coordinator for the design issue shown in Figure 53, which includes the location, involved systems, snapshot(s) if available, entry and solution dates, status, and a brief description of how it could be resolved.

Table 15: Typical design issue documentation shared after the coordination meeting

CLASH No.	RECEIVED DATE	DESIGN DWG REF#	DESCRIPTION	PLAN / SECTION/ 3D	REQUIRED BY WHO	RESOLVED DATE	STATUS	DESCRIPTION
3 EAST B	21ST APRIL	A2.13 E4.04 M2.08 M2.09 P2.05	LEVEL 3 EAST THIRD FLOOR CABLE TRAY TOO LOW AND CLASH WITH MECH DUCT ALONG COL GRID 9 BETWEEND C & D		ELECTRICAL	21ST APRIL		CABLE TRAY TO MOVE OVER TO MAIL ROOM. WPE TO ALTER TRAY ROUTE

- *Inefficient communication among stakeholders*: Similar to Dossick and Neff (2010), we found insufficient communication among stakeholders contributed to an inefficient design coordination process. One interviewee mentioned, *"While issues were identified, we did not know how important they were, often we did not know the urgency of these issues and how vital their resolution is."* Moreover, both our observations and interviewee feedback revealed that there is insufficient communication across the same building system. The same interview stated, *"Often, the discipline is done by the same trade, but goes to different sections, so their models are largely clashing with each other."*

In this section, we outlined the challenges of BIM-based design coordination through a series of case study observations. We found that these challenges impeded the efficiency of design coordination, and limited the utility of the knowledge captured. In the next section, we present our taxonomy for characterizing design issue representation.

4.5 Characterizing Design Coordination Issues

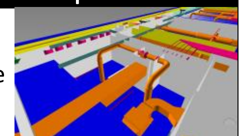
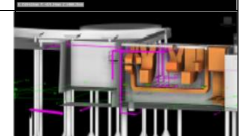
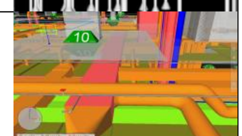
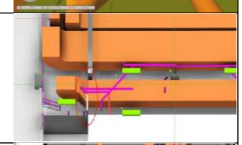
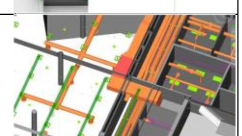
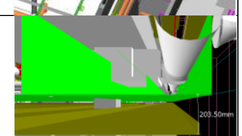
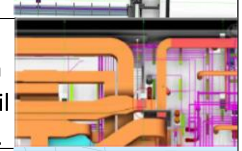
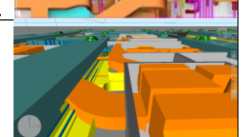
Based on our analysis of design coordination issues from both case studies, we developed a taxonomy to classify the BIM-based building design coordination issues that builds on and extends the work of others. Specifically, our taxonomy builds on the findings of Korman et al. (2003), Tommelein and Gholami (2012), Wang and Leite (2016), and Lee et al. (2012) to better capture process-based and model-based design issues. As Table 16 illustrates, we have identified three major categories of physical, process and model-based design coordination issues. The 'physical' coordination issues typically detected using the clash detection functionality of BIM tools while the 'process' and 'model' based categories typically require further investigation of the design. We identified several new types of coordination issues, which are shown in bold in Table 16 and briefly described below:

- *Repeated clash*: Repeated clash issues are best described as patterns or groups of physical design issues within building systems. This frequent design issue often indicates a substantial design change of the building system involved. For instance, as the sample in Table 16 shows, when the ducts collided with structural columns, all ducts involved had to revise their route to accommodate the space limitations. The identification of this design coordination issue was often initiated by observing multiple instances of the same clash in the clash detection function, and typically required feedback and expertise of multiple building trades.
- *Multiple-systems conflict*: This type of design coordination issue refers mostly to attempting to fit multiple systems within a confined space. Examples of confined spaces include ceiling areas in labs, theatre rooms, and mechanical rooms. The resolution of this type of design issue typically took a long time, required the feedback of multiple project stakeholders, and often involved fundamental changes to systems.
- *As-built Inconsistency*: Often what occurred on site (due to space, resource, or technical) did not match with the initial design. As-builts were mostly missing when BIM creation

and coordination occurred in a similar timeline as construction of the building. These design issues frequently stopped the flow of design coordination until a request for information was returned from site or the entire system and area were updated with what had been built.

- *Missing information*: Although missing information about various building components has been discussed in prior literature (e.g., Hartmann and Fischer (2008), we believe the frequency and scope of this issue requires a well-defined category and scope specifically for the design coordination process. The processes of how building systems work together—and are installed or maintained—was often missing from the BIM, creating a dilemma among trades and requiring further input from other responsible trades. We refer to missing items as un-modelled BIM components or missing building systems, whereas missing information refers to a lack of sufficient information, such as missing guidelines, codes, installation or maintenance processes, or required clearances.

Table 16: BIM-based building design coordination issue representation taxonomy. Bold font indicates issues not previously identified in prior work. Notations: 1: Korman et al (2003), 2: Tommelein and Gholami (2012), 3: Wang and Leite (2016), and 4: Lee et al (2012)

Category	Sub-Category	Description	Example	Snapshot
Physical	Temporal [1,2]	2 or more components occupying the same space-constructability /operability issues.	Duct collide with the cable tray. Tray to move down.	
	Functional [1,2]	locations of components jeopardize the intended function of component	Location of heating unit next to HVAC duct interferes with function of systems.	
	Clearance [1,2,3]	Components interfere with extended spaces (e.g. Access).	Plumbing conflicts with access ladder, due to insufficient space surrounding it.	
	Clash [1,2,3]	Single conflict of 2 systems. Only 2 trades required to resolve in the meeting.	HVAC duct collides with structural column cap.	
	Repeated Clash (es)	Substantial conflicts of 2 or more systems which require e-design of a system(s).	All ducts conflict with structural columns. Zone C ducts require redesign.	
Process	Design Error [4]	2 or more building systems designed independent from each other.	All level 3 mechanical ducts conflict with structural concrete beams.	
	Multiple Systems Conflict	Multiple building systems can not fit in confined space.	Heating, hot water, sprinkler, cable tray all required to fit in ceiling under slab band.	
	Design Discrepancy [4]	Design Information on trade designs do not match.	Structural floor opening is not designed big enough for mechanical duct.	
Model	**As-Built Inconsistency**	The built system on site does not match the BIM.	Duct openings in wall panels are moved when built. Routing stops until as-built location known.	
	Missing Items [4]	Details related to components, or parts of BIM are missing.	Dimensions of mechanical component not specified. Elect. Fixture are missing.	
	Missing Information	Lack of sufficient information about building system(s) stop coordination & building	How do building users control HVAC unit above? is noise level a concern?	

To better understand the relationships between the different types of design issues, we developed an ontology. As described earlier, the physical design issues were the ones leading to more complex design issues. The arrows on Figure 55 show the ontology of design coordination issues. The ontology highlights the relationship and possibility of some coordination design issues being a subtype of another. For instance, an issue related to multiple-system conflicts could contain smaller conflicts of clearance and functional issues. This relationship is of significance since during inter-coder reliability and expert interviews of this study (see Section 4.7), both the coder in the experiment and the interviewees initially had difficulty classifying various design issues during experiments; once the participants fully understood the relationship, the classification of design issues became easier. In addition, the figure shows the design issues that can be identified using state of the art BIM tools in the bottom rectangle, and the remaining issues that require further expert involvement are placed on the higher level. The figure also elaborates on the significance of how smaller scale design coordination issues (often detected by state of the art BIM tools) lead to more complex design coordination issues.

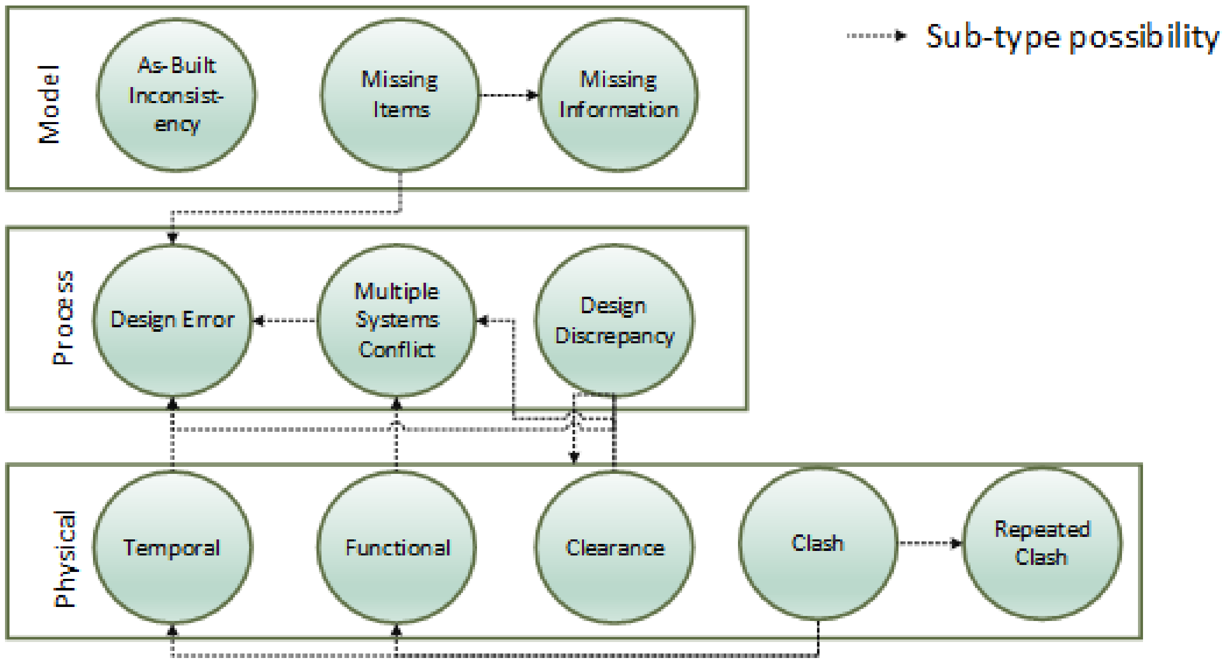


Figure 55: Ontology that represents the potential relationships across the design issue categories.

