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A FRAMEWORK FOR CLASSIFYING BIM DESIGN COORDINATION ISSUES.

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Abstract: Design coordination and conflict detection are the most common and highly valued uses of Building Information Modeling (BIM). The process is essential as critical design decisions are often made in this stage. BIM promises to support automatic evaluation of building design, rather than the manual, iterative and time-consuming evaluation of CAD drawings. However, we have observed that current BIM tools are unable to identify many types of design coordination issues and that these issues are particularly challenging to manage and resolve. This research is based on ethnographic field studies of two building design coordination processes, examining how practitioners identify, resolve and document design issues during design coordination process. We coded and analyzed over 60 meetings to investigate the characteristics of BIM design coordination issues, and developed a framework based on prior research and our own observations to classify design coordination issues. We classified design coordination issues into seven categorize of spatial, clearance, physical, inquiry, systematic design errors and missing information. We also observed and analysed design issues' frequency of occurrence, and investigated the resolution rate of design issues. We believe our characterization of design issues can help practitioners better identify, categorize, resolve, and document design issues, as well as re-using generated knowledge of resolving same type of issues throughout design coordination.

Keywords: BIM, Design Coordination, Design Issue, Errors, Clash Detection, Collaboration, Interactive Workspaces, Design Artifacts, Building Systems, MEP coordination.

1 INTRODUCTION

In complex building projects, design coordination is a critical and challenging task. It involves the detailed layout and configuration of the various building systems such that it complies with design, construction, and operations criteria (Tatum and Korman 2000). Recent advancements in Building Information Modeling (BIM) tools have had a significant impact on the efficiency and efficacy of the design coordination process. Studies have shown that design coordination and conflict detection with BIM is one of the most frequent and valued uses of BIM in the construction sector (Bernstein and Jones 2012). Communication of project information through paper-based information representations limits the team's ability to work *t*ogether, to solve problems and make decisions during design meetings (Fischer et al.

2002). In contrast, teams using BIM tools for Mechanical Electrical & Plumbing (MEP) coordination are found more likely to be satisfied with the meeting process and spend less time arguing over issues compared to paper based design coordination meetings. (Liston, Fischer, and Kunz 2000).

BIM supports the automatic evaluation of building design, rather than the manual, iterative and time-consuming evaluation of CAD drawings (Lee, Park, and Won 2012). However, we observed that not all design coordination issues are identifiable using state of the art BIM tools, specifically the design issues that are not geometrically identifiable (using the geometry of building components to automatically detect conflicts). Prior research (e.g. Tabesh and Staub-French (2006), Wang and Liete (2014)) have addressed many aspects of design issues including their context and classification. However, they focused on design issues that are geometrically identifiable (e.g. conflicts between two components), rather than non-geometrically identifiable (e.g. inquiries, and missing model components).

We conducted two ethnographic case studies of complex building design coordination processes using state of the art BIM tools. We characterized the design issues practitioners identified, resolved and documented throughout design coordination, through developing a framework for classifying design issues based on prior studies and our own observations, analyzing their frequency of occurrence in both case studies, and investigating the resolution rate of the design issues in one of the case studies. We found that the case study in early construction stage, involved more design issues of constructability and incorrect design details whereas the one in late construction stage faced more design issues of inquiry, and as-built missing components.

2 MOTIVATING CASE STUDIES

We performed two ethnographic field studies of design coordination processes to gain a better understating of the current practice and identify its shortcomings. Over the course of design and construction, BIM was used extensively to coordinate designs involving different consultants and sub-trades. In both projects, the meeting participants consisted of representatives from the different trades involved in the project, including the owner, the construction manager, architect, engineering consultants and construction sub-trades. The meetings always had at least six active participants and in most cases the MEP coordinator and the BIM navigator were present. On some occasions, when a participant was not present, he/she participated remotely through conference calls or online video conferencing tools

