BEYOND THE CLASH: INVESTIGATING BIM-BASED BUILDING DESIGN COORDINATION ISSUE REPRESENTATION AND RESOLUTION

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SUMMARY: *Successful management of the building design coordination process is critical to the efficient delivery of cost-effective and quality projects. Building information modeling (BIM) has had a significant impact on design coordination, supporting the identification and management of 'clashes' between building systems. However, many design coordination issues go beyond the traditional definition of a 'clash' and either go undetected or require further time, resources, and expertise to resolve. The goal of this research is to better understand the causes of coordination issues and the factors that affect their resolution. 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 applied the taxonomy to two case studies and analyzed the frequency of issue types, the distribution of issue types across disciplines, and the resolution rates of issue types. We found that the most frequent causes of design coordination issues were design discrepancy, design error, clashes and missing items. The most common design coordination issue across both case studies was design error. 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. The taxonomy was validated through inter-coder reliability testing. The experts we interviewed confirmed that the taxonomy of coordination issues could improve design coordination processes, particularly in the issue identification stage prior to communicating the issue with the team.*

KEYWORDS: *BIM; construction; ethnographic study; design issues; knowledge capture; coordination process design trades; design coordination; BIM cloud; issue resolution.*

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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, Park and Won (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 (caused by the process of BIM creation) and model-based conflicts (caused by deficiencies in the BIM). 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. This research bases its findings primarily from two state of the art, public sector case studies involving some of the largest general contractors, and the most BIM-savvy design consultants and sub-contractors in western Canada. The design coordination issues investigated, include various complexity and relate to different project stages. 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. 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 level of development (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 2, our research methodology in Section 3, and our analysis of the BIM coordination process in section 4. Next, we describe the BIM design coordination representation taxonomy we formalized in Section 5, the application and analysis of the taxonomy to the two case studies in Section 6, and Validation of our findings in Section 7. Finally, we discuss our analysis in detail in section 7.2, and then finally, describe our conclusions and recommendations for future work.

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.

2.1 BIM-based design coordination issue characterization

In an early attempt, Korman, Fischer and Tatum (2003) classified design issues into three main categories of design criteria, construction, and operations issues. They also identified design issue attributes as geometric characteristics (component dimensions) and topological characteristics (spatial relationships). 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, Park and Won (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.

2.2 Design coordination knowledge capture strategies

Most construction knowledge is tacit and resides in the minds of domain experts (Khalfan et al., 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 et al., 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.

3. METHODS

Our research approach involved two steps: (1) design coordination issue taxonomy construction, and (2) evaluation and validation of findings (FIG. 1). 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.

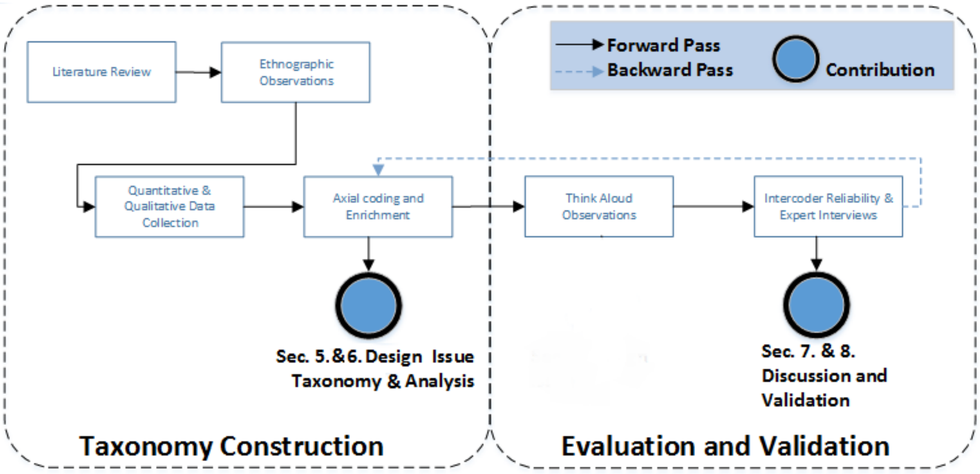


FIG. 1: Methodology implemented in this research included two phases: (1) taxonomy construction and (2) evaluation and validation.

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). This research bases its findings primarily from two case studies, though it is worth mentioning 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. The general contractor had substantial prior BIM experience from prior projects and the organizations had sufficient prior BIM adoption experience. Generally, it is extremely hard for researchers to gain full access to such projects, which involve similar level of complexity, scale, significance, and level of BIM 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. While attempts were made to generalize the findings of this research, it is important that more case studies are investigated to verify the findings presented in this research.

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 (FIG. 2). 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.

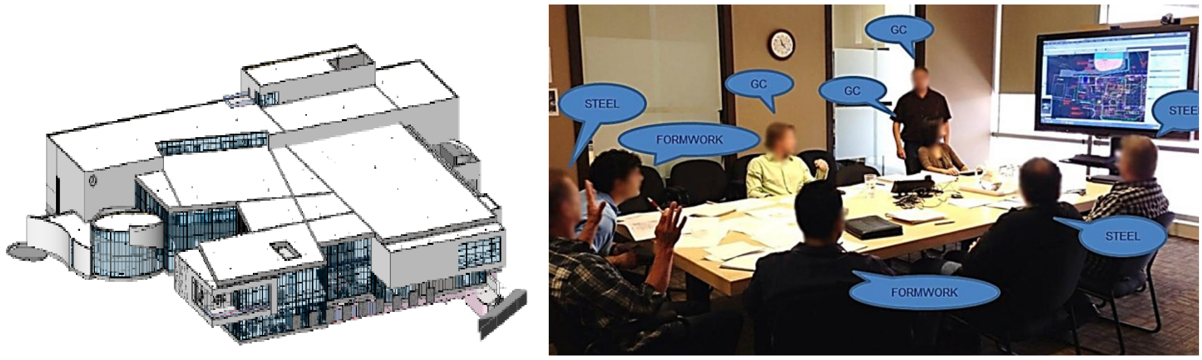


FIG. 2: The Royal Alberta Museum - an architectural model of the RAM project that was used to validate the research findings (left) and a snapshot of design coordination meeting environment for RAM case study (right) (GC indicates general contractor).

