ITcon

www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

EXPLORING THE APPROACHES IN THE IMPLEMENTATION OF BIM-BASED MEP COORDINATION IN THE USA

SUBMITTED: January 2015
REVISED: July 2015
PUBLISHED: September 2015 at http://www.itcon.org/2015/22
EDITOR: Ruikar K.

Saman Yarmohammadi, Graduate Research Assistant
Economics of the Sustainable Built Environment (ESBE) Lab,
School of Building Construction, Georgia Institute of Technology, USA
Saman.yar@gatech.edu

Baabak Ashuri, Associate Professor
Economics of the Sustainable Built Environment (ESBE) Lab, School of Building Construction/School of Civil & Environmental Engineering, Georgia Institute of Technology, USA
Baabak@gatech.edu

S*UMMARY*: *The design coordination of Mechanical, Electrical, and Plumbing (MEP) systems is a manual process conducted during preconstruction phase of building projects. The difficulties associated with the conventional MEP coordination process have resulted in extensive efforts to enhance the process through utilization of BIM technology. The widespread adoption of BIM technology by AEC (architecture/engineering/construction) firms has given rise to new means and methods of conducting MEP coordination. However, there is limited knowledge about various approaches that are currently practiced as BIM-based coordination. Also, there is a need to identify information items and metrics needed to properly capture and measure the effect of BIM on enhancing coordination process. The major objective of this study is to capture the underpinnings of BIM-based coordination process as currently practiced by AEC firms in the U.S. A nationwide survey was conducted to capture the subject matter experts' opinions in the following areas of BIM-based coordination: (1) Current approaches of conducting coordination using BIM; (2) Information items collected to monitor coordination process; (3) Factors affecting coordination production rate; (4) Metrics used by AEC companies to measure production rate; and (5) Identified best practices leveraged by companies to enhance BIM utilization in the coordination process. The findings of this study indicated that "remote coordination" and "regular coordination" are the most widely used BIM-based coordination approaches. Number of clashes resolved in each meeting, BIM competency of team members, and number of trades attending meetings were identified as the most commonly collected information items by AEC firms throughout the MEP coordination process. Team experience level, preliminary design quality, and MEP system complexity were found as the most important factors that impact the MEP coordination process. Several best practices were recommend by participants in this study to improve the efficiency of MEP coordination process. These strategies were described under the four different phases of an MEP project: initiation and planning, 3D modeling, MEP coordination, and construction and installation. The results of this study are expected to enhance our knowledge about differences among various BIM-based coordination approaches, their popularity among practitioners, and their effects on the coordination progress. The findings of this research will help AEC firms by describing information requirements for establishing a procedure to track, measure, and compare MEP coordination progress across different construction projects.*

KEYWORDS: *Building Information Modeling***,** *MEP Coordination, Design Coordination, Progress Management, Production Rate*

REFERENCE: *Saman Yarmohammadi, Baabak Ashuri (2015). Exploring the approaches in the implementation of BIM-based MEP coordination in the USA. Journal of Information Technology in Construction (ITcon), Vol. 20, pg. 347-363, http://www.itcon.org/2015/22*

1. INTRODUCTION

Design coordination for mechanical, electrical, and plumbing systems is a critical task conducted during preconstruction phase of construction projects (Tatum and Korman, 2000; Korman et al., 2003). Through this challenging task, several building components including heating and ventilating equipment, air-conditioning duct, water supply piping, sanitary drainage piping, electrical conduit and raceway, and fire protection systems are relocated and rerouted (Korman and Huey-King, 2014), in order to fulfill specific structural, architectural, and engineering constraints of the building envelope (Tao and Janis, 2001). These constraints facilitate avoiding spatial interferences during the actual construction phase and ensure that all building systems perform as expected. Meeting these constraints is particularly difficult when designing congested spaces with a large number of complex components in a limited space (Riley et al., 2001, Riley, 2005). The difficulty encountered in performing design coordination has made it one of the major challenges in the delivery process for building construction projects.