Case study A: The newly constructed Pharmaceutical Sciences Building (Figure 2) at the University of British Columbia, Vancouver campus is a 18,000 m2 facility, providing a variety of teaching and learning spaces from lecture halls and seminar rooms, to a pharmacist clinic and three floors of research laboratories. The project had considerably complicated MEP systems along with a unique architectural design, which made design coordination and constructability the key concerns for this fast track project. Since the beginning of construction, weekly meetings were held in our BIM Trailer (Figure 1) on the construction site. The BIM Trailer was equipped with two large-screen touch displays, connected to separate computers displaying 2D and 3D digital information. Construction of the project started in June 2010 and the building was delivered on time for occupancy in September 2012. Most participants were the ones creating the BIM for trades, so they had considerable experience with BIM. However, few participants were less familiar with interactions with BIM and digital tools.

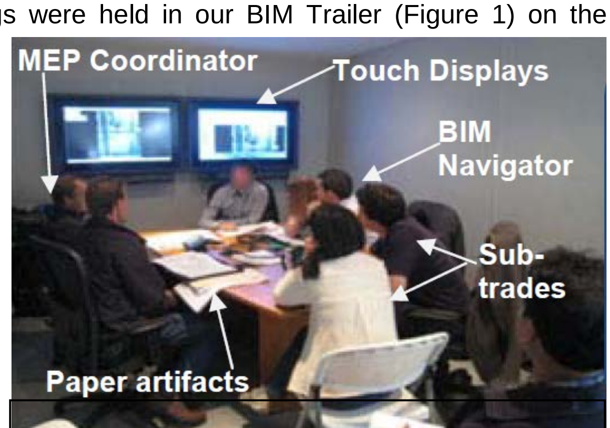


Figure 1: Meeting environment from a design coordination meeting in case study A.

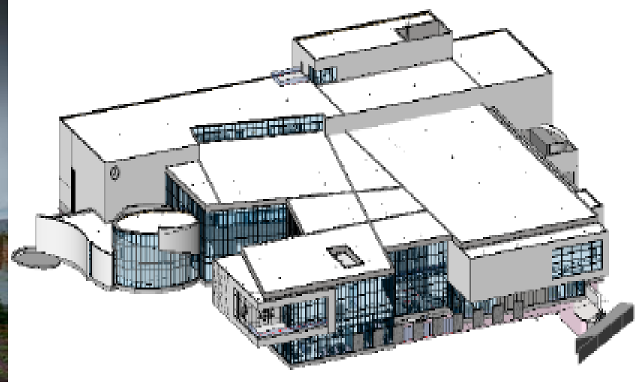


Figure 2: (Left) - UBC Pharmaceutical Building (Image courtesy of UBC Treasury)

Figure 3: (Right) Royal Alberta Museum Architectural model (courtesy of Ledcor Design-Build Inc.)

Case study B: currently under construction (early construction stage), the Royal Alberta Museum (Figure 3) building project involves the construction of a 25,349 m2 building located in downtown Edmonton, Alberta on a site measuring 20,024 m2. The project, in its current state, was initiated in 2011 under a design-build procurement mode. The total budget for this project is $340M while the construction budget alone is $260M. The project is scheduled to be completed in June of 2016. In terms of level of expertise with BIM, most project participants have no experience (35%) or consider themselves as beginners (35%) while 22% consider themselves advanced BIM users. We remotely participated, recorded and observed participants conducting design coordination, as well as observing and analysing various design coordination issues participants identified, resolved and documented throughout design coordination.

2.1 Design Coordination Issue Resolution Process

Based on our observations, we have come to understand that resolving a design coordination issue using BIM involves a cycle of three interconnected steps: Issue preparation (identification) issue resolution and issue documentation (Figure 4). Each of these design coordination steps shown in Figure 4 are comprised of smaller (micro) steps that shape the current practice of identifying, resolving and documenting BIM design coordination tools. This section attempts to better illustrate the micro steps involved the process as well as highlighting the observed challenges practitioners face throughout design coordination process. We elaborate this by showing how one particular issue which we observed was identified, resolved and documented in a case study.

