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ANALYSIS OF BOTTLENECKS IN BIM-BASED BUILDING DESIGN COORDINATION PROCESS AND BENCHMARKING STATE OF THE ART BIM TOOLS

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Abstract: Design coordination and conflict detection with BIM are of the most frequent and valued uses of BIM in the construction sector. However, through prior studies and our own observations of design coordination meetings, we have found that even when BIM tools are readily available. Practitioners frequently revert back to 2D digital and paper drawings and rarely interact with BIM tools on their own without the help of a BIM navigator, and many coordination issues are resolved on construction sites, knowledge regarding the design issues often get lost throughout coordination process. Having rigorously analyzed existing literature, we proposed a set of functionalities to address these challenges, and analyzed widely used state of the art BIM tools to benchmark their capabilities and functionalities. We conducted interviews with practitioners to assess priority of each function. We found Solibiri followed by BIM 360 Glue as most, and Autodesk Revit and Tekla BIMSight, as least compatible platforms. The best-supported functionalities were zooming, panning, and commenting, and the least supported were multi-model format and design issue documentation across all platforms. We believe the results of this research are useful for the AEC industry researchers and professionals, as well as the BIM software development community, as it highlights the bottlenecks, the functionalities needed and their priority during design coordination meetings.

Keywords: BIM, Design Coordination, Design Issue, Clash Detection, Collaboration, Interactive Workspaces, Interaction with Artifacts, Design Artifacts, Cloud BIM, Knowledge Capture, MEP coordination.

1. Introduction

Design coordination is a critical and challenging task to ensure that the building design meets the functional, aesthetic, and economic requirements of project stakeholders. The coordination process requires extensive knowledge of building systems themselves, e.g. checking that water lines are not routed above electrical equipment and assuring adequate access for cleaning reheat coils located in ductwork. The design coordination process allows project stakeholders to detect potential issues and conflicts in building systems before they become an issue on the construction site. The cost of design coordination can be significant, with some estimates of six percent of the MEP cost or two percent of the total cost on light industrial construction projects (Tatum and Korman 1999). Many construction industry professionals cite MEP coordination as one of the most challenging tasks encountered in the delivery of construction projects (Korman, Fischer, and Tatum 2003). In a traditional setting, design coordination is usually conducted through visual inspection of 2D drawings, which are then compared for potential conflicts.

Recent advancements in Building Information Modeling (BIM) tools have had a significant impact on the efficiency and efficacy of the design coordination process. The competitive advantage, process problems, technological opportunity, and institutional requirements drive the adoption of innovative tools such as Building Information Modelling (BIM) (Mitropoulos and Tatum 2000). Also, as more advancements are made in 3D design and navigation tools, more governmental bodies are requiring BIM as part of their contractual requirements (Shafiq, Matthews, and Lockley 2013). Despite advantages of BIM, we have found that even when BIM tools are readily available in design coordination settings, project participants face significant challenges and bottlenecks when interacting with BIM, which disrupts and hinders the design coordination process. Practitioners often revert back to 2D paper-based technical drawings as their first choice for technical data exchange between project members, and 3D design information is still underutilized (Leicht et al. 2014). In addition, while BIM promises full cycle automatic evaluation of building design, many design coordination issues are yet to be detected using state of the art BIM tools (Lee, Park, and Won 2012). Furthermore, the more critical issue of BIM design coordination remains not the absence of enabling technologies or methodologies, but the lack of efficient coordination strategies for integrating fragmented work processes e.g. (Dossick and Neff 2010) and (Lee and Kim 2014). BIM in isolation, with little or no discussion or interaction with industry partners (each consultant creating their own in-house representation of the design and components), without any model-based exchange or coordination is commonly not far removed from a traditional 2D process, with document-based exchange and coordination and little or no collaboration (Dossick and Neff 2010).