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 provides a variety of teaching and learning spaces from lecture halls and seminar rooms to a pharmacist clinic and three floors of research laboratories (FIG. 3).

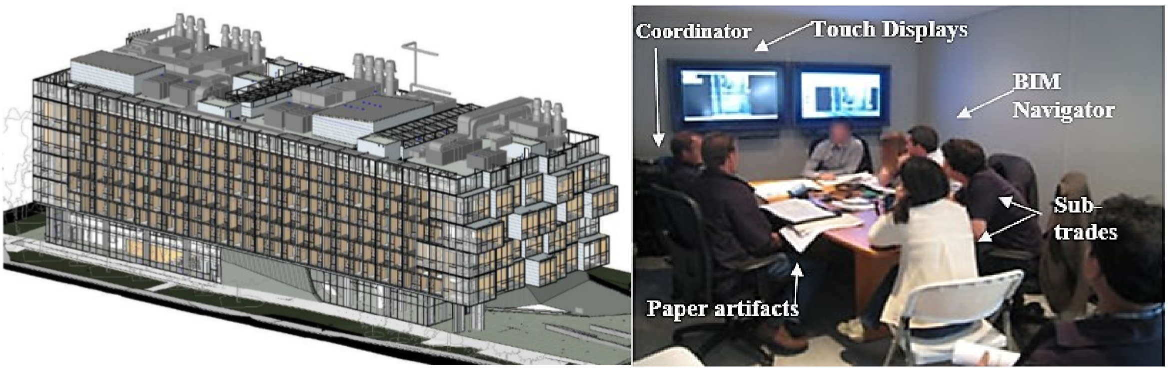


FIG. 3: Integrated BIM model of the UBC Pharmaceutical Building (left) (image courtesy of Hughes Condon Marler Architects) and BIM Trailer used during design coordination on site (right).

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.

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.

3.3 Data collection and analysis

An ethnographic approach was chosen to collect the "richest possible data" (John and Lofland, 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 B, which was at a later stage, and 120 issues from case study A which at an earlier project stage. As described earlier, we define design issues, as the more complex conflicts between systems that are either not detected through automated clash detection or require further examination. The issue design coordination meetings revolved around resolution of design issues that were previously identified during design issue identification stage. During each round of design coordination (between meetings) hundreds of new Clashes were identified, however the focus of this study is on design coordination issues alone.

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 1 demonstrates how design issues were documented, shortened, and analyzed during the final stages of data collection. The table demonstrates, some of the design coordination issues captured during this phase. It is important to mention that the design coordination issues were captured as they appeared in the meetings, in addition we could categorize one design issue into to or more categories as a design issue could be labeled as both *Repeated patterns* and a process-based *Design error*. We elaborate further on this concept on section 5.

TABLE 1: 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, Design Error*	*Ceiling type to be reviewed - tray to be stopped*	*Removed Item, Re-Routing*	*Unresolved*

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. The merging occurred mostly when two or more categories could be contained on a broader concept. For instance, the labels, *Missing modeled components,* and *Missing object detail*, were combined into a broader classification of *Missing Information*. Later on, 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 5.

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 involved prior 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 (FIG. 4), 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.

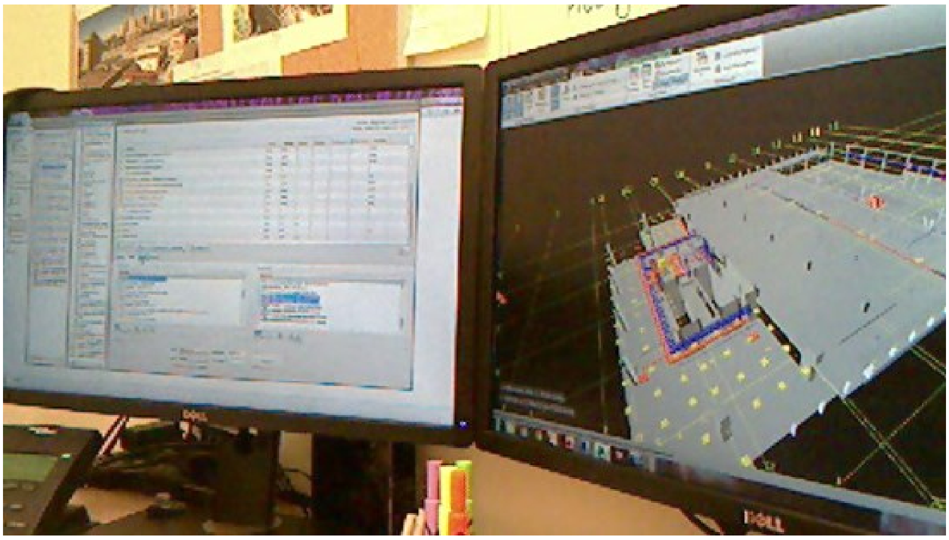


FIG. 4: Observing a BIM Coordinator conducting issue identification. Reviewing the automatically identified clashes on the left and analysing them on the right.