Conventional MEP coordination process has been an especially cumbersome process. In traditional coordination, 2D drawings of different MEP systems are sequentially overlaid on a glass lighting table and compared with one another to find possible conflicts. The manual nature of the traditional approach not only lengthens the process, but also undermines the benefits gained by performing MEP coordination (Simonian and Korman, 2011). Such shortcomings have resulted in extensive efforts to improve coordination efficiency by utilizing the emerging capabilities of BIM (building information modeling) technologies. BIM-based coordination process enables participants to integrate 3D models of different building systems into a single integrated model. The integrated model is later used to automatically detect system interferences in a matter of seconds.

It is believed that automatic detection and resolution of system conflicts have significantly improved the coordination process through making considerable changes in the traditional coordination workflow (Hartmann et al., 2010, Korman et al., 2008, Eastman et al., 2008, Hanna et al., 2013, Boktor et al., 2014). Several researchers have examined the effect of BIM on expediting coordination process. In a case study of a medical center in California, Staub-French and Khanzode (2007) concluded that using 3D models for coordination has resulted in a decrease in time spent for designing building systems. Becerik-Gerber and Rice (2010) also conducted an industry-wide online survey to understand the perceived value of BIM in the U.S. building industry. The findings of the survey showed that the respondents perceive expediting MEP coordination through automatic clash detection among top three benefits of utilizing BIM. Improvement in design coordination process speed has been reported in several other studies (Sacks and Barak, 2010, McGraw-Hill, 2014). Collectively, these studies concluded that using BIM in coordination activities expedites coordination process, and subsequently increases coordination team's production rate. However, these studies did not outline the information items and metrics needed to track and measure coordination progress. As stated by Succar (2010), accurate metrics and benchmarks need to be established to assess overall BIM performance across different industry sectors and organizational sizes. Also, proper measurement of coordination progress in terms of the team's production rate is essential to identify inefficiencies of BIM utilization in MEP coordination process (Sacks et al., 2010). In addition to identifying inefficiencies, progress measurement enables practitioners to further enhance the best practices already employed in BIM-based coordination.

The success of the BIM-based approach in improving the MEP coordination process has resulted in the extensive adoption of BIM technology by at least 60% of construction companies to conduct their coordination activities (McGraw-Hill, 2013). The widespread adoption of new technologies by construction professionals has resulted in significant changes in the process field of BIM-based MEP coordination (Succar, 2009). Also, the advancements in the technology field of BIM have made new practices, such as coordinating from remote locations, possible. However, there is limited knowledge about various approaches that are currently practiced as BIM-based coordination.

In a rare case study, Lee and Kim (2014) investigated the impact of parallel vs. sequential design coordination on coordination progress. In the parallel approach, MEP trades develop their models simultaneously. Unlike parallel approach, MEP coordination tasks in sequential approach are prioritized, and are conducted based on Sequential Comparison Overlay Process (SCOP) (Korman and Tatum, 2001). The subject of Lee and Kim's case study is a seven-story office building with two basement floors. The results of the study indicate that contrary to the general concurrent-engineering theory, sequential cascading coordination has a higher production rate compared to parallel coordination. Although Lee and Kim investigated sequential and parallel coordination approaches with regard to process differences, their study did not specify how frequent each method is used in practice. Moreover, the study did not account for variations caused by incorporating new technologies (e.g., remote connection) in coordination process. Therefore, there is a gap in our understanding about differences among various coordination approaches, their popularity among practitioners, and their effects on the coordination progress.