In our observations of two long-term ethnographic case studies of BIM-based building design coordination, we found bottlenecks in two major areas of design coordination process and interactions with design artifacts. In terms of the BIM design coordination we found (Mehrbod et al. 2015) many coordination issues were resolved on construction sites, translating to additional cost and delays on the project (Assaf and Al-Hejji 2006), and the details and knowledge regarding the design issues, responsible stake holders, and routine 'know-who's often got lost throughout the BIM design coordination process. In terms of interactions with design artifacts, we found (Mehrbod, Staub-French, and Tory 2013) that even when BIM tools are readily available in design coordination settings, project participants face significant challenges and bottlenecks when interacting with BIM, which disrupts and hinders the design coordination process.

In this paper, we highlight the bottlenecks practitioners face during BIM design coordination process, analyze the literature and our own observations on current gaps in the domain, propose functionalities that we believe are essential to more efficient delivery of design coordination processes. In addition, we define priorities based on each design coordination bottleneck, and functionality, and finally analyze the widely used state of the art BIM tools to benchmark their capabilities and functionalities. In terms of our findings, we found inefficient transitions between artifacts, lack of easy to use basic BIM navigation during meetings, inadequate BIM Coordination task capabilities, insufficient issue documentation & knowledge capture and finally, lack of communication and design awareness as key bottlenecks in design coordination. We found Solibiri followed by Autodesk BIM 360 Glue as most compatible platforms with required functionalities, BIMServer, Graphisoft's ArchiCAD and Navisworks to be in the mid-range and the least favourable platforms were Autodesk Revit and Tekla BIMSight, supporting our proposed functionalities.

2. Point of Departure

In this section we summarise the points departure in the fields of interactions with design artifacts, state of the art tool evaluation methods and design coordination knowledge capturing strategies. We briefly summarize the research in each field below.

Interactions and Transitions with Design Artifacts: Earlier work by members of our team (Tory et al. 2008) conducted an ethnographic study exploring how meeting participants used representational artifacts in paper-based building design coordination. They characterized primary interactions with paper and limited 2D digital design artifacts, identified bottlenecks in the coordination process, and provided a taxonomy that characterized the different types of interactions and goals team members had with artifacts digital information during meetings. In terms of transitions between design artifacts, few research have investigated this matter, one notable project was the JUMP project (Terry et al. 2007), which developed a set of tangible tools to navigate and interact with design artifacts using 2D augmented technical drawings.

In JUMP, filter tokens were placed on top of paper drawings to access the 2D visualization of design information. Other research (Tory 2004) found that 3D information is useful for providing an overview of the object being designed and conveys the 3D shape, while 2D information is better for displaying interior details, making precise measurements, and enabling simpler navigation.

State of the Art BIM Platform Evaluation Strategies: With the adoption and growth of cloud based platforms in the recent years, and considering the large and complicated format of BIM files, with the expensive hardware required for operating state of the art BIM platforms, many industry pioneers have attempted to provide a platform for cloud based BIM support. As one of the key points of departure for this research, work of (Shafiq, Matthews, and Lockley 2013) in the BIM cloud domain benchmarked state of the art BIM cloud platforms, identifying the strength and shortcomings of different model collaboration systems. They found that the main barrier for cloud computing is lack of a unified BIM language that can support all trades, need in a project. Other research (Redmond et al. 2012) conducted a survey among industry practitioners to assess and benchmark BIM tools in terms of their capabilities, interoperability, etc.

Design Coordination Knowledge Capturing Strategies: Many studies note that, most construction knowledge is tacit, which resides in the minds of domain experts e.g. (Khalfan et al. 2002). A great portion of construction knowledge is generated and used in the coordination process, which is usually lost afterward, but can be utilized if systematically documented (Wang and Leite 2012). Some researchers (Khalfan et al. 2002) believe that there is a lack of organized processes to capture lessons learned and disseminate useful knowledge to other projects in the AEC industry, there is a strong reliance on informal networks and collaboration and 'know-who' to locate the repository of knowledge (Kamara et al. 2002).