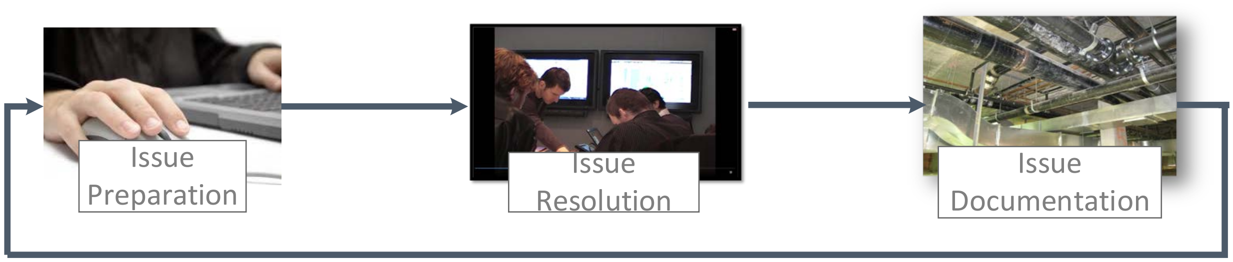
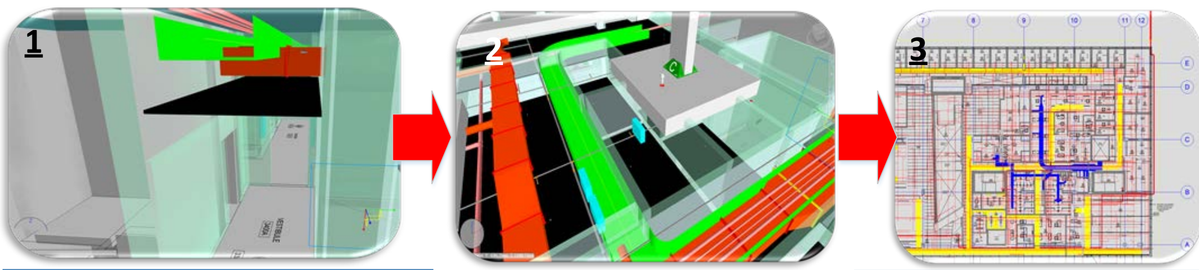


Figure 4: BIM design coordination process

Figure 5 - image 1 shows an issue the BIM navigator picked among hundreds of geometrically identified issues. He examined it in detail, and communicated it with project coordinator. In the same figure - image 2, shows how the coordinator zoomed out to inspect the issue. He then communicated it with different building systems representatives and found the need for a group discussion. He prepares another view (Image 3) to better outline the issue and the systems involved prior to issue resolution meeting.



-BIM Navigator (N) distinguishes a clash B/W Cable Tray & Duct.
- determines a conflict B/W 3 systems.
-Takes snapshot & sends to Coordinator.

-Coordinator (C) finds 3 systems are *congested* near column cap.
- e-mails electrical & Mechanical Reps.
- Determines a discussion is needed.

- (C) Prepares & Highlights electrical & mechanical clashing systems in 2D.
-Sends to team prior to meeting.
-Asks Structrural to find alternatives.

Figure 5: Design Issue Identification Process

To better show the remaining steps involved in resolution of above design issue, Figure 6 – images 1 and 2 shows how that issue was presented, shown and discussed in the coordination meeting as well as how participants interacted with the design artifacts. In image 3, the architect sates that the issue needs to be further discussed as input from other project stake holders are required. At this stage the coordinator determines that the issue needs to be documented for future follow-ups.

-(C) Brings 2D snapshot
-*Explains* which Electrical & mechanical parts need moving.
-Highlights *congestion* under ceiling.

-(N) Brings 3D view, uses section codes and Grids to find issue. He zooms in, makes objects transparent, changes view, & turns off the structural model.