This section described the formalization of design issue types; next we apply this formalization to the case study projects to better understand how the types of issues affect issue resolution.

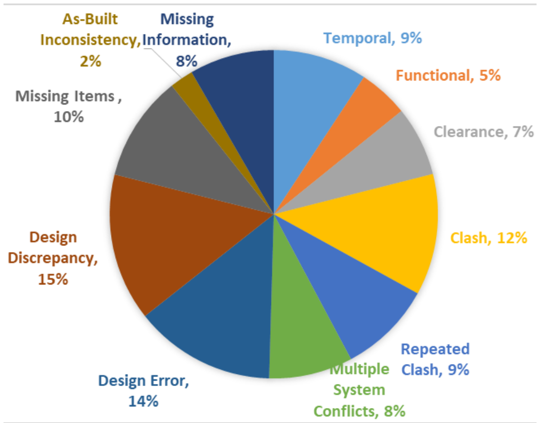
4.6 Analysis of Design Coordination Issue Resolution

We applied the design coordination issue taxonomy to the case studies to identify the frequency of issue types, the distribution of issue types across the disciplines, and the resolution rates of issue types. We investigated the issues in each case study independently based on what the practitioners documented and our own observations of the meetings. The analysis was iterative, requiring us to revisit issue categories, terminology, and examples multiple times. As mentioned in the methods section, we analyzed 120 issues from the RAM case study and 98 issues from the Pharmacy case study.

4.6.1 Analysis of Design Issue Type Frequency

As the first stage of analysis, design coordination issues were analyzed based on the categories outlined in the taxonomy. We present these findings in two forms, collectively and per case study. In terms of all design issues analyzed collectively (Figure 56-left), *design discrepancy*, *design error*, *clashes* and *missing items* were respectively the most common type of design coordination issues across both case studies. On the other hand, the least common design coordination issues types were *as-built inconsistency*, *functional*, and *clearance*. In total, 46% of the design issues were comprised of process-based, 21% were model-based, and 33% were physical design coordination issues. It was also evident that physical design coordination issues were often the beginning of a larger discussion that led to process and model based design issues.

In terms of individual case studies (Figure 56-right), both projects had nearly equal proportions of process-based design issues, which included *design errors*, *design discrepancy*, and *multiple-system conflicts*, with the most common design coordination issue type across both case studies as *design error*. *Design discrepancies* (e.g., wrong opening sizes) were 41% more frequent in the Pharmacy case study compared with the RAM case study, and *missing items* were more frequent in the RAM case study. The nature of design issues handled by each team varied since the Pharmacy case study was in the finishing stage and finalization of MEP placement, whereas the RAM case study was mainly in early design coordination stages and prior to MEP system placements and building enclosure, at the time of this study. Hence it is not surprising to see the Pharmacy case study's temporal design issues (constructability) half the size of temporal design issues in the RAM case study. Also, missing information design issues were more frequent in the Pharmacy case study, which could be due to the final stages of the project as multi-project stakeholders require the BIMs to be fully equipped with dimensions, components, and latest design changes. Few as-built inconsistency design issues were found in the RAM case study, since there was less construction progress at the time of our observations.



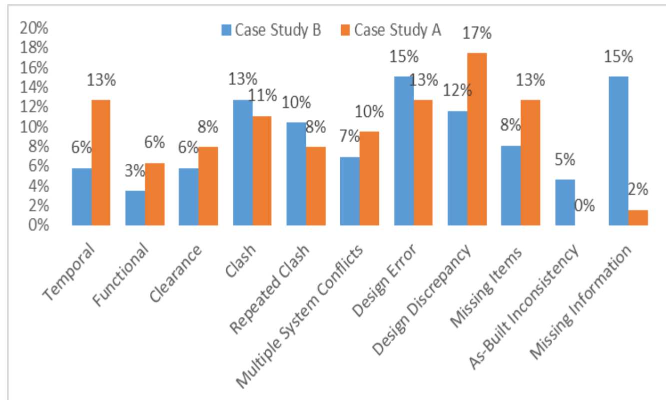


Figure 56: Left- percentage of all design issues types analyzed across both case studies. Analyzed BIM-based design coordination issues in case studs based on frequency of occurrence (% of total issues analysed)

Missing information made up a significant portion of design issues in both case studies. We found 15% of the design issues in the Pharmacy case study and 9% of design issues in the RAM case study to be comprised of *missing information*. These issues included questions regarding RFIs and the model, installation, or performance of components. In addition, we found *repeated clash* to be a frequent factor in both case studies (10% in the Pharmacy case study and 8% in the RAM case study). Our findings showed that 13% and 15% of design issues on RAM and the Pharmacy case study respectively to be comprised of *design errors*.

4.6.2 Analysis of Design Issue Type Distribution across Disciplines

We also investigated the correlation of how different project trades took responsibility for resolving various issue types (Table 17). As the table shows, frequency of involvement of each trade to resolve specific design coordination issues are presented using different shades of grey. The table also elaborates on general involvement of each trade, it is noteworthy that the construction management teams were rarely involved in resolving design issues outside meetings themselves. Also the structural design team was actively involved in resolution of various design issues in the Pharmacy case study, compared with rarely taking responsibility in the RAM case study. this is surprising since structural designs in the Pharmacy case study were already finalized and the structure was built when the design coordination of issues were being conducted.

Unsurprisingly, *missing items* required the most attention from all trades during both case studies, mostly when trades were required to complete BIMs. Furthermore, it appears that the ductwork trade took the most responsibility followed by the electrical trade when resolving design coordination issues. In terms of the most common type of design issues resolved by each trade, we found the following:

- the architectural team took responsibility for *missing information* and *multiple systems conflicts*;
- the HVAC team took responsibility for *design discrepancy* and *design error* issues;
- the electrical team uniformly took responsibility for all design issues;
- the fire protection team took responsibilityfor *missing items*,
- the plumbing team took responsibility for *design discrepancies* and *functional* design issues,
- and the structural team mainly resolved *design discrepancy* and *design error* issues.

It is also worth mentioning that by nature, some trades had more flexibility with their designs compared with others, and the flexibility impacted how they were held responsible during design coordination. For instance, the fire protection trade had less tolerance and flexibility to move their components as per building code whereas ductwork could re-routed form different locations and still accommodate the required air quality.

Table 17: Issue types in each case study versus the trades held responsible. The darkness of each cell indicates frequency of occurrence. CM: construction management. Case study A: RAM, B: Pharmacy.

	Architectural		Duct-work		Electrical		Fire protection		Plumbing		Structural		CM	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Clash														
As-Built Inconsistency														
Clearance														
Functional														
Missing Information														
Design Discrepancy														
Missing Items														
Multiple System Confl.														
Repeated Clash														
Temporal														
Design Error														

4.6.3 Analysis of Design Issue Type Distribution across Locations

We further investigated the location of where design coordination issues took place. As Figure 57 presents, on the left, design issue location of the RAM case study, and on the right, design coordination issues in the Pharmacy case study are shown. Design coordination issues in the RAM case study were recorded more broadly, indicating the floor only, but in the Pharmacy case study the floors were divided to 5 zones of east, west, north, south and center. Although both case studies used Grids in BIM to able to locate components in BIM, we found dividing floors in the Pharmacy case study, made understanding locations easier for trades and site staff who were less BIM savvy. Interestingly, design coordination issues occurred across more floors and zones in the Pharmacy case study, whereas almost two third of design issues were concentrated in just two levels of the RAM case study, although level 4 on the Pharmacy case study, had almost the same concentration of design coordination issues of levels P1 and 1 on the RAM case study. It is also worth mentioning that due to complexity of building systems, datacenter and vivarium on the Pharmacy case study, they were assigned a special zone, 4% of total design coordination issues occurred in these areas.

Upon closer examination of the location of design coordination issues in the Pharmacy case study, it appears that level 4 East was the location of the mechanical room, and level 4 west, was the location of components that lead to the mechanical room, which had to be fitted under the condensed space between slab bands and ceilings. In addition, on the RAM case study, the mechanical room was placed on parking 1, which could explain the high number of design issues on that level. Also, analysis showed that due to unique structure of the main floor (level 1) which had round staircases and open spaces, building mechanical systems especially pipes and ducts connecting mechanical room from parking 1 to the rest of the building, had to be fitted between extensive structural steel and concrete and complex architectural design of level 1. Based on the location of mechanical rooms in each building and the distribution of design issues, we can confirm that the mechanical rooms are in need of intense design coordination, as well as the spaces leading to the mechanical rooms (e.g. adjacent zone and levels) have high distribution of design coordination issues.