In this section, the relevant literature in terms of interactions with design artifacts, BIM tools benchmarking and transitions, and design coordination knowledge capturing strategies were described. Although the above research provides a comprehensive point of departure for this research through highlighting contributions in each domain, the previous research rarely focuses on the requirements of practitioners in the BIM design coordination settings. This study has advanced the prior state of knowledge in the field by highlighting the bottlenecks practitioners face during design coordination and proposing functionalities that could improve efficiency of BIM design coordination and recue frequency of the bottlenecks. In the following section, we briefly describe the methods used to conduct this research.

3. Case studies

In this section we introduce the two case studies we have observed. The projects had considerably complicated MEP systems along with a unique architectural design, which made design coordination and constructability the key concerns for these fast track projects. Over the course of design and construction, BIM was used extensively to coordinate designs from different consultants and sub-trades.

Case study A - Royal Alberta Museum: The recently constructed Royal Alberta Museum (RAM) building project (**Error! Reference source not found.**- RIGHT) 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. We remotely participated in the design coordination meetings, recorded and observed participants conducting design coordination, and had access to construction drawings, BIM files. We even had access to a series of informal communication between team members (such as circulated emails about design issues), and post meeting design coordination issue documents.

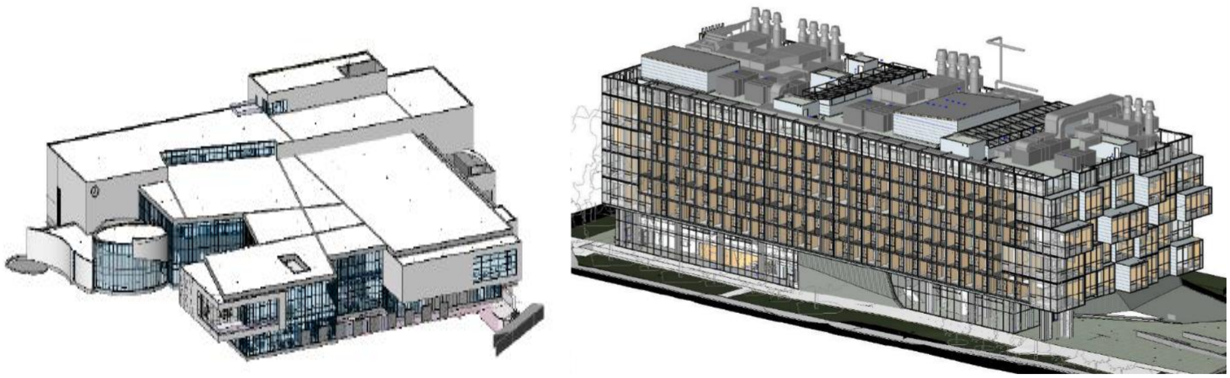

Figure 1: An architectural BIM of Royal Alberta Muslim (left) Integrated BIM of the UBC Pharmaceutical Building (left) (image courtesy of Hughes Condon Marler Architects) (right).

Case study B - UBC Pharmaceutical Building: The newly constructed Pharmaceutical Sciences Building (**Error! Reference source not found.**- LEFT) at the University of British Columbia, Vancouver campus is an 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. Over the course of design and construction, BIM was used extensively to coordinate designs from different consultants and sub-trades. 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.

4. Methods

Throughout this section, we briefly discuss our research methodology involving ethnographic observation of practitioners. We employed a hybrid research method, inspired by prior research (Glaser 1978). Our data included observation of design coordination meetings throughout the design process. Initially, we analyzed the meetings qualitatively (through five-minute vignettes). We then enriched our collected data using axial coding and verified our findings against current literature followed by expert interviews. Due to space constraints, we briefly elaborate on each area of research, essential to the delivery of this research.

Ethnographic Observations: An ethnographic approach was chosen to collect the richest possible data, and to observe meeting participants in their natural setting. We observed and video recorded over 90 weekly design coordination meetings from the early stages of design through construction of the building systems on both case studies.

Data Collection, Analysis, and Enrichment: We collected data analyzed the meetings qualitatively (through five-minute vignettes). These vignettes were selected from the meetings based on richness of interactions, participation of project stake holders and stage in the construction. In the qualitative data collection process, the data was collected un-biasedly through both qualitative and quantitative observations. The guidelines of were also followed by ensuring careful attention to the methodology and rigorous documentation of the meetings. We then enriched our data, by analysing groundedness (frequency of how often a sequence has been applied) and density (number of interlinked actions).