Although BIM is perceived as a great facilitator in coordination process, there is a need to identify information items and metrics needed to properly capture and measure the effect of BIM on coordination production rate. Also, considering variations in current practices of performing BIM-based coordination, there is a need for a study to enhance our understanding regarding the difference of the current approaches in terms of their means, methods, and popularity among practitioners. The major objective of this study is to capture the underpinnings of BIM-based coordination process as currently practiced by AEC firms in the U.S. Specifically, main information items collected by AEC firms throughout coordination process will be identified, major metrics used to measure the progress of MEP coordination process will be determined, and recommended best practices to enhance BIM-based coordination process will be recognized. In order to achieve these objectives, a national survey was developed and sent to 50 MEP coordination professionals from 28 different design, engineering, and construction companies. Results of this survey were examined and analyzed in detail. The survey findings add several arguments to the literature. The next section explains the research methodology used to develop and conduct the survey. The survey results and discussion are then provided before conclusions are presented in the last section.

2. RESEARCH METHODOLOGY

The survey questionnaire research method was used to better understand the state of practice in BIM-based MEP coordination among AEC firms in the U.S. Considering the objectives of this study a survey questionnaire was designed to capture subject matter experts' opinions in the following areas of BIM-based coordination: (1) Current approaches of conducting MEP coordination using BIM technology; (2) Information items collected by (architecture/engineering/construction) AEC companies to monitor coordination process; (3) Factors affecting coordination production rate; (4) Metrics used by AEC companies to measure the production rate of their MEP coordination teams; and (5) Identified best practices employed by AEC companies to enhance the utilization of BIM in coordination process. Within each section, the survey respondents were required to identify and rate statements based on their importance and expand responses if it was deemed appropriate. Unipolar rating scales and word labeled scales were used through the survey to minimize potential bias (Schaeffer and Presser, 2003). One of the most important goals in our survey design was to achieve a sufficient level of rigor. Thus, every attempt was made to avoid general arguments and include well-explained statements that had grounds in the academic and professional building design literature.

The survey was designed in two parts based on a comprehensive review of existing literature. The questions in the first part were designed to collect general information, such as respondent's role in the company and company type. The second part focused on obtaining information to address study's objectives. Three industry professionals knowledgeable about design coordination initially tested the developed survey. Based on the feedbacks from these individuals, some minor modifications were made to the survey terminology and statements with the potential to deviate the respondents from the survey objectives. The final survey was distributed in an online format through e-mail to 75 architects, engineers, contractors, and BIM software developers over a period of 6 months in 2013-2014. The main target audience included BIM/VDC (Virtual Design & Construction) managers, MEP coordinators, project managers, and specialty trade engineers. These professionals were recruited through partnership and close collaboration with the industry members of the Digital Building Laboratory (DBL) at the Georgia Institute of Technology. BIM experts, especially those who have been actively engaged with several MEP coordination projects, were identified as the main candidates for responding to the survey. In total, 48 responses from 28 different companies were received. In case of incomplete responses, we only use the portion of the survey that was answered completely. The next section presents the survey results and analysis.

3. ANALYSIS OF THE SURVEY RESULTS

3.1. Descriptive Information of the Respondents

In the first section of the survey, information was gathered about the role of the respondents in their companies, as well as the company type. Fig. 1 presents various titles that the respondents hold in their companies. It can be seen that the majority of respondents are BIM/VDC managers who are typically responsible for facilitating MEP coordination meetings. There are different other titles for the position of the professional who is in charge of MEP coordination among the surveyed firms, for instance, project manager, system engineer, and program analyst.