-Architect says rooms are small and the *ceiling cannot be lowered*.
-Pulls out his paper drawings shows *height restrictions*.
- (C) Flags issue to discuss W Owner

Figure 6: Design Issue Resolution Process

In terms of issue documentation, once the discussion on a certain issue reached an end (e.g. resolved, required further input from a different source, or needed follow up in the future), depending on the importance of the issue, the coordinator documented the details of each issue including its status, location, involved systems, snapshot(s), entry and solution dates, proposed solution and details of how it could be resolved in a spreadsheet containing all issues (Figure 7). In both projects A & B, the same documentation format, and details were used to document the issues. However, in project A, participants kept all resolved and non-resolved issues in a single file, and in case study B they used multiple files.

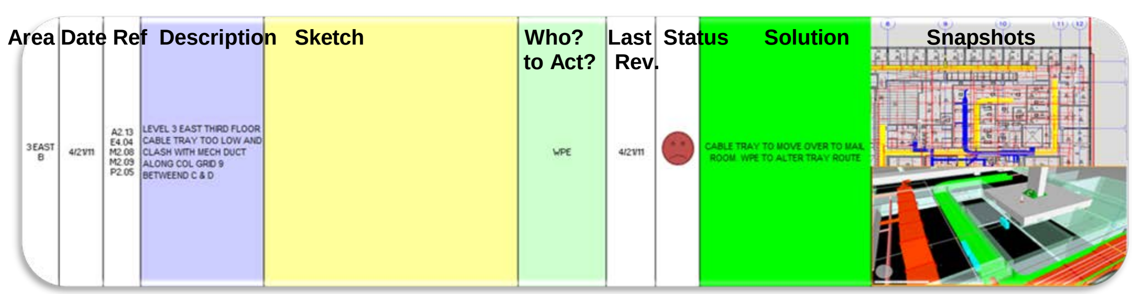


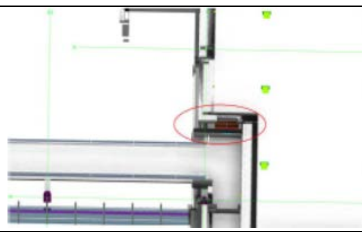
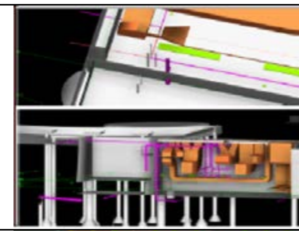
Figure 7: Design Issue Documentation

2.2 Limitations of Current Practice

Although the current process of identifying and preparing Issues seem ad-hoc, often when two building systems are integrated using state of the art BIM tools, thousands of design conflicts are detected, including numerous false ones. As Table 1 shows, the issues involved in design coordination sometimes go beyond simply geometrically detected design issues. Such design issues involve practitioners' knowledge and expertise to be able to be identified. In prior research this is often called practitioner's rationale (Tommelein and Gholami 2012), which requires deep understanding of different construction systems, requirements and the codes.

While attempting to classify the issues observed in both case studies, we were unable to classify observed issues using the current points of departure in the field. Although previous studies (e.g. Tabesh and Staub-French (2006), Tommelein and Gholami (2012), Wang and Liete (2014), and Lee, Park, and Won (2012)) have effectively addressed major geometrically identifiable design coordination issues (e.g. a mechanical duct conflicting with structural column caps), few research characterized issues that are more complex in nature and are not identified through model based automatic clash detection (we call these non-geometrically identifiable). Design issues such as inquiries about maintenance and installation, or wrong dedicated openings in different systems (Table 1) have a significant impact on the design coordination process.

Table 1: non-geometrically identifiable design coordination issue examples

# & Case Study	Description	Snapshot	# & Case Study	Description	Snapshot
1- A	Structural floor opening is not big enough for the mechanical duct (1025X 350)		**2 - B**	Plumbing conflicts W/ access ladder – confirm if there is enough room to climb ladder.	
3 - B	HVAC duct vs. cable tray vs. column cap. Ask UBC – if ceiling can be lowered.		**4 - B**	Electrical lighting conflicts W structural beams. Cannot fit any lights. Lighting system change required.	