Expert Interviews: We asked three BIM coordinator and navigators who had sufficient BIM expertise to review the BIM building design coordination challenges, the functionalities proposed to address these challenges, and to prioritize these functions, stating the urgency and usability of each function. Many prior research in the field have adopted this approach to ensure validity and generalization (Kreider, Messner, and Dubler 2010).

In this section we summarized the research methods we employed that resulted in better understanding of design coordination issue process and meetings bottlenecks, investigating the literature and proposing functionalities required to address these bottlenecks.

5. Identifying The Bottlenecks in Design Coordination and Functionalities Required Supporting Them.

Throughout the ethnographic case studies and review of our previous findings we have identified five main bottlenecks within the BIM design coordination process. These include Inefficient transitions between artifacts, lack of easy to use basic BIM navigation for fast paced environments, inadequate BIM coordination task capabilities, insufficient issue documentation & knowledge capture, and inconsistencies across design representations. We believe these bottlenecks impede efficiency and efficacy of BIM design coordination process. These bottlenecks have emerged from rigorous analysis of interactions with BIM tools in design coordination meetings e.g. (Mehrbod, Staub-French, and Tory 2013) and analysis of design coordination issue resolution e.g. (Mehrbod et al. 2015). This study has advanced the prior state of knowledge by highlighting these bottlenecks and proposing functionalities that could improve efficiency of BIM design coordination and reduce frequency of the bottlenecks.

In this section we summarize the bottlenecks in design coordination that we have observed throughout our studies and summarize them as shown on table 1. We also, propose the functionalities that we believe could help practitioners better tackle these bottlenecks, in the column next to each bottleneck. We also highlight the priority of having these functionalities as per use and urgency of each function in BIM design coordination.

Table 1: Summary of observed design coordination bottlenecks, and the functionalities required to support them. Numbers next to functionalities indicate items mentioned in prior studies.

bottlenecks observed	Functionality needed	
Challenge & Description	**Functionality**	**Priority**
Inefficient transitions between artifacts: frequent transitions between design artifacts interfered with participants' goals, it typically took several minutes to transition and participants had difficulty finding the required view.	Saving and Loading Views (1,3)	High
	Group Views Together (1)	Low
	Simultaneous 2D access	High
	Link to 2D trade designs	High
Lack of easy to use basic BIM navigation for fast paced environments: although participants had prior experience using BIM, BIM tools were often not fully utilized, initiated by BIM tools not being sufficiently fit for fast-paced navigation environments of the meetings.	Panning (3)	High
	Zooming (1,3)	High
	Rotate (1,3)	High
	Take dimension (1)	Low
	Model Modification (1)	Low
	Grid Support (1)	High
Inadequate BIM coordination task capabilities: BIM tools often did not provide clash detection capabilities, so tools had to be combined, increasing transitions and errors.	Clash Detection (2,4)	High
	Model Comparison (4)	High
	Color Code (1)	Low
	Hide/Unhide components (1)	Low
Insufficient Issue Documentation & Knowledge Capture: most of the knowledge regarding design coordination issues get lost during issue resolution, this knowledge was comprised of two major parts, and the details	Commenting	High
	Annotating (1,3)	High
	Highlighting (1)	Low
	Record Changes	High

captured documenting issues, low-level knowledge of know-hows & resolution progress.	Record Design issues	High
Lack of Communication, other design awareness, inconsistencies across designs: many design issues occurred due to insufficient coordination between trades. E.g. designing teams used incorrect reference points when placing systems, or routed building components within the same space as other trades.	Model Upload/Download (4)	High
	Model Merging (4)	High
	Remote Model Viewing (4)	Low
	Dedicated hardware & bandwidth	Low
	Model Tracking	High
	Support multiple model format (1,4)	High
Legend: 1:(Mehrbod, Staub-French, and Tory 2013), 2:(Mehrbod et al. 2015), 3:(Tory et al. 2008), 4:(Shafiq, Matthews, and Lockley 2013)		