3.6 Inter-coder reliability testing and expert interviews

We employed two user testing and validation strategies in order to achieve generalization of our results. For the first attempt for reliability testing, we coded 50% of the case study B transcriptions with the categories that emerged from case study A. In addition, we employed inter-coder reliability testing (Tinsley and Weiss, 2000) on 10% of the issues in case study B. 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 and generalization (Kreider et al 2010; Howard and Bjork 2007; Wang and Leite 2016). The details of our expert interviews and inter-coder reliability testing can be found in section 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. BIM-BASED DESIGN COORDINATION PROCESS AND CHALLENGES

The design coordination process typically consisted of a cycle of three interconnected steps, as shown in FIG. 5:

- **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.

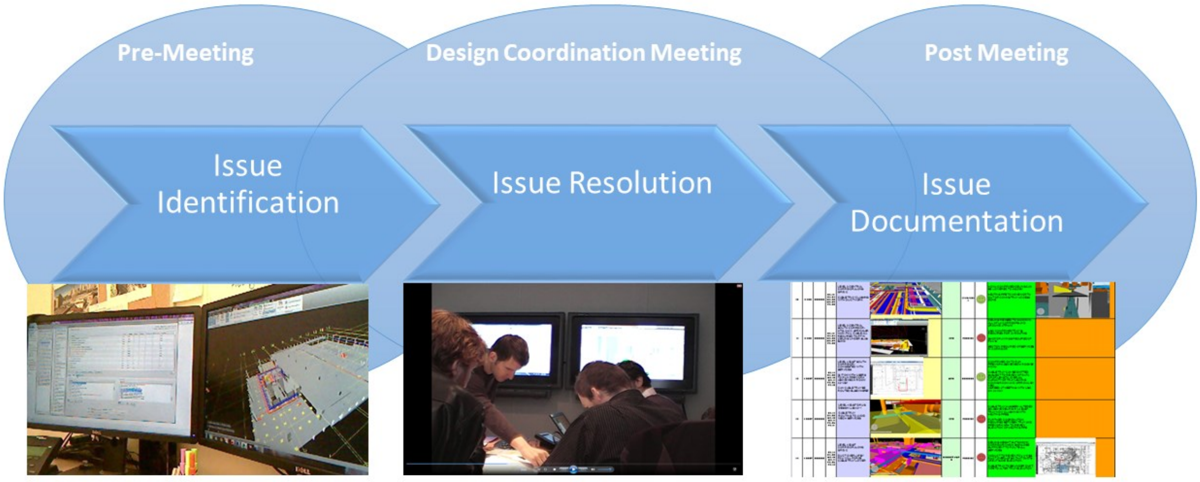


FIG. 5: Three critical steps in the BIM-based design coordination process. Design coordination issue identification, resolution, and issue documentation.

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 FIG. 6 shows, throughout the issue identification stage, the erroneous clashes are cleaned up, and only a small fraction of these clashes, which represent actual conflicts between different systems are selected, the reminder contain repeated or erroneous conflicts known as 'false positives' (Leite et al, 2011). MEP and BIM Coordinators eliminate these false positives by close examination of automated conflict detection tools and exploration of integrated BIMs. Once the false positives are eliminated, the conflicts are then examined in detail to identify more complex 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.

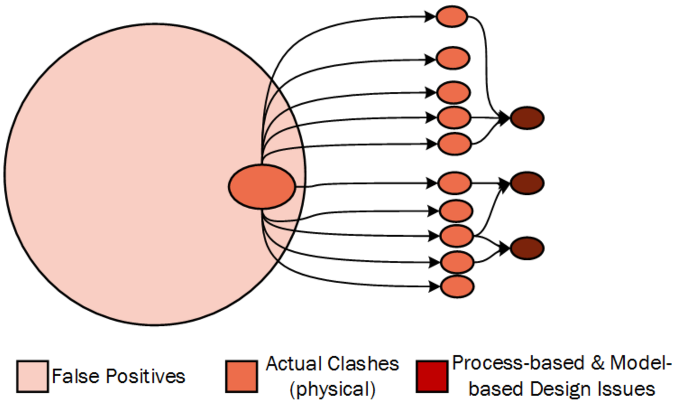


FIG. 6: Graphical illustration of design issue identification - filtering out 'false positives', identifying 'actual clashes' and then, in some cases, emergence of 'process' and 'model' based design coordination issues.

FIG. 7 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.

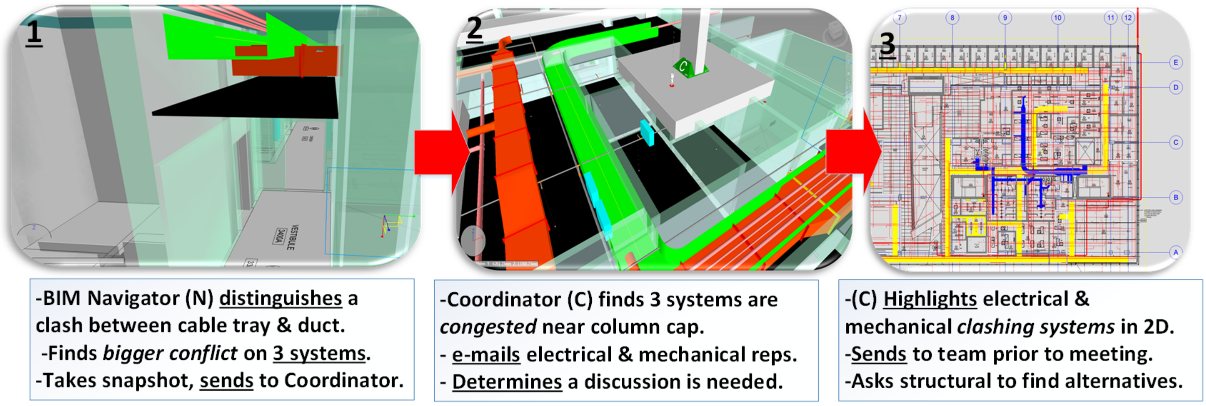


FIG. 7: Example of how a simple coordination clash leads to a more complex design issue. Underline indicates actions taken, italics indicates more complex design coordination issues resolution