Most researchers (Inc. Tabesh and Staub-French 2006, Tommelein and Gholami 2012, Wang and Leite 2012) have focused on geometrically identifiable design issues, however, we believe there is a need for a wider framework that can address and classify both geometrically and non-geometrically identifiable BIM design issues. We believe having access to such framework can improve design issue identification and documentation for BIM based design coordination processes. We envision having a framework combined with a central repository for design issues for classifying design issues can help practitioners classify design issues from the beginning of issue identification, track issues throughout their resolution and help with issue documentation throughout the BIM design Coordination process.

3 RELEVANT LITERATURE

This research has built on findings of past research as a foundation of the framework we have developed in section 5.1. although different researchers have used different terminologies (including design errors, conflicts and MEP clash) for referring to what we call BIM design coordination issue (design issue in short) in this article, there are notable similarities between their research and ours that helped us significantly to build the framework. In this section we aim to address these points of departures briefly and highlight what we have built on:

As one of the pioneers of design coordination issue characterization, (Korman, Fischer, and Tatum 2003) classified design issues into three main categories of design criteria, construction, and operations issues. They also identified design issue attributes as geometric characteristics (component dimensions) and topological characteristics (spatial relationships). This work later on became a foundation to which (Tabesh and Staub-French 2006) built on to further classify design issues as tasks of conceptual reasoning (i.e. design validation, detailing, and sequencing), spatial reasoning (i.e., layout, routing and positioning) and underlying reasons behind the constraints identified in each discipline (i.e., tolerance, productivity, space, performance, access, safety and aesthetics).

Other researchers such as (Wang and Liete 2014) attempted to address design issue resolution knowledge capture, they attempted to provide a formalized representation schema for MEP coordination to present factors involved in cash analysis, clash resolution and management. Similar to this study their schema was developed based on literature review and findings of two case studies. On the other hand, they solely focused on geometrically identifiable issues, covering clash description, clash context, clash evaluation, and clash management items. In another attempt, while proposing a structured method for analysing BIM's return on investment other research (Lee, Park, and Won 2012) classified design issues in terms of their cause, likelihood of identification, impact on schedule, impact on quality and impact on direct cost.

Previous research mainly focused on characterizing geometrically identifiable design issues for BIM building design coordination meetings. Most issues identified in the previous research focused on the components itself. These included highlighting BIM's capabilities and strength for visualization of design issues (Tabesh and Staub-French 2006), representing geometrically identified clashes (Wang and Liete 2014), and formalizing knowledge representation for clashes (Tommelein and Gholami 2012). BIM design coordination issues are comprised of both non-geometrically and geometrically identified design issues. Non-geometrically intedentified issues are mostly manually identified, often comprising of multiple geometrically identified design issues. Although the current research has provided a good point of departure for characterizing and classifying design issues, our findings suggest that there is a need a for a better design issue classification framework that can address all design issues in BIM design coordination processes.

4 METHODOLOGY

We observed (in-person and remotely) and video recorded weekly design coordination meetings from the early stages of design through construction of the building systems, recorded over 43 design coordination meetings of which 32 meetings were held in our BIM trailer on case study A, observed the design coordination process in case study B through design and early construction of building structures, and analysed design coordination meetings in both case studies A & B. We conducted a qualitative assessment of the meetings initially to determine our focus area for a detailed analysis. We had access to construction documents, BIM files, site progress, design issue spreadsheets and some of the communication between project participants.

In particular, we investigated how design issue were identified, communicated among project coordinators and navigators, presented and resolved issues, their documentation approach and their future follow-up regarding each issue. We considered each issue first and tracked how that issue was identified through checking the BIM files of each meeting, how it was resolved through observing specific segments of the meeting related to that issue and by analyzing participants' notes and issue documentation spreadsheets regarding each issue. This methodology enabled us to conduct most of our research qualitatively, rather than the quantitatively.