6. BIM Design Coordination Tool Assessment:

Having described the bottlenecks in the BIM design coordination process and the functionalities required to better support them. We analysed the widely used BIM tools in the construction industries we have observed, we initially focused on the most widely used software (Autodesk Revit 2016 & Autodesk Navisworks 2016). Afterwards, this evaluation was expanded to explore Industry Foundation Class (IFC) based BIM tools such as Solibiri Model Checker and Graphisoft Archicad 20. This was later on followed by, creating a platform for analyzing state of the art BIM tools based on findings of : 1:(Mehrbod, Staub-French, and Tory 2013), 2:(Mehrbod et al. 2015), 3:(Tory et al. 2008), 4:(Shafiq, Matthews, and Lockley 2013). In addition, over the course of this study, improvements and new releases of navigation and design software were monitored, and benchmarked. To this date, this research has tested and evaluated various local and cloud based platforms, including: BIMServer; an opens source IFC based Platform (setup as server, conducting model integration and clash detection) (Figure 2-left), Autodesk BIM 360 Glue and Filed, a cloud based being improved constantly using java applets and Revit based models (in a post graduate course, conducting multi-disciplinary clash diction and design coordination) (Figure 2-right). Other platforms evaluated include Advance 2000 M-six VEO, Autodesk Revit, Navisworks, Tekla BIMSight, Solibiri and Graphisoft Archicad. To better understand the domain and its tools, we have further evaluated and benchmarked various 2D platforms including BIM A360, AutoCAD 3D and Adobe Acrobat Professional which are not reflected in this paper.

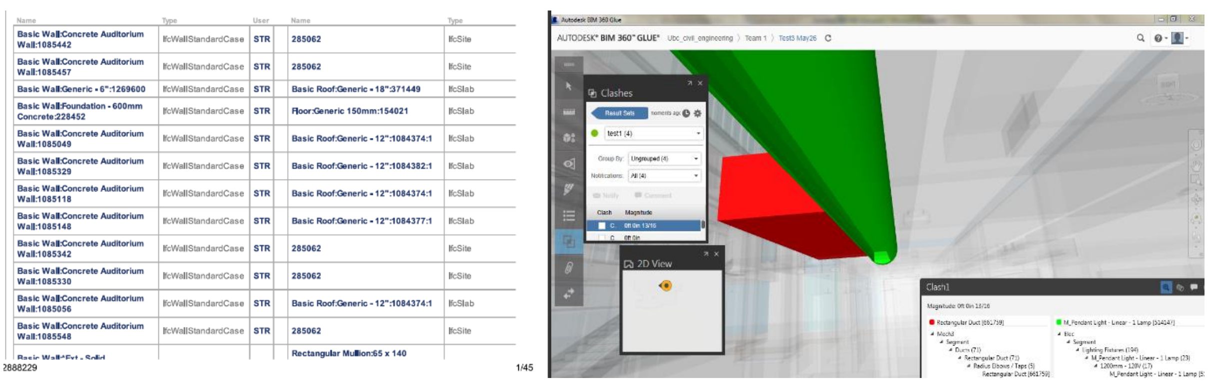

Figure 2: Left - evaluation of BIMServer, errors and conflicts when merging different discipline's models. Right- BIM Glue 360, navigating through merged models, performing clash detection.

in order to better characterize these state of the art BIM tools and provide a clearer picture of their capabilities to support bottlenecks in design coordination. We benchmarked 7 of the most widely used platforms in industry (based on past research, and our own observations of the tools practitioners used).

These platforms included Autodesk Revit, Autodesk Navisworks, Autodesk BIM 360 Glue, Solibiri, Graphisoft Archicad, BIMServer, and Tekla BIMSight.