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 FIG. 8 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 (meeting n). One week later (meeting n+1), the electrical design representative asked for the reason why this issue was flagged. Two weeks later (meeting n+2), the mechanical contractor stated, he could not find the viewpoint and whereabouts of this 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.
- *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 2 highlights the details captured by the BIM Coordinator for the design issue shown in FIG. 7, 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.
- *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."*

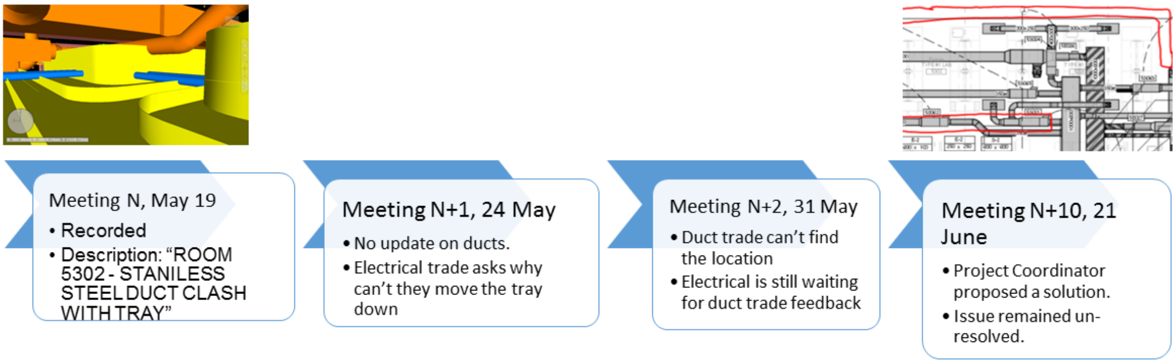


FIG. 8: Example illustrating the slow progress of a design coordination issue resolved over many meetings.

TABLE 2: 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

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.

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 3 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. As shown on FIG. 7 the design coordination issues are generally first identified as 'physical' design coordination issues and upon closer examination by MEP or BIM Coordinators, they are either converted to a 'model' or 'process' based design issue or stay as 'physical' issues. Generally, 'process' and 'model' based design issues needed more discussion and practitioner engagement during design issue resolution meetings. Most prior studies (e.g. Korman et al (2003), Tommelein and Gholami (2012), and Wang and Leite (2016)) have focused on identification of 'physical' design coordination issues, and fewer studies (e.g. Lee et al (2012)) have investigated the design coordination issues beyond a typical 'clash' that is identified using state of the art BIM tools. Identification of 'process' and 'model' based design coordination issues often requires in depth knowledge of all building systems and project requirements and they are often flagged by MEP or BIM Coordinators. The new types of coordination issues which are identified during this study are shown in bold in TABLE 3 and briefly described below:

- *Repeated clash*: Repeated clash issues are best described as patterns or groups of physical design issues within only two building systems. This design issue generally indicates a substantial re-design of at least one of the building systems involved. For instance, as the example in TABLE 3 shows, when the all mechanical ducts conflict with all structural columns of all floors in zone C (a central part of the building), all ducts involved had to be re-routed 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 the coordination team.
- *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*: Missing information refers to a lack of sufficient information about building system(s) that interfere with design coordination and building cycle. These include missing guidelines and project requirements, installation sequences, processes, or required clearances between certain objects. In contract, we refer to *Missing items* as un-modelled BIM components or missing building systems. 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 separate category. The processes of how building systems work together—and are installed or maintained— is often missing from the BIM, creating a dilemma among stake-holders and requires further input from other responsible trades/ consultants. As the example on the table presents, due to lack of knowledge of serviceability and access of the HVAC (Heating, Ventilation, and Air Conditioning) unit, and lack of knowledge of acceptable noise level to building end users, the coordination of this part of the building is stopped.

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 FIG. 9 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 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.

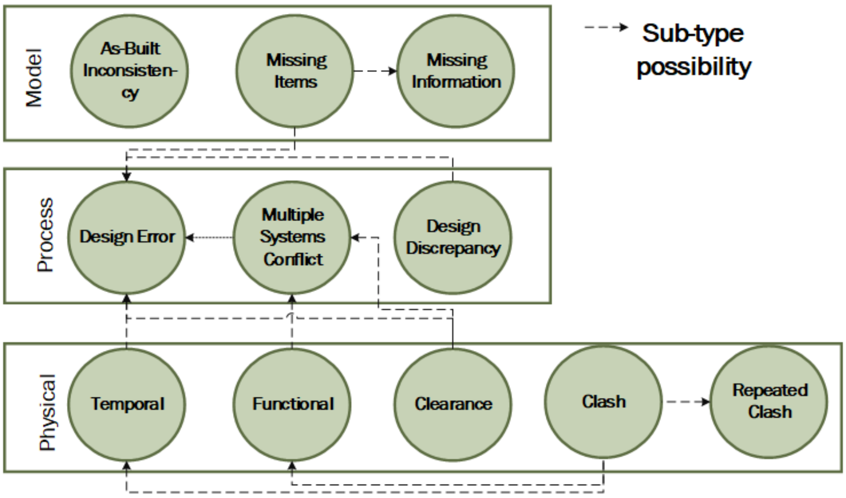
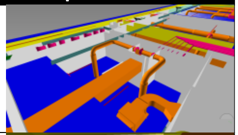
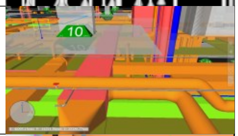
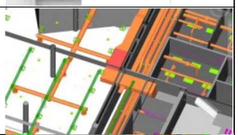
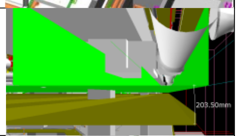
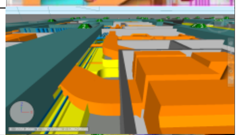
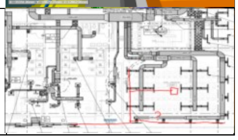


FIG. 9: Ontology that represents the potential relationships across the design issue categories.