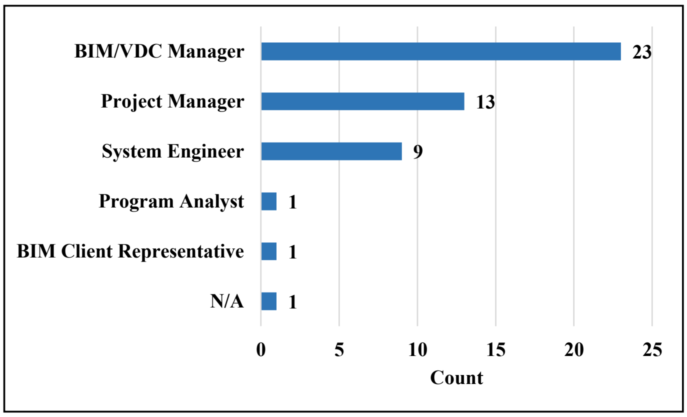

FIG. 1: Count of Respondents Based on Their Titles

The count of respondents based on their company types is shown in Fig. 2. Most responses were received from professionals who work for general contractors. This was expected since contractors are usually responsible for design coordination during the preconstruction phase of the projects (Korman and Huey-King 2014).

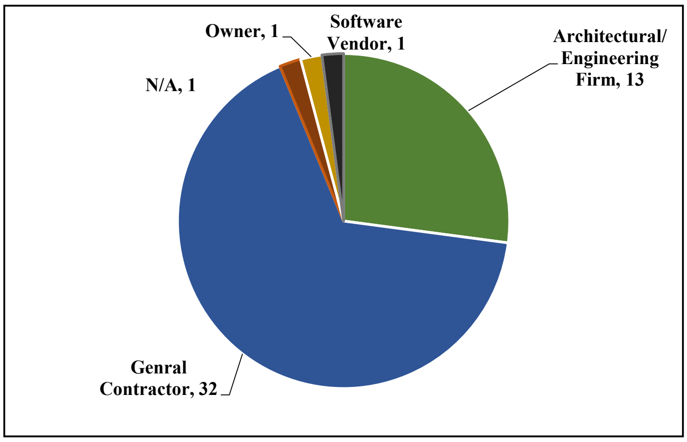

FIG. 2: Count of Respondents Based on Company Type

3.2. Current Approaches of Conducting Design Coordination

The choice of a proper approach for conducting design coordination is affected by different factors, such as project type, project schedule, and software packages used by different specialty trades. Complex projects (e.g., data centers, hospitals) require more intensive coordination efforts. Also, in such projects, coordination meetings should be held quite frequently to address issues arising from the complex nature of building systems (Leite et al., 2011). Under strict schedule requirements, the coordination process can be expedited through assigning several teams to conduct coordination concurrently. In such cases, different project zones are coordinated by different teams (Lee and Kim, 2014). The communication and collaboration among coordination parties can be streamlined through cloud-based tools. But, the decision to utilize such tools depends on whether all team members have the ability and expertise required to access and operate cloud-based software packages. Based on such factors, different types of MEP coordination approaches have been utilize to meet project requirements. The following five specific MEP coordination approaches were provided in the questionnaire:

- *Regular coordination:* one day of coordination and four days of design and modeling per week. Various design models are integrated and analyzed through weekly coordination sessions. The clashes detected in each coordination session are assigned to the corresponding trades to find resolutions. The modified models are later submitted for the review in the following coordination session.

- *Parallel coordination:* concurrent multiple teams working together on coordination tasks. The project is divided into distinct zones and each zone is assigned to a team to coordinate.
- *Coordination conducted by specialty trades:* transfer of coordination responsibility to the participating trades. The general contractor only handles coordination when major design modifications are required.
- *Remote coordination:* utilization of remote connection tools to virtually engage participating trades in conducting coordination. Remote connection technology facilitates communication and collaboration among trades that are located in distant places.
- *Cloud computing-based coordination:* utilization of cloud-based products to review and resolve coordination clashes in almost real-time. Cloud-based tools enable coordination participants to access most recent virtual models anytime from anywhere.

The major factors that distinguish these methods from each other are the location and pattern of communication between the participants in a coordination process. The classification of coordination methods based on these factors is shown in Fig. 3.

		Communication Pattern	
		Same Time	**Different Times**
Location	**Same Place**	- Regular	- Parallel
	Different Places	- Cloud computing-based	- By trades - Remote

FIG. 3: Organization of MEP Coordination Approaches based on Space-Time Communication Matrix - Adopted from Ugwu et al. (1999).