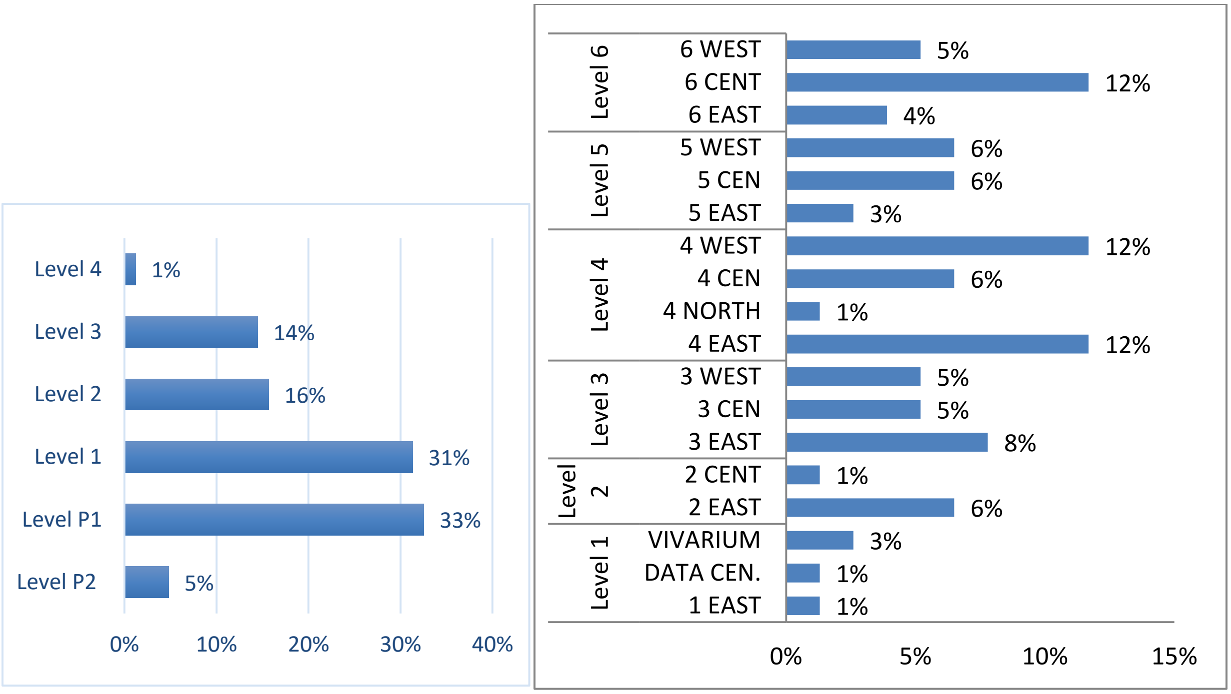


Figure 57: Left- location of design coordination issue occurrences in the RAM case study. Right- location of design coordination issue occurrences in the Pharmacy case study. The size of each segment shows percentage out of all design issues.

In this sub-section, we analyzed the design coordination observed in the case studies based on our developed taxonomy. The next section describes the results of analysis of design issue resolution rates.

4.6.4 Analysis of Design Issue Resolution Rate

We found that by the end of the last design coordination meeting in the Pharmacy case study (which was two months before construction was completed), 28% of documented design coordination issues were still unresolved. All un-resolved design coordination issues were model-based and process based design issues. As described earlier, if these design coordination issues are resolved on site, they typically impact cost and time on the project. Therefore, an issue resolution rate analysis was conducted to better understand how often design issues were added, resolved, and how many remained unresolved by the end of each meeting. This was performed by tracking and analyzing issues of 21 consecutive design coordination meetings of the RAM case study, and 12 consecutive design coordination meetings of the Pharmacy case study (Figure 58). The 12 meetings of the Pharmacy case study were the last design coordination meetings before construction completion.

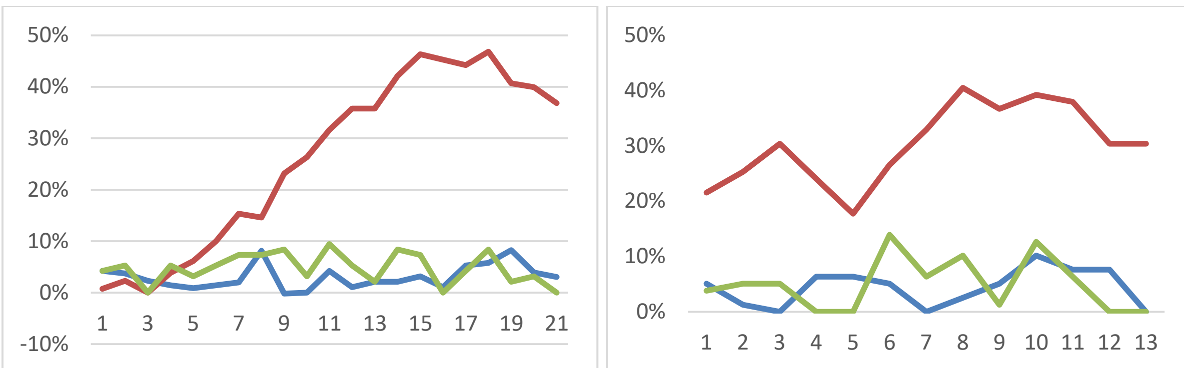


Figure 58: Left- Issue resolution rate in 21 consecutive meetings in the RAM case study. Right- Issue resolution rate in the last 12 consecutive meetings in the Pharmacy case study. Blue: % of resolved issues per meeting, Green: % of new issues added, Red: % of total design issue

As Figure 58 demonstrates, the number of design coordination issues resolved or added remained consistently below 10 to 15% of all design issues, however, the number of unresolved issues in both case studies increased as meetings progress. This suggests that a large portion of unresolved issues were resolved on site without further discussion in meetings. In addition, participants often spent one entire meeting on resolving one large-scale design issue, whereas sometimes they resolved more than 11 issues per meeting, or added over 10 design coordination issues at once. This highlights the complexity of some design issues over the others. Both case studies had almost one third of the design coordination issues as unresolved by end of design coordination process.

In addition, since the analysis of issue resolutions revealed that a large number of design issues remained unresolved, we conducted further investigation to identify the categories of each design coordination issue. Figure 58-(left) illustrates the ratio of design issue types remaining unresolved per design issue category by the end of construction on the Pharmacy case study. The highest number of issues remaining unresolved belonged to *design discrepancy*, followed by *missing information*, *design errors*, and *repeated clash*. As the figure shows, 67% of the *design discrepancy* issues identified at meetings remained unresolved by the end of construction. Also, 50% of the identified *repeated clashes* remained unresolved by the end of construction. This finding is crucial and surprising due to the urgency of rectifying design discrepancies; they often are comprised of multiple conflicts within various building systems and required extensive time and effort to resolve.

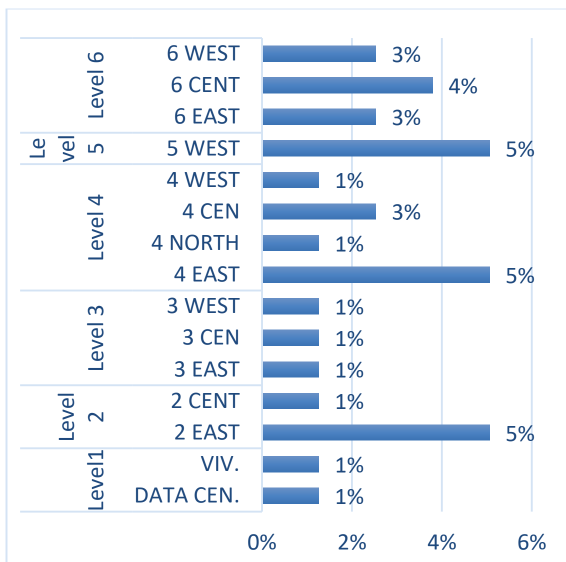


Figure 59: Left - Percentage of design issues remaining unresolved per all design issues in each issue category on the Pharmacy case study. Right - Distribution of unresolved design issues across various levels and zones on the Pharmacy case study.

The most unresolved design coordination issues were related to *design discrepancy*. It is significant to rectify design discrepancies, since they often are comprised of multiple conflicts within building systems. It is surprising to see that 65% of the design discrepancy issues remained unresolved by end of construction, because resolution of such issues directly impacts construction, sequences, and multiple building systems. Furthermore, a considerable number of *missing information* issues remained unresolved. When a design detail or information was missing, the resolution process was often disrupted, requiring team members to revisit the design issue at a later meeting or via correspondence. Although it is reasonable that missing information could have been responded to in a different format—such as private emails or phone calls—we could not observe and verify these issues as resolved.

Furthermore, Figure 59-right shows the distribution of unresolved design coordination issues per level and zones by the end of the last design coordination meeting we observed. The greatest number of unresolved design issues were on Level 4, specifically Level 4 East, which is the location of the mechanical room. Next, Level 6 Center, West and East had the highest concentration of unresolved design coordination issues. Upon further examination, most of these unresolved issues were consisting of *design discrepancy* and *repeated clashes* related to condensed space above the ceilings of Level 6. Most importantly, the distribution of design coordination issues per floor stayed the same. If we compare Figure 57 (right), with Figure 59 (right), the distribution percentage of all design issues versus unresolved design issues per level has remained consistent.

In terms of design issues that were not resolved by the last design coordination meeting, our analysis suggests that these design issues were addressed on the construction sites, resulting in additional costs and delays on the project. According to the interviewees, after handing over of the Pharmacy case study, the general contractor invited all construction trades back on site to evaluate the unresolved design issues and compare lessons learned. Most construction trades indicated that the issues resolved on site resulted in unexpected additional costs.