In addition, in order to investigate issue identification process in detail, we conducted a think-aloud observation (Lewis, 1982) while a BIM Navigator performed issue preparations on a high-rise multipurpose facility in Vancouver, BC. We asked the navigator to say whatever he was looking at, thinking, doing, and feeling as he performed task. This enabled us to see first-hand the process of task completion. We observed how the navigator performed 3D model integrations and clash detection, distinguished between true and false clashes, communicated with the project coordinator to discuss each issue and prepared the coordination meeting agenda. This observation method helped us to better capture how design issues are identified and how participants communicate and work together prior to meetings.

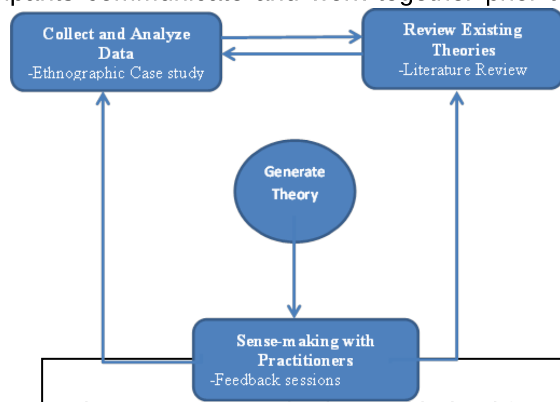


Figure 8: RQ1 Methodology (derived from Green et al. 2010)

Throughout this study, we have aimed to build our research methodology based on recommendations of (Green, Kao, and Larsen 2010). We are following their research protocol to continuously compare collected data and search "for resonance with conceptual ideas derived from ongoing literature searches". Figure 8 shows our adaptation of methodology for their suggested methodology for generating theory through ethnographic case study. This methodology has allowed us to continuously improve our findings as we studied the literature.

5 CHARACTERIZATION OF DESIGN COORDINATION ISSUES

5.1 Design Issue Classification Framework

As discussed above, through observation and characterization of design issues in both case studies A & B, we found essential points of departure to help us better shape our understanding of issue classification. In Table 2, we have shown various design issues we observed along with their identification (detection) method, category, sub description, example of an actual issue that we captured, as well as a snapshot of that issue, to better elaborate our classification of the design issues. We also have identified the design issues previously identified by each key point of departure. The key points of departure used in the framework are respectively (Korman, Fischer, and Tatum 2003),(Tommelein and Gholami 2012),(Wong and Leite 2014), and (Lee, Park, and Won 2012).

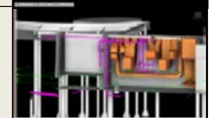
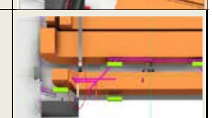
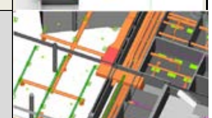
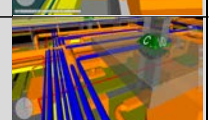
To elaborate further on what we have built on in terms of classification of design issues from the existing knowledge, we have adopted he most common classification of design issues: hard (actual) and soft (extended) ((Korman, Fischer, and Tatum 2003) and (Tabesh and Staub-French 2006)). As well as the time clash which refers to constructability and order of components being installed (Tommelein and Gholami 2012). We also built on (Lee, Park, and Won 2012)'s identification design issue causes: illogical design, discrepancies between drawings, and missing items. These classifications are explained below.

5.2 Analysing Design Issues in Case Studies A & B

We have classified the observed issues in both case studies A & B based on our developed framework (Table 2). The issues in each case study were investigated independently based on what the practitioners have documented and our own observations of the meetings. Having two case studies helped us to validate and evaluate the framework. During the analysis of the issues, the framework was re-iterated multiple times, revisiting issue categories, terminology and examples multiple times to ensure all design issues in both case studies could be classified using the developed framework. Also, having two case studies helped us achieve a wider generalizability for the developed framework. In total we analysed 98 issues from case study A and 120 issues from case study B (Figure 9). The figures show each design issue sub-category using different colours, as well as their frequency of occurrence in relation to total number of issues in each case study in a percentage format.