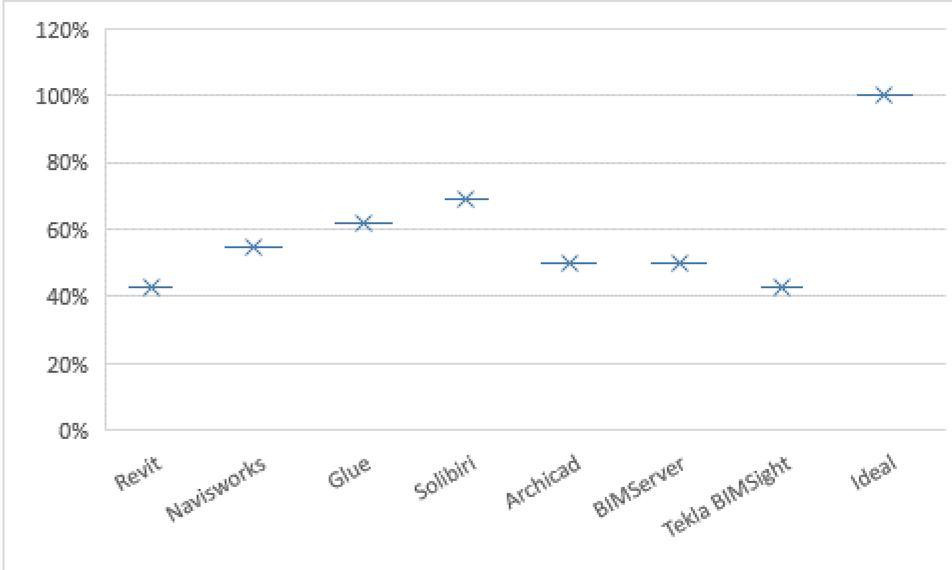

Figure 3: Analysis of state of the art BIM tools against proposed functionalities. based on each functionality having 1 point and weighted priorities. Total score of out of ideal 100%.

As Figure 3 demonstrates, we benchmarked the platforms based on each functionality and we took in to account the priority for each function. We considered 2 points for high priority functions, vs. 1 point for low priority functions. The ideal platform was to support all functionalities, which would have scored 100%. Based on the platforms, we found Solibiri to rank as the most compatible platform with our proposed functionalities required supporting the bottlenecks supporting 69% of the functionalities, followed by Autodesk BIM 360 Glue supporting 62% of the functionalities. We the least favourable platforms were Autodesk Revit and Tekla BIMSight. They both only supported 43% of the functionalities. Based on the chart, we can consider BIMServer, Graphisoft Archicad and Navisworks to be in the mid-range of supporting the required functionalities. Although most BIM cloud tools are designed for model viewing, and document sharing for leading BIM platforms including Graphisoft's ArchiCAD and Autodesk's Revit. (Adamu et al. 2015), found that use of cloud-based technology for BIM projects has several challenges in data management including responsibility, ownership and liability of cloud-based models.

In addition to benchmarking platforms, we performed analysis of how well our requirements are supported through widely utilized platforms. Figure 4 presents our findings regarding availability of each function in the analyzed platforms. To reiterate, these platforms included Autodesk Revit, Autodesk Navisworks, Autodesk BIM 360 Glue, Solibiri, Graphisoft ArchiCAD, BIMServer, and Tekla BIMSight. The best-supported functionalities across all platforms were zooming, panning, and commenting. 100% of the platforms supported these functions. Other well-supported functions were, model merging, rotating, saving / loading views, commenting and highlighting. It is worth mentioning that none of the platform supported multi model format (e.g. ifc, rvt, dwf, etc.) and design issue documentation (recording).