In addition to the resolution rate of the design issues as a whole, we investigated how long each design issue type took to resolve for the final 12 consecutive design coordination meetings of Case Study B. Specifically, each individual design issue was tracked and studied to identify how many subsequent design coordination meetings it took before being resolved. This involved tracking the BIMs, construction documents, and project records. As Figure 60 shows, *temporal* and *functional design issues* took the longest time to resolve and *missing information* took the shortest. It appears that physical design issues (temporal and functional) took longer to resolve compared with model-based and process-based design issues. Also, issues related to *design discrepancy*, *missing information*, and *clearance* took relatively shorter times to resolve; these issues often relied on one trade to complete their BIM, address the discrepancy, or provide enough clearance.

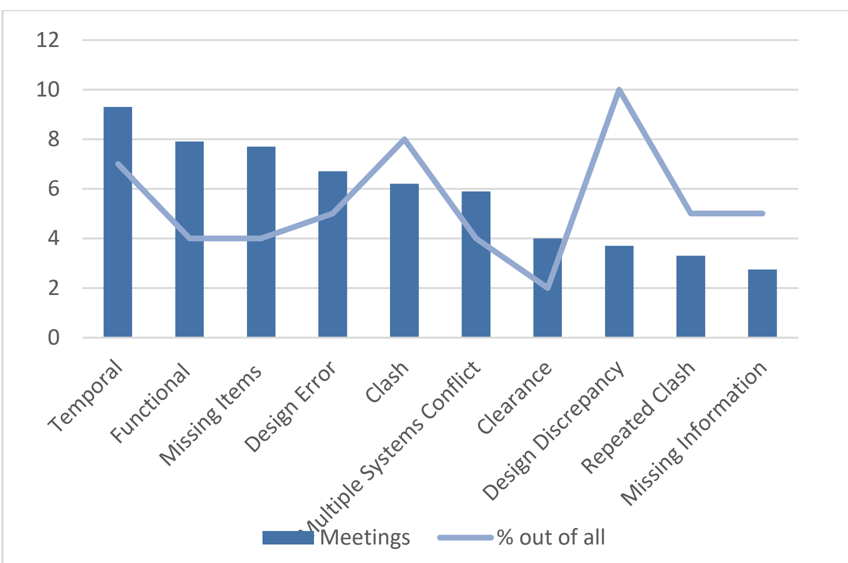


Figure 60: The average number of meetings it took to resolve design issues (bar chart). The line bar on top of bars represents the percentage out of all of the design issues we analyzed.

In this section, we have presented our analysis of the BIM-based design coordination issues on both case study projects. While having two case studies helped us to validate and evaluate the taxonomy, in the next section we present the results of our expert interviews and inter-coder reliability to elaborate on our validation strategies.

4.7 Validation

We validated the taxonomy provided in this study, as well as the identified contextual factors, by employing three approaches to validate of our findings, including employing reliability assessment, inter-coder reliability testing, and expert interviews. In terms of reliability assessment, we coded the Pharmacy case study transcription with the categories that emerged from the RAM case study. We were able to categorize all design issues based on our taxonomy emerging from the RAM case study. It is worth mentioning that since the observation of case studies were done simultaneously; we had a sound understanding of design issue types and the context of the Pharmacy case study, concurrent with production of the taxonomy.

In terms of inter-coder reliability testing (Tinsley and Weiss, 2000), we performed inter-coder reliability testing on 10% of the issues in the Pharmacy case study, which occurred during the later phase of this study at the same time as the creation of the taxonomy. During this process, we asked a mechanical engineer who had sufficient BIM expertise to code these issues based on the design issue taxonomy provided in this paper. We provided a brief description of our findings, the taxonomy, and some coded examples to the coder to initially train the coder, then asked them to code the design issues using the taxonomy. Once the coder finished with coding of the design issues, we then coded these issues ourselves and compared the two classification results together. The resulting Cohen's Kappa coefficient was 0.85, which is an acceptable value for reliability (Sabelli et al., 2011). The coder expressed concerns as to the relationship of the design issues presented in the taxonomy, which persuaded the authors to create the ontology illustrating the relationships between issue types.

In terms of interviews with experts in the field , most prior research in the field has adopted this approach to ensure validity (Howard and Bjork, 2007; Kreider et al., 2010; Wang and Leite, 2016). We asked three BIM experts, including MEP and BIM Coordinators involved in the case study, to evaluate the design issue taxonomy and compare their own knowledge and experience with our findings. We then asked them to code 20 design issues from both case studies using our taxonomy. We transcribed the interviews and analyzed the feedback from the experts. Similar to the coder, the interviewees also initially needed help understanding the relationship between process-based and model-based design coordination and physical issues. In terms of interviewee feedback, they found the issue representation taxonomy as a useful tool to classify BIM-based building design coordination issues, particularly in the issue identification stage prior to communicating the issue with the team.

The taxonomy also appeared helpful for them in terms of classifying the design coordination issues more rigorously when identifying design issues. However, they highlighted that the taxonomy may be best utilized when all trades involved were able to maintain a sufficient level of detail in BIM. One interviewee stated, *"to me this framework works best if minimum requirements are applied to project. You might have LOD 350 mechanical but it may lack the whole fire protection system. So it goes hand in hand. To me this is assuming a minimum set of pre-requisites are checked."* Specifically, the interviewees' feedback about the taxonomy was that *"with model-based design issues category (e.g. missing items, as-built inconsistency), you would never know as a BIM Coordinator what is missing. They only come up during the meeting. So it would be hard to capture them on model preparation stage."* In addition, one interviewee expressed interest on the *missing information* category: *"Oh I like this one inquiry/missing information. This is what I have always wanted to incorporate into the system".* Another interview mentioned: *"to me if BIM is on the project, this is useful and should be part of client requirement."*

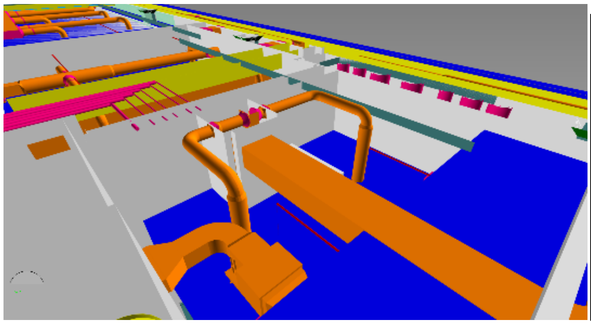
Finally, all interviewees identified classifications that were vague, or could be contained in other classifications. Hence, the taxonomy was re-iterated according to their feedback. During this process, similar classifications of specific types of design issues, were merged together to form broader classifications that could contain one or more prior categories. The total number of design issue classifications was reduced from an initial 15 categories to 12 categories.

In this section, we summarized the research methods employed to verify our findings and validate our taxonomy, ontology, and analysis. In the next section, we summarize our process, contributions, analysis and findings.

4.8 Discussion

In this section, we discuss the contextual factors that may have affected issue identification, documentation and resolution in the two case studies.

- **Fast Track Construction**: In fast-paced construction projects where design coordination and construction is completed simultaneously, the design coordination task is constrained by what has been completed on-site. For instance, as Figure 61 shows, in the Pharmacy case study parts of the ducts of the mechanical building systems were already fabricated in the shop and other components had to be fitted around these installed components. According to one interviewee: *"everything was already CNC'ed for ducts and we had to work around them, whoever went on site first, took all clearance and spaces, and all other trades had to go by what was built already."* We found a high number of *design* *errors* in the case studies caused by trades designing and building without consulting with other designs. Also, *design discrepancies* were often caused by trades assuming details and components of missing items from other trades' BIM. For instance, in one meeting, the ductwork trade mentioned, *"I knew there is fire protection missing from this room, so I routed my ducts from the left.*

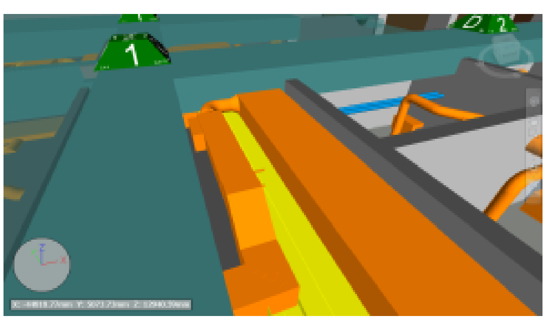


The already constructed ducts (orange) on open space has created a challenge for the plumbing and electrical trades to route their systems. Re-design of a portion of their system was required. Approximate time impact: 2 weeks at discovery of the issue. Actual time impact: 6 weeks to resolve.

Figure 61: Example of a coordination issue that arose because the ducts installed were obstructing the routing of electrical and plumbing systems.

- **Delivery method:** The case studies analyzed were delivered using design-build and construction management, which could explain some of the differences in coordination issues encountered. For instance, in the RAM case study, where the delivery method was design-build, there were fewer *design error* and *repeated clashes*, and no *as-built inconsistency* design issues found. In contrast, in the Pharmacy case study, which used a Construction Management delivery method, there were more *missing information*, *as-built inconsistency*, and *design error* issues, but fewer *temporal, functional* and *clearance* issues found. Also, the RAM case study was in an earlier project stage which explains the lower number of *missing information* and *as-built inconsistency* design issues. Finally, although trades rarely contacted each other directly throughout the meetings, we observed that in field notes and emails that among trades in the RAM case study, direct communication was more frequent, which is not surprising given that the design of the project was under the responsibility of the general contractor in the design-build setting.