As Figure 9 shows, both projects nearly equal proportions of issues due to systematic design errors, these include illogical design, trade design conflict, and multiple systems conflicts. However, due to the stage of each case study the design issues handled by each team differ

Table 2: Framework for classifying issues in BIM design coordination

Identification	Category	Sub-Category	Description	Example	Snapshot
Geometrically Identified	**Spatial**	**Time** [1,2]	Components occupying the same space- constructability /operability	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 W function of systems.	
	Clearance	**Clearance** [1,2,3]	Components interfere with extended spaces (e.g. Access)	Plumbing conflicts W access ladder – is there enough room to climb ladder?	
	Physical	**2 Objects** [1,2,3]	Physical interferences BW 2 single components	HVAC duct collides W column	
		Multiple Objects	Physical interferences BW components , multiple times	Column colliding with Ducts in all floors.	
Non- Geometrically Identified	**Systematic Design Error**	**Illogical design** [4]	System wide conflicts Due to lack of coordination BW trades.	Mechanical duct conflicts with structural concrete beam.	
		Multiple Systems Conflict	Multiple building systems are involved in a single area.	HTG, CHW, sprinkler main, FCU, cable all required to fit in ceiling under slab band	
		Trades Design Conflict	Condensed Systems, Essential change of type, systems required	Electrical lighting conflicts W structural beams. Cannot fit any lights.	
		Incorrect Design Details [4]	Not design to fit, too big, to small openings. Too big to bring in	Structural floor opening is not big enough for the mechanical duct	
	Missing Information	**As-Built Missing** [4]	As built missing/ installation info not provided	Location of mechanical duct openings in metal wall panels.	
		Object Related Info Missing	Details related to specific components missing	Dimensions of mechanical component not specified	
		Modeled Component Missing	Model of component not ready yet, or needs remodeling.	Pipework clashing with duct- waiting for final Architectural model	
	Inquiry	**Inquiry**	More info needed regarding model details	Is cable tray required along south side of room?	
		Legend:	1 - Korman et al. (2003) 2-Tommelein (2012)	3-Wang & Leite (2014) 4-Lee et al (2012)	W=With BW=Between

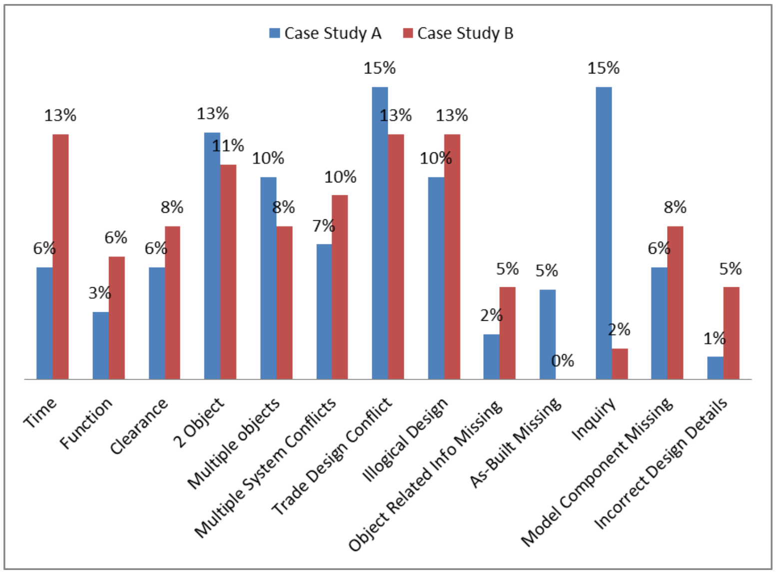


Figure 9: Analysed BIM design coordination issues in case study A & B (% of total issues analysed)

Since, case study A was in the handover phase whereas case study B only had its major structure built at the time of this study, it is not surprising to see case study A's time design issues (constructability) twice the size of design issues in case study A. On the other hand, we can see more inquiries in case study A, which could be due to the final stages of the project where multi project stake holders require different things.