To elaborate further on FIG. 9, we demonstrate a design coordination issue that was identified in case study B. FIG. 10 shows the description and screenshot of this design issue. As the chart on bottom right shows. This design coordination which relates to a tight ceiling space holding multiple bulk mechanical equipment and systems can be categorized initially as a *Temporal* design issue, but upon closer examination of the design issue by MEP and BIM coordinator it can be classified into both categories of *Multiple systems conflict* (many systems fitting into a tight space) and *Design Error* (parts of the congested systems could have been moved away in the early design, if the space considerations were known to the design consultants).

TABLE 3: BIM-Based Building Design Coordination Issue Representation Taxonomy. 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
	Temporal [1,2]	2 or more components occupying the same space-constructability /operability issues.	Duct connecting to level 2 runs in corridor along same route as cable tray.	
	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.	
Physical	Clearance [1,2,3]	Components interfere with extended spaces (e.g. Access).	Plumbing conflicts with access ladder – is there enough room to climb ladder?	
	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.	
	Design Error [4]	2 or more building systems designed independent from each other.	All mechanical ducts conflict with structural concrete beams.	
Process	**Multiple Systems Conflict**	Multiple building systems can not fit in a confined space.	Heating, hot water, sprinkler, cable tray all required to fit in ceiling under slab band.	
	Design Discrepancy [4]	Design Information on 2 trade designs do not match.	Structural floor opening is not designed big enough for mechanical duct.	
	As-Built Inconsistency	The built system on site does not match BIM.	Duct openings in wall panels are moved. Duct routes can't route until current location known.	
Model	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 cycle.	How do building users control HVAC unit above? is noise level a concern?	

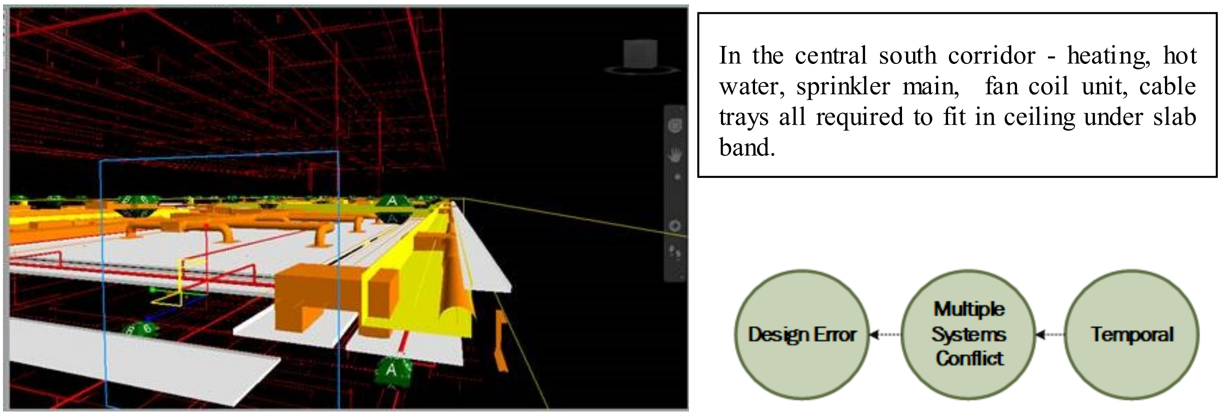


FIG. 10: Example of how a design coordination issue can be categorized in multiple categories. Left – screen shot of the design coordination issue. Top right – description of the issue. Bottom Right – dependency of the design coordination issue types for this design issue.

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

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 case study A and 98 issues from case study B. It is worth noting that coding the design coordination issues in the case studies, enabled us to ensure the taxonomy can include as many design issue categories as possible, and the labeling of categories are broad to contain all issue types. More details regarding our validation strategies are provided on section 7. More importantly, analysis of the design coordination issues in the case studies enabled us to investigate distribution of design coordination issue types, design issue type distribution across disciplines, design issue type distribution across various locations, resolution rate of design issues, as well as the contextual factors that may have affected issue identification, documentation and resolution in the two case studies.

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 (Fig. 11-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 (Fig. 11-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 case study B compared with case study A, and *mising items* were more frequenct in case study A. The nature of design issues handled by each team varied since case study B was in the finishing stage and finalization of MEP placement, whereas case study A 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 case study B's temporal design issues (constructability) half the size of temporal design issues in case study A. Also, missing information design issues were more frequent in case study B, 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 case study A, since there was less construction progress at the time of our observations.