- **Communication and coordination between trades**: Our observations and interview records indicated that aside from the construction management team, design and construction trades rarely contacted each other directly to coordinate designs and construction sequences. Although, in the RAM case study there were often communications among the trades during the design phase, interviewees indicated that trades were often not aware of what spaces are being used up by other trades and what components were fixed essential components (e.g. structural beams taking certain portion of the ceiling space). Also, trades frequently asked about various design details from other trades in meetings instead of prior to meetings. We believe this could be a contributing factor to the high ratio of *design discrepancy* issues in both case studies, as trades frequently presumed design details of other trades when the others' BIM was not complete or when design was accomplished simultaneously. As one interviewee stated, "*you can't just go and do your own clash detection. This is part of a systematic approach; you may change unnecessary things or do more damage.*" As Figure 62 shows, sometimes an entire floor had to be re-modeled and re-routed to rectify a coordination issue.

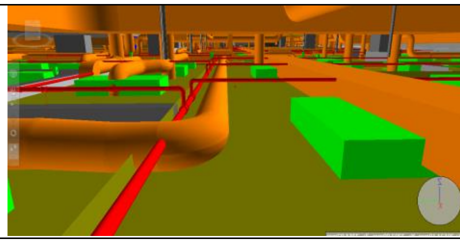


All ducts are routed on the same route as slab bands in level 2. A re-route and re-design of the entire floor ducts was required. Approximate time impact: 1 month at discovery of the issue. Actual time impact: 2 months to resolve.

Figure 62: Design error due to lack of sufficient coordination among team members.

- **Design coordination protocol:** Throughout our informal and formal interviews with BIM Navigators and Coordinators, several industry professionals emphasized the lack of implementation of a comprehensive BIM implementation protocol that enables every stakeholder in the project to be on the same page. One interviewee stated that: *"every trade is following their own rules and understanding when it comes to BIM"*. For instance, we observed that often the same LOD level was not maintained across all BIMs (e.g., missing fire protection details, or missing component details) which could influence the high frequency of *missing information* and *missing item* issues.
- **Coordination issue terminology:** Most of the design coordination issues in both projects were documented through spreadsheets as shown in Table 18, However, we observed numerous inconsistencies as to how different trades interpreted various design coordination issues, their complexity, and the steps involved in resolving them. As Table 18 shows, the some documented design coordination issues were interpreted differently by various trades. The ductwork trade assumed this was a *temporal* design issue, solved through moving components down. However, the sprinkler and electrical trades assumed the ceiling height should change as their components were in place and it would be hard to change. Moreover, the architect disagreed with any change in ceiling height, making this issue a *multiple system conflict*. Disagreements as to how complex design coordination issues were resolved occurred frequently. In addition, in this instance, the fact that a temporal (physical) design issue could be part of a more complex multiple systems conflict (process-based) caused further confusion for project stakeholders.

Table 18: How the same design issue was interpreted differently, by various trades in a subsequent meeting.

Documented Issue:	Snapshot:	Interpretation #1 by ductwork trade:	Interpretation #2 by electrical and sprinkler trades:
level 1- vivarium ceiling void - clean corridor Ducts and sprinkler collide		Sprinkler to move down. Electrical to move lights down.	Essential re-design of lights will be required. Sprinkler cannot move down as flow will be changed.

- **Issue documentation practices:** Practitioners often had difficulty reverting back to previously documented design issues in BIM and poor documentation of design issues was significant factor. In terms of retrieving issues in BIM and in 2D digital information, in the Pharmacy case study, design issues were tagged with trade-specific drawing page number and a zone on each floor (e.g. Level 4 Center, M5, A3). On the Pharmacy case study however, the general contractor added an extra notation of grids on the BIM (e.g. GL-F 14) when documenting design issues. The practitioners interviewed stated that this was an attempt to better support locating design coordination issues in BIM. However, this approach also had limitations as loading these intersections was time consuming, and secondly, the intersection of two grids on a 3D space consisted of a vast area that had to be re-scanned manually during the meetings so that design issue could be found in BIM. In terms of documentation of design issues, as Table 15 presents, the details recorded while documenting design coordination meetings was kept to a few words and screenshots. This practice limited the team's ability to retrieve information and recall details related to the unresolved issue later on. We believe this challenge contributed the most to the increased number of unresolved design coordination across both case studies.

In this section, we discussed the results of our analysis and described some of the contextual factors that influence the coordination issues that arise and the frequency of their occurrence. In the next section, we highlight the conclusions of this study.

4.9 Conclusions

This paper initially outlines the challenges of the current BIM-based building design coordination process, highlighting the reality that many coordination issues go undetected, issue resolution is inefficient, and coordination issues are poorly documented. In the two projects we studied, we found that 28% of design issues remained unresolved by the end of the design coordination stage. These issues must then be resolved on site, which can lead to increased costs and schedule delays.

In this research, we analyzed the BIM-based design coordination process of design issue identification, resolution, and documentation. We classified BIM-based design coordination issues based on prior findings and our own observations through a classification taxonomy that explicitly represents process-based, model-based, and physical design issues. We analyzed two case studies at different stages of construction based on the taxonomy and investigated design issue types within each project. We found that nearly two-thirds of design issues we analyzed were process-based and model-based and that these issues often emerge from physical design issues. Design issues were followed up less frequently when there was uncertainty as to their impact and what they referred to. We found that BIM Coordinator's and MEP Coordinator's familiarity with various building systems, as well as completeness of design guidelines and requirements, impacted how design issues are identified and communicated to the project team. In terms of design issue types, *temporal* design issues took the longest time to resolve, and most unresolved issues by end of construction were related to *design discrepancies*. Both case studies had almost one third of the design coordination issues as unresolved by end of design coordination process.

Experts we interviewed found the developed taxonomy to be a useful tool in enhancing the efficiency of BIM-based building design coordination. However, they believed maintaining a sufficient level of detail across all disciplines could prove a barrier to successful adoption. As for analysis of design issues, a majority of automated clashes were between ducts and cable trays or lighting systems; the case study delivered using construction management method had more instances of *missing information*, *as-built inconsistencies*, and *design errors,* but fewer *temporal, functional* and *clearance* issues, compared with the case study delivered using a design-build delivery method. We believe poor coordination and miscommunication among different trades when designing building systems is a contributing factor to design discrepancy issues. In addition, the least flexible design trade was structural (other project stakeholders had to work around that) and most flexible designs were related to electrical and ductwork when resolving a design issue. Regarding the design issue resolution rate, it is surprising to see a majority (65%) of the design discrepancy issues, and approximately one fifth of missing information issues, remained unresolved before the end of construction. Our study shows that although physical design coordination issues are easier to identify, they take longer to resolve since they often led to process and model based design issues.

In terms of the validation of our findings, we based our taxonomy on the findings of the RAM case study and coded the Pharmacy case study with our taxonomy. In addition, we employed inter-coder reliability testing and conducted an expert review of our developed taxonomy.

In terms of future work, we intend to apply the taxonomy to more case studies with different types of projects and project contexts. In particular, we would like to better understand how different delivery methods and levels of collaboration impact the types and frequency of coordination issues encountered. In addition, further field observation and analysis are required to provide more efficient mechanisms for capturing coordination knowledge. Moreover, as technology will advance, more projects involving different set of design information representation should be studied to further examine the taxonomy identified in this thesis. Specifically, the taxonomy should be re-examined with alternative settings, and collaboration tools (e.g. heavier use of Virtual Reality, Cloud BIM).

As final suggestion for the software development community, the taxonomy can improve incorporation of design coordination issues within BIM (through model-based design issue documentation) for more effective design coordination issue retrieval, and preserving of knowledge throughout the design coordination process.

Chapter 5: Conclusions

Successful management of the design coordination process is critical to the efficient delivery of cost-effective and quality projects, and it is imperative that design coordination issues get resolved as efficiently as possible. While numerous benefits of BIM in design coordination are well established, project participants face significant challenges that disrupt and hinder the design coordination process even when BIM tools are readily available. The focus of this research was to investigate BIM-based building design coordination processes from the perspective of project stakeholders and practitioners utilizing multiple types of design artifacts. Specifically, the research:

(1) Identified the bottlenecks practitioners face during BIM-based design coordination, proposed design considerations to address the bottlenecked encountered, and benchmarks widely used BIM platforms;

(2) Analyzed how and why practitioners interact with different design artifacts during the coordination process, with a particular emphasis on interactions with BIM tools. It identified the low-level interactions with design artifacts, analysed the frequency of their interactions, and evaluated the artifact utilization rates; and

(3) Formalized design coordination issue representation, resolution and documentation, defined the relationships between various design issue types, and identifies necessary functionality for BM-enabled building design coordination environments.

Each phase of the research was validated individually, although the validation methods informed one another. For validation of phase (1) - design coordination processes (Chapter 2) - the findings were validated through interviews with experts in the field. For validation of phase (2) - characterization of interactions (Chapter 3) – a replica case study was used to seek validity of the interaction taxonomy, followed by informal interviews with two BIM experts in the field. Finally, to validate findings of phase (3) - design issue characterization (Chapter 4) - reliability assessment, inter-coder reliability testing, and expert interviews were performed.

The remainder of this chapter is organized as follows: Section 5.1 describes the contributions; Section 5.2 explains the validation strategies adopted; Section 5.3 briefly outlines the practical implications of the research; and Section 5.4 describes the limitations of the current research and provides directions for future research.

5.1 Research Contributions

The contributions of this research are summarized in this section, according to each focus of the research. The three consecutive manuscripts that form the main body of this dissertation contain different scales of analysis, starting with BIM-based design coordination processes, interaction with artifacts in meetings, and lastly, design coordination issue representation. The key contributions are outlined below and illustrated graphically in Figure 63.