In addition, it is not surprising to see no design issues relating to as built models, since there were little mechanical components installed at the time of design coordination. However, it is noticeable that incorrect design detail issues (e.g. wrong opening sizes) were almost 3 times higher in case study B. this could reflect the miss-coordination between different system prior to construction phase. In addition, missing model components contributed to an average of 7% of design issues in both case studies, which can emphasis on the importance of having every discipline meeting the coordination deadlines.

5.3 Analyzing Issue Resolution Rate

Classifying the design issues in the previous section, we found that in some issue resolution meetings, participants identified and resolved more issues than other ones. Also, towards the end of construction on case study A, a large number of design issues remained un-resolved on the documents. Therefore, we conducted an issue resolution rate study to better understand how often design issues were added, resolved and how many of them remained unresolved by the end of each meeting. We performed this study by tracking and analyzing issues of 12 consecutive design coordination meetings (Figure 10). These 12 meetings were the last design coordination meetings for case study A.

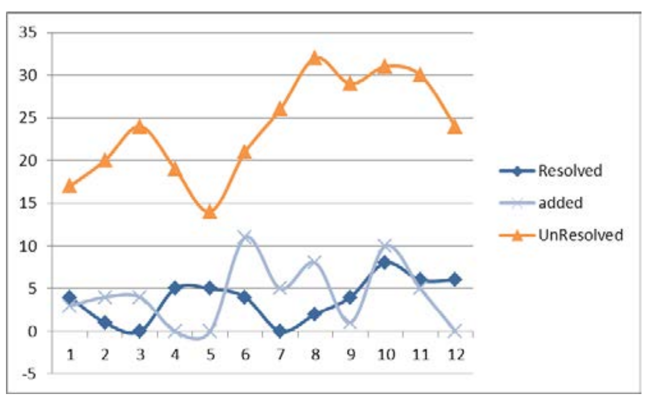


Figure 10: Issue Resolution Rate in 12 Consecutive Meetings

Furthermore, it is surprising that 20% of the design issues remained unresolved by the end of design coordination stage (final days of construction). We believe some of these issues could have been resolved on site, or they were not on the priority to-do list. Also, we observed that participants often spent an entire meeting resolving one large scale design issues, whereas in another one they added more than 10 and resolved more than 11 issues, which could highlight the complexity of some design issues over the others.

Finally, In terms of design issue documentation, we observed when design coordination meetings were poorly documented, the result had a direct influence as to preparations of the next meeting. For instance, in one occasion, the meeting coordinator could not attend the meeting and no other participant was in charge of the meeting documentation and task assignment, as a result the first 30 minutes of the next meeting was dedicated to revise prior progress and the meeting ended early as the necessary models were not prepared by responsible trades for design coordination.

6 CONCLUSION AND FUTURE WORK

We have conducted two ethnographic field studies to understand how participants identify, resolve and document design coordination issues in BIM based building design coordination processes. We developed a framework to classify both geometrically and non-geometrically identifiable design coordination issues, analyzed two case studies based on developed framework, investigated design issue resolution rates, and highlighted the role of documentation on issue preparations of subsequent meetings. Our characterization identified the non-geometrically identifiable design issues that were rarely identified in the previous research.

We believe further validation strategies are required at this stage in order to highlight the shortcomings of the developed framework. In particular we envision conducting feedback sessions with practitioners to ensure that the developed framework resonates with their knowledge. Other strategies could include performing industry workshops, in order to capture insights of other practitioners specifically not those in Feedback Sessions to achieve wider generalizability.

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