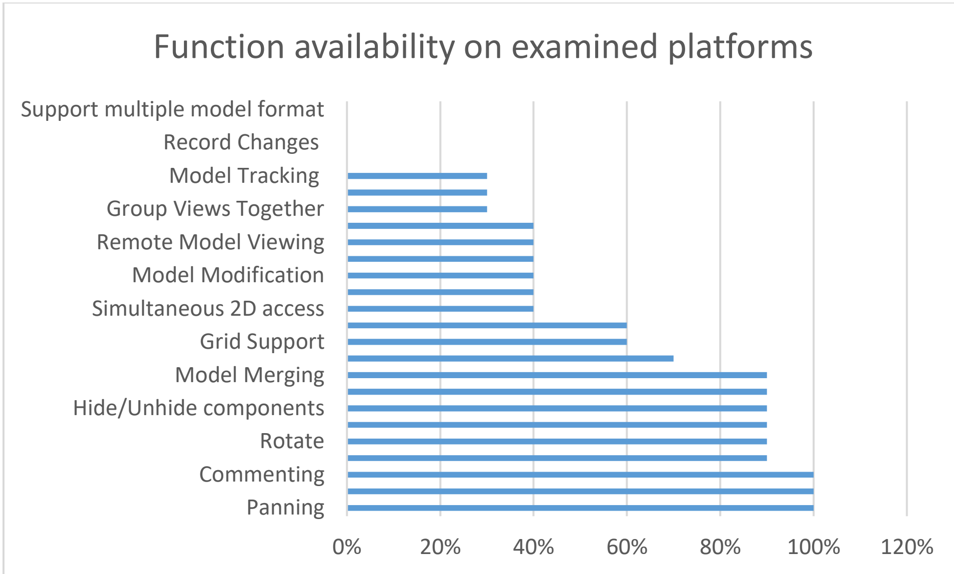

Figure 4: Analysis of availability of required practitioners functionalities across tested state of the art BIM platforms.

In this section, we provided our analysis of widely used state of the art BIM platforms, we benchmarked these platforms based on our understanding of the functionalities required to support BIM design coordination issues. In the next section, we propose future design considerations to better support BIM design coordination needs.

7. Conclusion

In this paper, we uncovered the bottlenecks practitioners face during BIM design coordination, analyzed the literature and our own observations to propose functionalities that we believe are essential to more efficient design coordination meetings and processes. We proposed priorities based on each design coordination bottleneck, and analyzed the widely used state of the art BIM tools to benchmark their capabilities and functionalities. In terms of our findings, we found inefficient transitions between artifacts, lack of easy to use basic BIM navigation during meetings, in adequate BIM Coordination task capabilities, insufficient issue documentation & knowledge capture and finally, lack of communication and design awareness as key bottlenecks in design coordination. We believe the results of this research are useful for the AEC industry researchers and professionals, as well as the BIM software development community, through a better understanding of the bottlenecks in design coordination process, the practitioners required functionalities and the priorities of implementing these functions.

We found Solibiri followed by Autodesk BIM 360 Glue as most compatible platforms, BIMServer, Graphisoft ArchiCAD and Navisworks to be in the mid-range and the least favourable platforms were Autodesk Revit and Tekla BIMSight, supporting our proposed functionalities. In terms of how well various functionalities were supported across different platforms, best-supported functionalities across all platforms were zooming, panning, and commenting. 100% of the platforms supported these functions. Other well-supported functions were, model merging, rotating, saving / loading views, commenting and highlighting. None of the platform supported multi model format (e.g. ifc, rvt, dwg, etc.) and design issue documentation (recording).

We would like to emphasize that the functionalities presented in this paper are only of those, which we believe improve observed BIM design coordination bottlenecks. We propose organizations and industry practitioners take other key factors, such as cost of licensing, BIM protocols and requirements of the clients, programmability and customization of the tools (e.g. add-ons) in to consideration before adopting or implantation of each state of the art BIM platform. We also believe each BIM tool is desirable for a certain function and practitioners should consult their needs prior to selecting a platform. Furthermore, the purpose of this study was to identify the bottlenecks in current BIM building design coordination process, identify the functionalities required to address these bottlenecks, and examine the current tools in use at the time of this study to identify their strength. Although we acknowledge that the state of art BIM tools functionalities may change in the future, however we believe the functionalities mentioned in this paper, could help the software development community to gain a better understanding of practitioners' requirements from state of the art BIM tools. Finally, in terms of future work, we suggest conducting observational quasi-experiments with a large sample of less experienced (more accessible) (e.g. BIM students after training) subjects to examine the impact of availability and accessibility on addressing the bottlenecks described above.

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