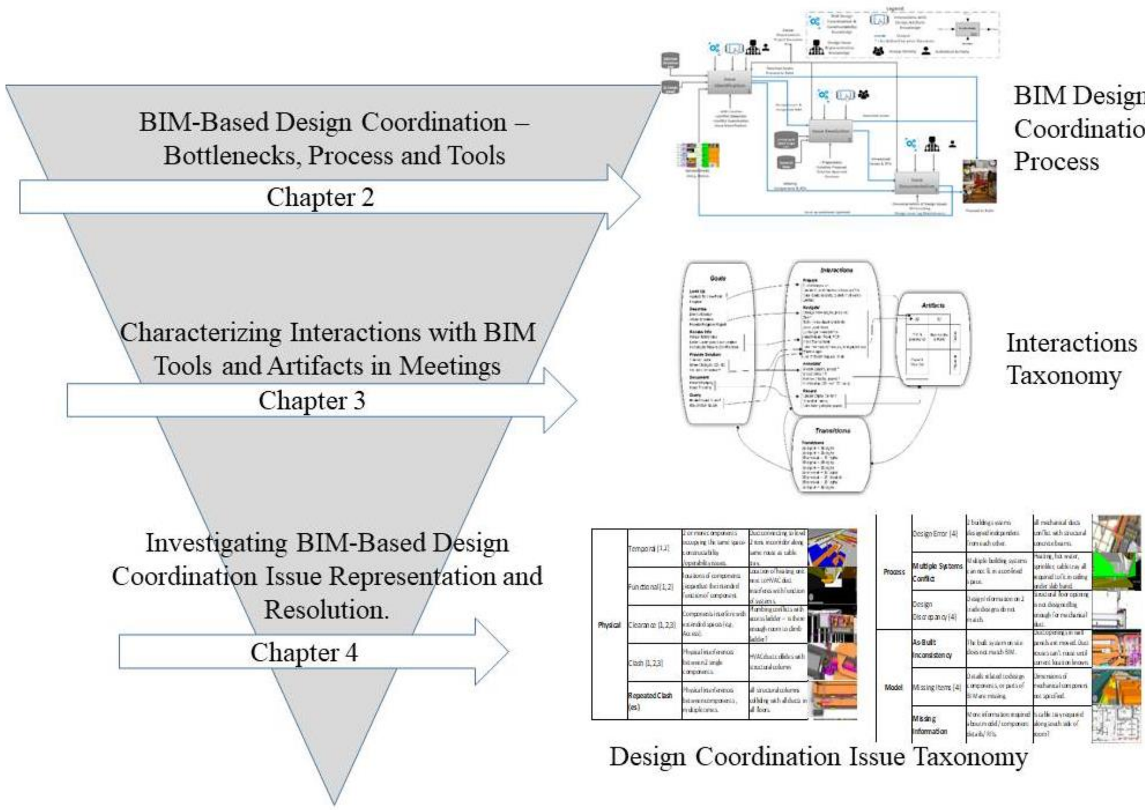


Figure 63: Illustration of three research contributions claimed in this thesis with corresponding chapters.

Research contribution 1 – Characterization of BIM-Based building design coordination processes, identification of bottlenecks, and design considerations for BIM tools: Chapter 2 characterizes the design coordination process, identifies the bottlenecks practitioners face during BIM-based design coordination, analyzes the literature and proposes design considerations. I built on the works of Yung et al. (2014) and Saram and Ahmed (2001) and characterized the ten sub-processes involved within the design coordination issue identification, resolution and documentation stages. I also identified the bottlenecks within each design coordination stage.

Research contribution 2 – Taxonomy of interactions with design artifacts, outlining the relationships between goals, artifacts, interactions and transitions: Chapter 3 provides a detailed description of the taxonomy I developed to characterize interactions with design artifacts. An important contribution of this research is the identification and characterization of the transitions participants had between design artifacts and views, which has not been studied in depth. The taxonomy builds on findings of Tory et al. (2008) and Liston (2009), and provides categories for the high level goals driving interactions with design artifacts (which contain some of the low-level goals identified previously), represents two new interaction categories of *preparation* and *recording*, and finally identifies the transitions between the design artifacts and views.

Research contribution 3 – Taxonomy of design coordination issues that explicitly represents process-based, model-based, and physical design issues: Chapter 4 classified BIM-based design coordination issues classification taxonomy. The taxonomy of design coordination issues builds on prior findings of Korman et al. (2003), Wang and Leite (2016a), and Lee et al. (2012) and develops four new design coordination classifications, including *'repeated clash', 'multiple-systems conflict', 'as-built inconsistency',* and *'missing information'*. In addition, I provided an ontology to represent the relationship between different design coordination issue types.

5.2 Validation

The validation methods for each phase were not performed in isolation, but rather, each phase informed the next. In this section I describe threats to validity and the validation process for each research contribution.

5.2.1 Threats to Validity

In terms of bias, one of the primary reasons qualitative methods have not been embraced by all researchers in the past is the types of bias and subjectivity associated with such approaches (Leicht et al., 2010). That is, many have argued that a researcher's personal bias plays too great of a role in gathering, synthesizing, and analyzing qualitative data (Hammersley and Gomm, 1997). To mitigate the observer bias, the bias created by the observer seeing what is expected during the observation (Yin, 2003), I used recorded sessions for verification of the coding and assumptions (Poole and DeSanctis, 1992). In addition, as described below, use of various methods of verification, such as a replica case study, and interviews with the practitioners helped to eliminate the bias to a great extent.

In addition, more projects involving different types of design information representation (e.g. 3D physical models) should be studied to further examine application and relativity of the taxonomy and processes developed in this thesis. The taxonomy on interactions should be re-examined with alternative design artifacts settings, and meeting space organization (e.g. change of layout in the BIM trailer). Also, it is worth examining the impact of organizational and project structure (such as contractual requirements, minimum LOD, and project delivery type).

Furthermore, while the complexity and depth of the case studies has allowed the issue representation taxonomy to include an acceptable level of variety of design coordination types, I acknowledge that the coordination issues studied in this thesis may not include all design coordination issues practitioners may encounter throughout the design coordination process. In addition, as technology will advance, more projects involving different set of design information representation should be studied to further examine the taxonomy identified in this thesis. Specifically, the taxonomy should be re-examined with alternative settings, and collaboration tools (e.g. heavier use of Virtual Reality, Cloud BIM).

5.2.2 Validation of Contribution 1 - Characterization of BIM-Based building design coordination processes, identification of bottlenecks, and design considerations for BIM tools:

For validation of design coordination processes (Chapter 2), the findings were validated through interviews with experts in the field. Similar to prior research (Kreider et al., 2010; Howard and Bjork, 2007), five interviews with BIM and trade experts in the field, and three interviews with other researchers were conducted. The five industry experts included two of the BIM experts involved in the case studies, and the other three were actively involved in BIM-based design coordination practices. I asked interviewees to evaluate the bottlenecks presented in Chapter 2 and compare their knowledge and experience with the findings. The interviewees initially needed help understanding the scope and relationship between bottlenecks and design considerations and I explained the scope and elaborating on the design considerations that were more from a computer science and software development perspective (e.g. gesture-based interactions). In their feedback, they found the bottlenecks reported in this study realistic, while they could not comment on the processes and BIM implementation protocols. They found most proposed technical design considerations feasible and easy to implement.

Table 19 shows the agreement rate for the five industry expert reviewees, the degree of agreement correlates with level of darkness in each cell. The agreement rates were represented through a Likert scale of 1-5, 1: disagreement 5: strong agreement. As the table shows, the interviewees relatively agreed that outdated BIM, disconnected trades, and unfit navigation tools were among the major bottlenecks which impede efficiency of BIM-based design coordination process. On a few occasions, interviewees were of the opinion that information discrepancy, unavailability of design artifacts and office/ site disconnect do not impact the design coordination process. Finally, interviewees also proposed their version of bottlenecks prior to consulting the list of bottlenecks which were developed in Chapter 2, they described the problems they faced while interacting with the tools. A majority of the bottlenecks described by interviews could be contained within the bottlenecks presented in Chapter 2.

Table 19: Expert interview, bottlenecks review agreement rate

Bottlenecks	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5
Outdated BIM					
Disconnected trades					
Lack of terminology					
Insufficient doc.					
Transitions					
Unavailability					
Information discrepancy					
Unfit navigation tools					
Office/site disconnect					

Strongly Agree (5):		**Disagree (1):**	

Table 20 shows the results of agreement rates for the review of design consideration presented on Chapter 2. The agreement rates were represented through a Likert scale of 1-5, 1: disagreement 5: strong agreement. As the table demonstrates, interviewees had relative agreement that 'BIM first' adoption, 2D/3D integration, and AR/VR integration were the most required design considerations to address the bottlenecks presented in Table 19. In addition, the interviewees believed that VR headsets, cloud BIM adoption and gesture-based interactions were among the least required design considerations, mainly due to the scope of preparations required for implementation. They also expressed concerns about whether the improvements would be worth the effort required to implement these design considerations. Moreover, they highlighted that the design considerations might be best utilized when all trades involved were able to maintain a sufficient level of detail in BIM. One interviewee stated, *"To me, this works best if minimum requirements are applied to project. You might have LOD 350 mechanical, but it may lack the whole fire protection system. So it goes hand in hand. To me this is assuming a minimum set of pre-requisites are checked."*

Table 20:Expert interview, design considerations agreement rate

Design consideration	Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5
BIM First adoption					
Cloud BIM adoption					
Coordination protocol					
2D/3D integration					
Digital stick-set artif.					
Gesture-based Interact.					
AR/VR integration					
VR headsets					
3D scan as-built					