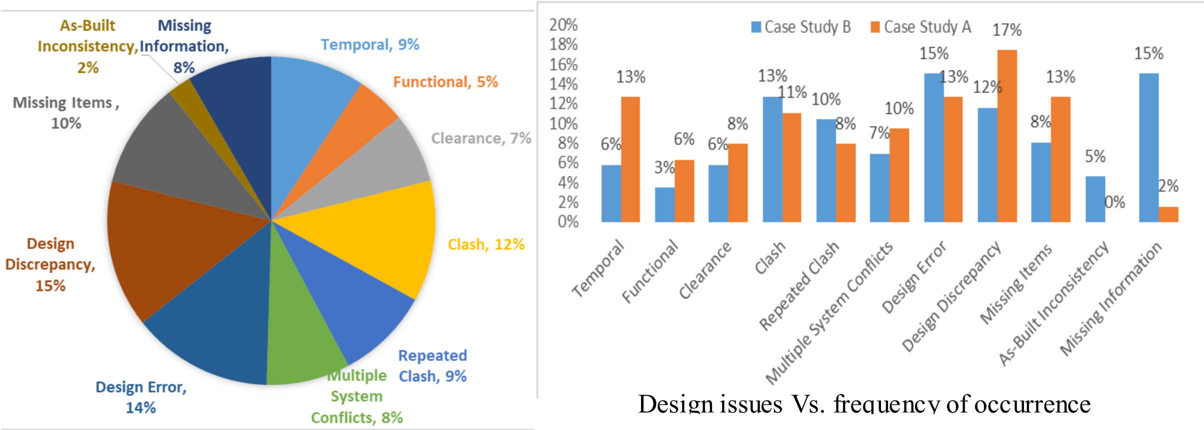


FIG. 11: Percentage of all design issues types analyzed across both case studies (left). Analyzed BIM design coordination issues in case studs based on frequency of occurrence (% of total issues analysed)(right).

Missing information made up a significant portion of design issues in both case studies. We found 15% of the design issues in case study B and 9% of design issues in case study A 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 case study B and 8% in case study A). Our findings showed that 13% and 15% of design issues on case study A and B respectively to be comprised of *design errors*.

6.2 Analysis of design issue type distribution across disciplines

We also investigated the correlation of how different project trades were held responsible for resolving various issue types (*TABLE 4*). 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 case study B, compared with rarely taking responsibility in case study A. this is surprising since structural designs in case study B 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 was the most responsible 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 was responsible for *missing information* and *multiple systems conflicts*;
- the HVAC team was more responsible for *design discrepancy* and *design error* issues;
- the electrical team was uniformly responsible for all design issues;
- the fire protection team was more responsible for *missing items*,
- the plumbing team was responsible 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 4: Issue types in each case study versus the trades held responsible. The darkness of each cell indicates frequency of occurrence. CM: construction management.

	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														

6.3 Analysis of design issue type distribution across locations

We further investigated the location of where design coordination issues took place. As FIG. 12 presents, on the left, design issue location of case study A, and on the right, design coordination issues in case studies B are shown. Design coordination issues in case study A were recorded more broadly, indicating the floor only, but in case study B 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 case study B, 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 case study B, whereas almost two third of design issues we concentrated in just two levels of case study A, although level 4 on case study B, had almost the same concentration of design coordination issues of levels P1 and 1 on case study A. It is also worth mentioning that due to complexity of building systems, datacenter and vivarium on case study B, 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 case study B, it appears that level 4 East was the location of the mechanical room, and level 4 west, was were components that lead to the mechanical room had to be fitted under the condensed space between slab bands and ceilings which proved challenging. In addition, on case study A, the mechanical room was placed on parking 1, which could explain the high number of design issues on that level.

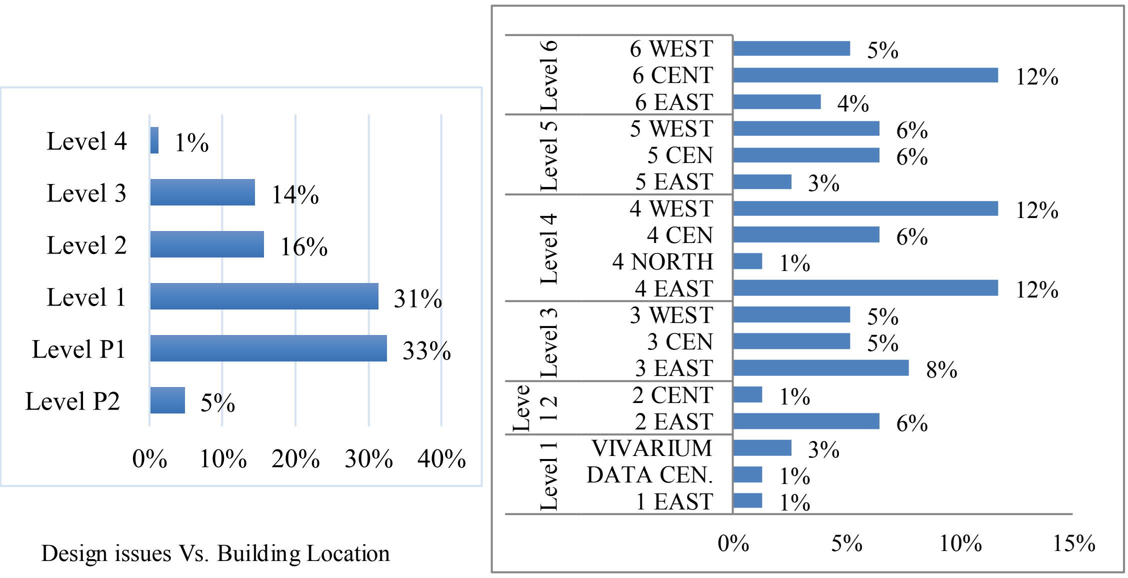


FIG. 12: Left- location of design coordination issue occurrences in case study A. Right- location of design coordination issue occurrences in case study B. The size of each segment shows percentage out of all design issues.

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 conclude that not only mechanical rooms are in need of intense design coordination, but also the spaces leading to the mechanical room (e.g. adjacent zone and levels) have high distribution of design coordination 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.