Strongly Agree (5):		**Disagree (1):**	

5.2.3 Validation of Contribution 2 - Taxonomy of interactions with design artifacts, outlining the relationships between goals, artifacts, interactions and transitions :

To validate the taxonomy of interactions (Chapter 3), first the RAM case study was used as a replica case study (LeCompte and Goetz, 1982), and informal interviews with two BIM experts in the field were conducted. For the replica case study, I performed a non-intrusive ethnographic case study of a design team (LeCompte and Goetz, 1982). Specifically, I sought to prospectively validate the characterization of interactions and goals observed. Similar to the qualitative analysis of the primary case study (Pharmacy), short vignettes from the second case study were selected to verify whether the interactions and goals could have been classified using the taxonomy presented in Chapter 3. The RAM study project had a similar setting and almost equal number of project participants. Although I acknowledge that because human behavior is never static, no study can be replicated exactly, regardless of the methods and designs employed (LeCompte and Goetz, 1982). Figure 64 presents the success rate for encoding 20 vignettes (5 minute video catalogs) from the RAM case study using the taxonomy. Success rate was determined based on percentage of correctly coded vignettes compared with how I would have used the taxonomy to code the vignettes. As Figure 64 illustrates, the success rate initially was low, but as more vignettes were coded, and as the categories were revised, the success rate improved significantly. Specifically, the first 5 vignettes showed that the categories initially developed, could not contain a significant portion of interactions and goals. Hence, revision to the terminology and description of categories were made. Although encoding the initial vignettes was unsatisfactory, with numerous revisions to the taxonomy, the average success rate using the taxonomy increased to 83%.

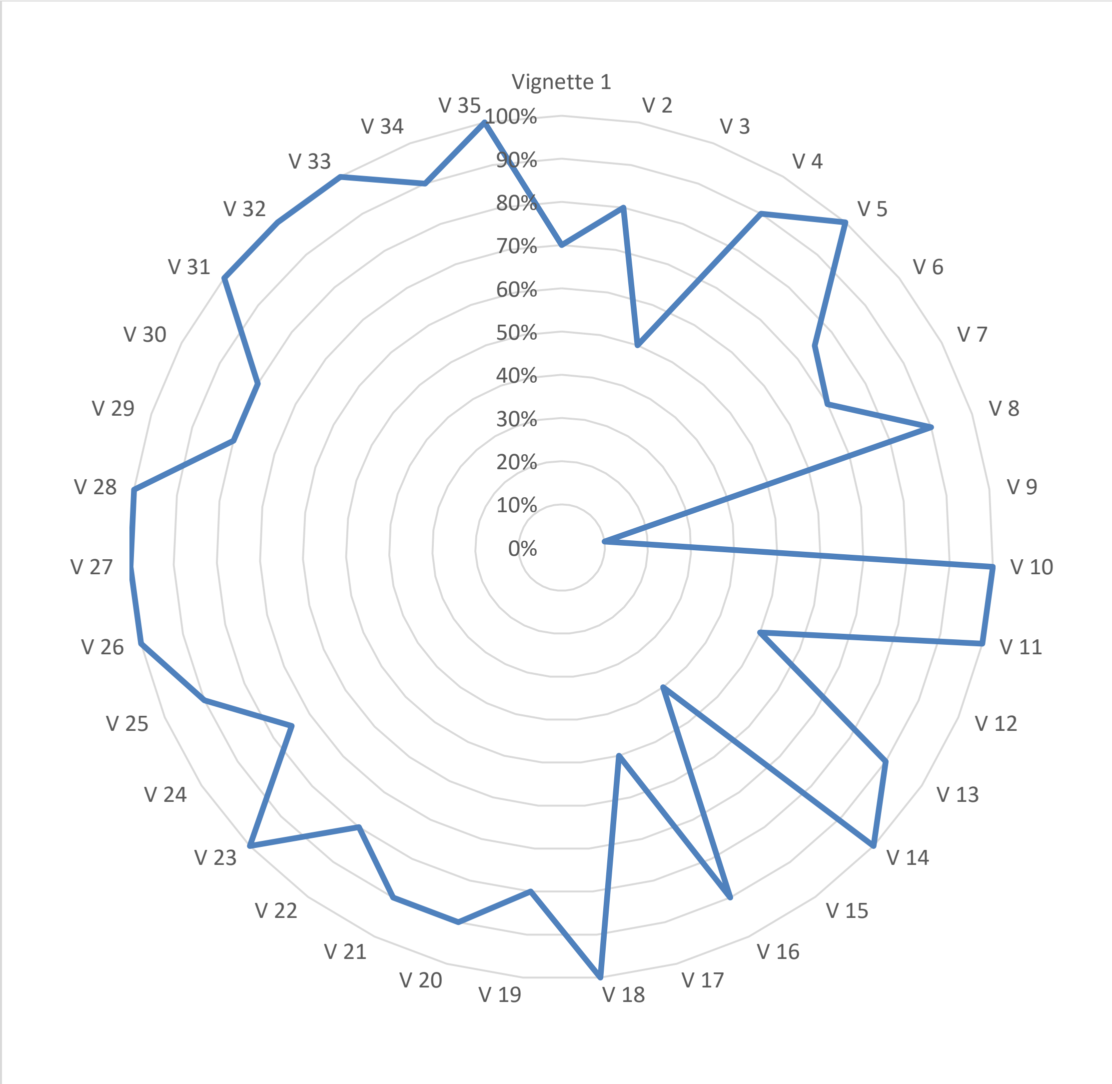


Figure 64: Average success rate for encoding video catalogs by interviewees. V: Vignette #

I also performed unstructured interviews with two BIM experts in the field, including one from the Pharmacy case study. Similar to others (Howard and Bjork, 2007; Kreider et al., 2010; Wang and Leite, 2016), I asked the BIM experts to comment on the interaction taxonomy presented in Chapter 3, and compare their own experience with the findings of this research. I then asked them to capture word by word (encode using the taxonomy codes) three 5-minute vignettes from the case studies using the taxonomy. The feedback of the experts was rigorously analyzed and the wording of the taxonomy was later revised to improve clarity. During this process, I constantly sought interviewee's opinions as to the interaction and artifact utilization analysis of this research and attempted to capture their thoughts regarding the utilization of artifacts. Specifically, I sought feedback of interviewees to better understand and confirm the interactions with 2D digital, paper and 3D design information, and asked them to outline the bottlenecks and challenges when interacting with design information in meetings.

5.2.4 Validation of Contribution 3 - Taxonomy of design coordination issues that explicitly represents process-based, model-based, and physical design issues:

The results of Chapter 4 were validated by employing three approaches to ensure validity of the findings, including reliability assessment, inter-coder reliability testing, and expert interviews. In terms of reliability assessment, I coded the Pharmacy case study transcription with the categories that emerged from the Pharmacy case study. I was able to categorize all design issues based on the taxonomy emerging from the Pharmacy case study.

In terms of inter-coder reliability testing (Tinsley and Weiss, 2000), I performed inter-coder reliability testing on 10% of the issues in the Pharmacy case study. During this process, I asked a mechanical engineer who had sufficient BIM expertise to code these issues based on the design issue taxonomy provided in Chapter. I provided a brief description of my findings, the taxonomy, and some coded examples to the coder to initially train the coder, then asked him to code the design issues using the taxonomy. Once the coder finished with coding of the design issues, I then coded these issues myself and compared the two classification results together. The process ensured that the taxonomy can be applied by other coders and industry experts in the field.

As Figure 65 presents, during the first attempt, the coder coded 63% of the design issues in a similar category. Based on his feedback of the categories, descriptions and examples were revised to include a broader range of categories of design coordination issues. Once the taxonomy was revised, the coder was given the same design coordination issues, and was asked to recode using the revised taxonomy. During the second attempt, the coder encoded 93% of the design issues with the expected categories.

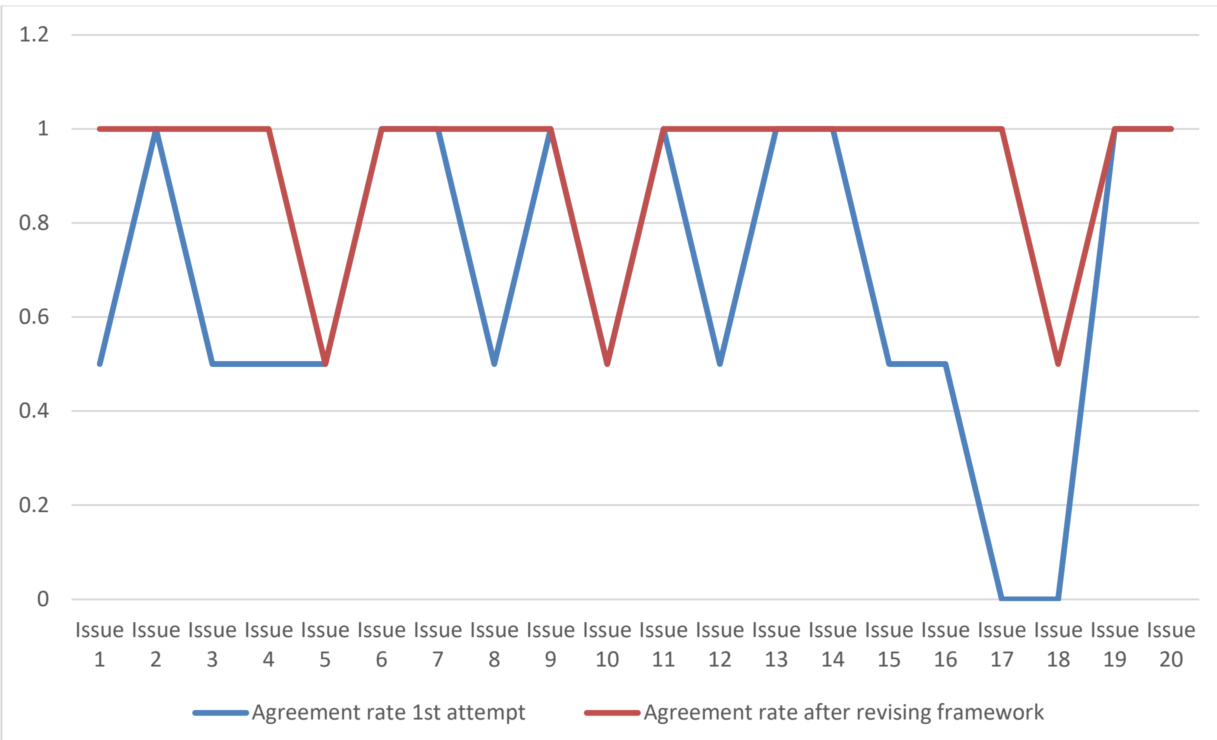


Figure 65: Inter-coder reliability approach; coder agreement rate, 1st and 2nd attempt.

The resulting Cohen's Kappa coefficient was 0.85, which is an acceptable value for reliability (Sabelli et al., 2011). The Cohen’s kappa (Cohen, 1960) (Formula 1) is a statistical coefficient that represents the degree of accuracy and reliability in a statistical classification. In Cohen’s kappa formula, (k) stands for Cohen's kappa coefficient, (P_0) is the relative observed agreement among raters, and (P_e) is the hypothetical probability of chance (random) agreement among raters, using the observed data to calculate the probabilities of each observer randomly seeing each category. If the raters are in complete agreement, then kappa = 1. If there is no agreement among the raters other than what would be expected by chance, kappa = 0. It is possible for the statistic to be negative as well.

$$k = \frac{p_0 - p_e}{1 - p_e}$$

Formula 1: Cohen's kappa

In terms of interviews with experts, most prior research in the field has adopted this approach to validate (Kreider et al., 2010; Howard and Bjork, 2007; Wang and Leite, 2016). I asked three BIM experts, including MEP and BIM Coordinators involved in the case study (both BIM Coordinators from the Ledcor Group) to evaluate the design issue taxonomy and compare their own knowledge and experience with the findings. I then asked them to code 20 design issues from both case studies using the taxonomy. I transcribed the interviews and analyzed the feedback from the experts. Similar to the coder, the interviewees also initially needed help understanding the relationship between process-based and model-based design coordination and physical issues. They found the issue representation taxonomy as a useful tool to classify BIM-based building design coordination issues, particularly in the issue identification stage prior to communicating the issue with the team.

The taxonomy also was helpful for them in terms of classifying the design coordination issues more rigorously when identifying design issues. However, they highlighted that the taxonomy may be best utilized when all trades involved were able to maintain a sufficient level of detail in BIM. One interviewee stated, *"to me this framework works best if minimum requirements are applied to project."* Specifically, the interviewees' feedback about the taxonomy was that *"with model-based design issues category (e.g. missing items, as-built inconsistency), you would never know as a BIM Coordinator what is missing. They only come up during the meeting. So it would be hard to capture them on model preparation stage."* In addition, one interviewee expressed interest in the *missing information* category: *"Oh I like this one inquiry/missing information. This is what I have always wanted to incorporate into the system".* Another interview mentioned: *"to me if BIM is on the project, this is useful and should be part of client requirement."*

Finally, all interviewees identified some of the classifications that were vague in the early version of the taxonomy, or could be part of other classifications. Hence, the taxonomy was revised according to their feedback. During this process, similar classifications of specific types of design issues were merged together to form broader classifications that could contain one or more prior categories. The total number of design issue classifications was reduced from an initial 15 categories to 12 categories.

In this section, the methods used for validation of findings of each chapter of this thesis were described. In the next section I explain the practical implications of this research

5.3 Practical Implications

This research has many practical implications for the construction industry, as well as the software development community. While in general the research contributes towards improving the efficiency and effectiveness of BIM-Based design coordination processes, I anticipate that the outcomes of this research could have an impact in the following ways:

(1) The findings presented in Chapter 2 could enable practitioners and researchers to better understand the challenges of BIM-based design coordination processes. Specifically, the results can help the software development community through the

identified design considerations and key functionalities requirement (Chapter 2, section 5) to improve state of the art BIM tools for design coordination practices. The results also provide insights for future building projects to effectively adopt and implement BIM throughout future building design coordination processes, and select the right BIM tool depending on the purpose and needs of the projects in the future.

(2) The taxonomy presented in Chapter 3 could help the software development community to design state of the art BIM tools that better support the needs of collaboration in design. In addition, these results will also help to inform BIM-based project teams to better adopt BIM-based design coordination and modelling strategies. I suggest the following design considerations to better align state of the art BIM tools with how the tools are being utilized:

- Provision of quick transition mechanisms between discipline's design information within the same building spatial location, so that details of other trade designs surrounding the design issues can be easily accessed.
- Adopting 'BIM First' approach, where project stakeholders start BIM early in the process to avoid future conversion from CAD to BIM.
- Integration of cloud BIM platforms to improve simultaneous access to design information.
- Integration of state of the art screen casting technologies with Interactive displays, so that practitioners can directly access and share design information during the meeting.

- Design of simpler navigation techniques for frequent BIM navigational interactions, so that practitioners can navigate through information easier with the tools.

(3) The taxonomy of design coordination issues presented in Chapter 4 could be utilized during design coordination issue identification to better represent design issues in terms of their priority, complexity and relation with other design issue types. Also, with the help of software development community, the taxonomy can improve incorporation of design coordination issues within BIM (through model-based design issue documentation) for more effective design coordination issue retrieval, and preserving of knowledge throughout the design coordination process.

To this date, there are very few projects that implement full BIM across entire design and construction phase with sufficient level of development (LOD). With future technological advancements and increased incentives on BIM adoption across AEC industry, the findings of this research can be utilized for future building projects and for the years to come. As of writing this thesis, there has not been a major change in the way practitioners conduct BIM-based design coordination process, interact with design artifacts, and handle design coordination issues throughout projects.

In addition, considering that there will be an increased pace for BIM adoption in the AEC industry, there could be a sizable demand for BIM experts with a sound knowledge of various building systems and design coordination skills across the construction sector. My recommendation for academia and future educational institutions are to train and educate future industry experts through multi-disciplinary courses where students from different backgrounds (e.g. architectural, structural, mechanical, electrical, and construction management) can work together on simulated projects and be prepared to work on design coordination environments of the future.

5.4 Limitations of the Current Research and Future Research Directions.

Throughout this thesis I use the term BIM in a broader sense of 'BIG BIM' (Redmond et al., 2012) that can be divided into interrelated functional, informational, technical and organizational/legal issues (Volk et al., 2014). I see BIM as a key component to efficient design coordination and review processes and believe the contributions outlined in this thesis could be integrated with existing BIM integration and adoption practices.

While extensive attempts where made to validate the findings of this thesis, it is important that more case studies are investigated to verify the results. I emphasize on the fact that, the case studies represent state of the art public sector projects involving some of the largest general contractors, and the most BIM-savvy design consultants and sub-contractors in western Canada. However, more case studies with other general contractors, different design artifact settings, additional design information representations, and non-fast track delivery, should be examined to verify the process and taxonomies identified in this thesis.

To further advance the work presented in Chapter 2, I suggest future research to focus further on the domain of BIM adoption processes and interoperability. Specifically, I suggest further research to identify factors influencing implementation of BIM for design coordination, interoperability across various platforms, and barriers to start with a BIM-First design approach. I believe that future software developers should aim to support the functionalities I identified and attempt to address the bottlenecks presented in this chapter. Further research is required to evaluate the impact of these functionalities as a whole rather than single functions and their impact. For instance, the process of BIM integration and concurrent design among various disciplines will be changed as a result of implementing BIM cloud coordination tools. Moreover, additional processes will be required to manage and control spaces available to each discipline during cloud-based design process, for example certain spaces are reserved for structural components are not to be used for MEP purposes. Finally, since a large number of details regarding each discipline resides as tacit knowledge in the practitioners' head, I believe design coordination meetings are still an integral part of the design coordination process, even when cloud BIM tools are fully utilized.

To continue advancement of the work presented in Chapter 3, further research is necessary to explore the impact of new collaborative technologies, such as cloud-based BIM tools and AR/VR, on design coordination processes and outcomes. Incorporation of such tools will presumably change the way practitioners interact with design artifacts, as well the accessibility and availability of design information. A possible future direction could be to conduct additional ethnographic case studies of teams performing design coordination with a particular emphasis on alternative environments and tools, such as cloud-based BIM platforms, big room settings, and cross-case analysis.

To advance the work presented in Chapter 4, the design coordination issue taxonomy developed should be applied and tested with more case studies with different types of projects and project contexts. In particular, it would be useful to better understand how different delivery methods and levels of collaboration impact the types and frequency of coordination issues encountered. In addition, further field observation and analysis are required to provide more efficient mechanisms for capturing coordination knowledge.

Finally, I recommend development of a prototype of model-based design coordination issue documentation within BIM tools, based on the taxonomy. A possible direction could include development of add-ons for tools similar to Autodesk Navisworks to store and utilize design coordination issue categories during design issue identification stage, and mapping the design issues to specific spatial locations with in BIM. Consequently, additional testing is needed to better understand the benefits and shortcomings of such prototype for construction practitioners, specifically for identification, management, and resolution of design coordination issues.

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