6.4 Analysis of design issue resolution rate

We found that by the end of the last design coordination meeting in case study B (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 case study A, and 12 consecutive design coordination meetings of case study B (FIG. 13). The 12 meetings of case study B were the last design coordination meetings before construction completion.

As FIG. 13 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.

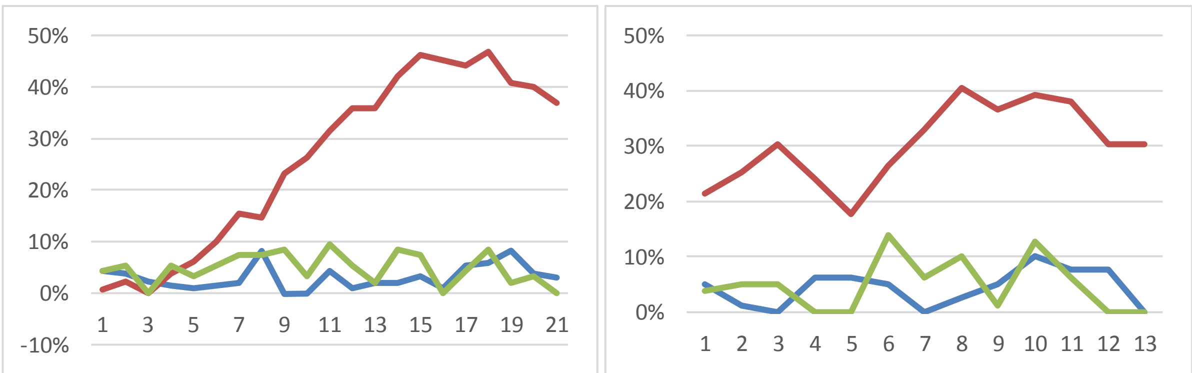
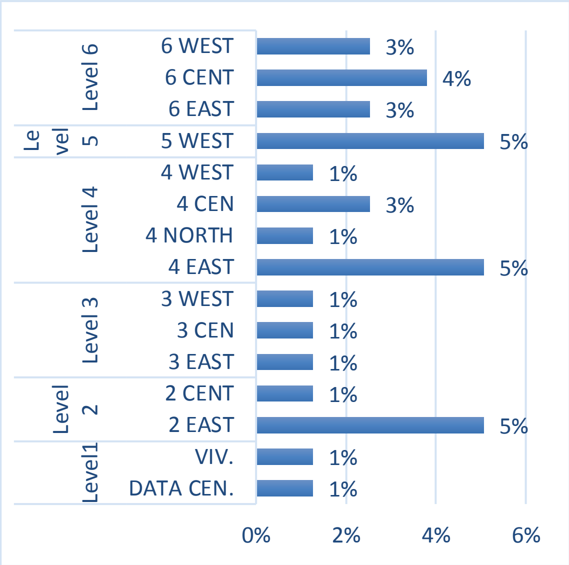


FIG. 13: Left- Issue resolution rate in 21 consecutive meetings in case study A. Right- Issue resolution rate in the last 12 consecutive meetings in case study B. Blue: % of resolved issues per meeting, Green: % of new issues added, Red: % of total design issues remaining unresolved at the end meeting.

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. FIG. 14-(left) illustrates the ratio of design issue types remaining unresolved per design issue category by the end of construction on case study B. 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.



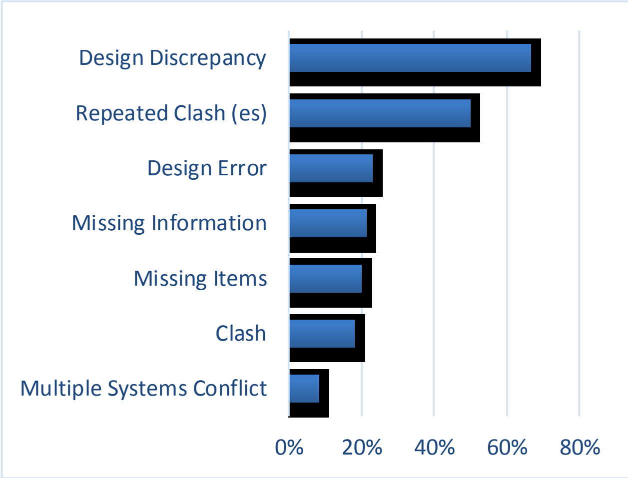


FIG. 14: Left - Percentage of design issues remaining unresolved per all design issues in each issue category on case study B. Right - Distribution of unresolved design issues across various levels and zones on case study B.

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, FIG. 14-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 FIG. 12 (right), with FIG. 14 (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 case study B, 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 FIG. 15 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.

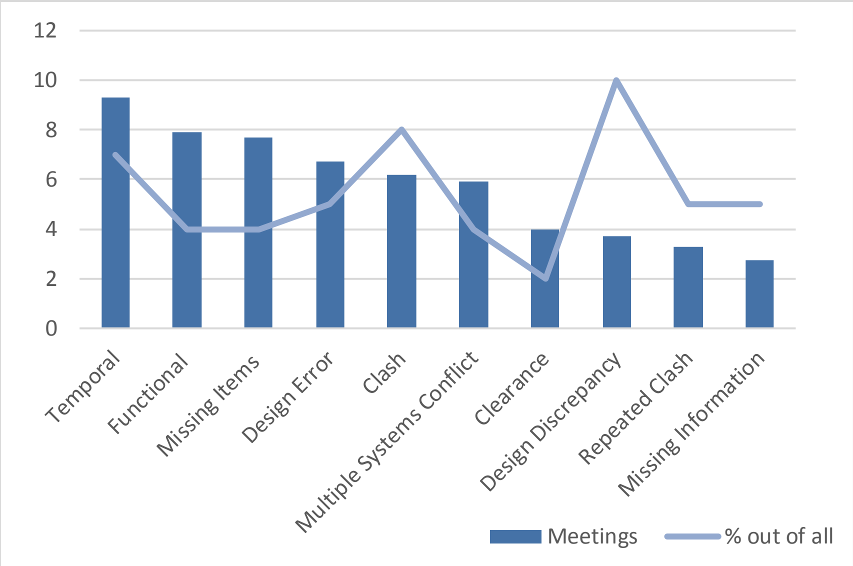


FIG. 15: The average number of meetings it took to resolve design issues (bar chart). The line bar on top of bars represents the percentage out of all of the design issues we analyzed.

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.

7. VALIDATION AND LIMITATIONS

In this section, we discuss our validation strategies as well as limitations of this study. These concepts are explained in the subsequent sub-sections in detail.

7.1 VALIDATION

We validated this study by employing three approaches to ensure generality of our findings, including employing reliability assessment, inter-coder reliability testing, and expert interviews. The validation methods utilized in this research were not performed in isolation, but rather, each phase informed the next. In terms of reliability assessment, we coded case study B transcription with the categories that emerged from case study A. We were able to categorize all design issues based on our taxonomy emerging from case study A. 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 case study B, 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 case study B, 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 him 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 0.88, 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 and generalization (Kreider et al 2010; Howard and Bjork 2007; 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. According to the interviewees the taxonomy could be applied when identifying design coordination issues at the design issue identification phase, raising the design issue during issue resolution meetings and identifying all parties involved, and when documenting issues during design coordination issue documentation.

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.

7.2 Limitations

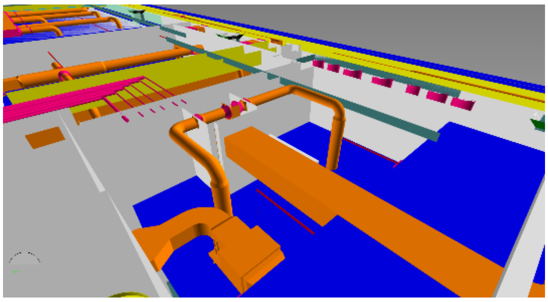
In terms of bias, one of the primary reasons qualitative methods have not been embraced by all researchers in the past, is the types of bias and subjectivity associated with such approaches (Leicht et al., 2010). That is, many have argued that a researcher's personal bias plays too great of a role in gathering, synthesizing, and analyzing qualitative data (Hammersley and Gomm, 1997). 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 various methods of verification such as a replica case study, and interviews with the practitioners helped eliminating the bias to a great extent.

In terms of analyzed design coordination issues, we acknowledge that the coordination issues studied in this project may not include all design coordination issues practitioners encounter throughout the design coordination process, we believe the complexity and depth of the case studies has allowed the taxonomy to include most complex design coordination types. 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 paper. Specifically, the taxonomy should be re-examined with alternative settings, and collaboration tools (e.g. heavier use of Virtual Reality, Cloud BIM). In addition, it is worth examining the impact of organizational and project structure (such as contractual requirements, minimum Level of Detail (LOD), and project delivery type) on the taxonomy developed in this paper.

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 FIG. 16 shows, in case study B 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.* "

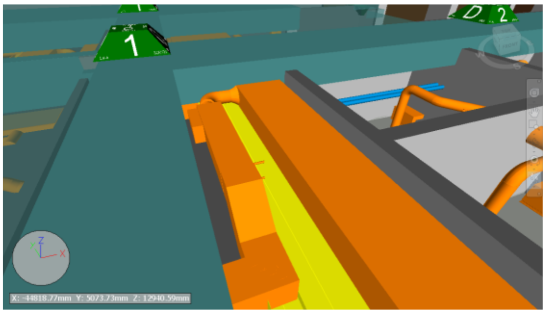


The already constructed ducts (orange) on open space has created a challenge for the plumbing and electrical trades to route their systems. Re-design of a portion of their system was required. Approximate time impact: 2 weeks at discovery of the issue. Actual time impact: 6 weeks to resolve.

FIG. 16: 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 case study A, 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 case study B, 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, case study A 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 case study A (design-build), direct communication was more frequent, which is not surprising given that the design of the project was under the responsibility of the general contractor.

- **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 case study A 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 FIG. 17 shows, sometimes an entire floor had to be re-modeled and re-routed to rectify a coordination issue.



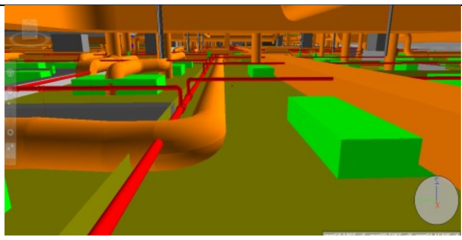
All ducts are routed on the same route as slab bands in level 2. A re-route and re-design of the entire floor ducts was required. Approximate time impact: 1 month at discovery of the issue. Actual time impact: 2 months to resolve.

FIG. 17: 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 5 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 5 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 disagrees 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 5: 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 case study B, design issues were tagged with trade-specific drawing page number and a zone on each floor (e.g. Level 4 Center, M5, A3). On case study A 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 5 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 increase of 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.

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 design coordination process of design issue identification, resolution, and documentation. We classified BIM 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 validation of our findings, we based our taxonomy on the findings of one case study and coded another case study with our taxonomy to ensure our findings are extendable to other BIM-based design coordination projects. 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. Finally, we recommend developing a prototype implementation of our taxonomy and testing it with in a new construction project to better understand how it can help practitioners to identify, manage, and resolve coordination issues.

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