The new advancements in BIM technology are particularly useful for conducting coordination from different places. Computer-mediated conferencing, video conferencing, and electronic group discussions enable coordination teams to "virtually co-locate" (Anumba, 2002). Also, cloud-based BIM management tools allow the participants to integrate and update models in real-time. In addition to location and communication pattern, other factors were considered in defining the coordination approaches. Table 1 shows a summary of these factors.

Table 1: Factors Affecting the Selection of Different MEP Coordination Approaches

Approach	Meeting Frequency	Location	Modeling Responsibility	Model Integration/Clash Detection Responsibility
Regular	One day of coordination and four days of design and modeling	On-Site	General Contractor (GC), Trades	GC
Parallel	Multiple teams working concurrently on different building zones	On-Site	GC, Trades	GC
By trades	Meetings held as needed	Remote	Trades	Trades
Remote	Meetings held regularly/as needed	Remote	GC, Trades	GC
Cloud computing-based	Meetings held regularly/as needed	Remote	GC, Trades	Automatic model integration, facilitated clash detection by GC or trades

The survey respondents were asked to specify how often they have used each coordination approach in their own practices. The choices were on a scale of one (never) to four (often). Fig. 4 shows the average utilization frequency of each identified coordination approach. Remote coordination and regular coordination are the two most frequently used approaches in the industry according to the survey respondents. The simplicity and user-friendliness of remote connection tools were cited by some respondents as reasons behind the popularity of remote coordination. Even though cloud computing-based coordination was ranked last in the survey, a number of respondents anticipated a rapid growth in utilization of cloud-based tools for coordination. The cloud-based products' capability to enhance collaboration among trades is believed to significantly improve the efficiency of coordination process. In addition to ranking coordination approaches, the respondents were asked to indicate whether they have seen any other coordination methods. "Staging coordination" is another coordination approach mentioned by a respondent. In this approach, coordination starts with the trades with "the least movable items" designing their system's major pieces. Next trade starts working on an area when the preceding trade is finished. After all trades finish modeling major pieces, the coordination process continues through regular meetings.

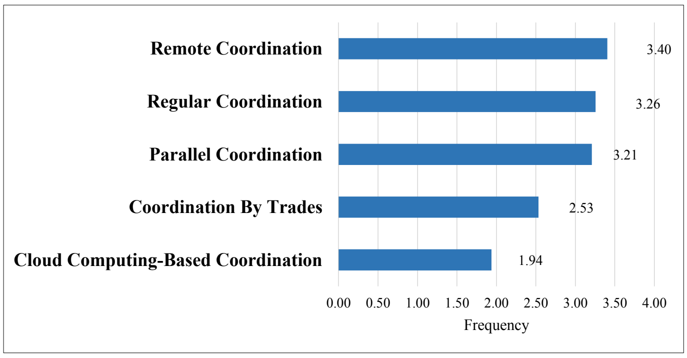

FIG. 4: Average Usage Frequency of Different Coordination Approaches

3.3 MEP Coordination Sequence

The early involvement of all participating parties in coordination process is believed to significantly improve collaboration efficiency (Kent and Becerik-Gerber, 2010). To understand how often trades are engaged early in the process, the survey respondents were asked whether they often see all trades involved from the beginning of coordination. Approximately 69% of responses (33 out of 48) were positive. Also, the most commonly cited order for trade involvement is as follows: 1) HVAC (heating, ventilating, and air conditioning) wet, 2) HVAC dry, 3) plumbing, 4) electrical, and 5) fire protection. The trades with larger system components usually start the process since they are more limited in terms of moving their equipment. Trades with smaller equipment later coordinate their systems around the already designed components.

3.4 Metrics to Measure the Production Rate of Coordination Team

Proper measurement of coordination progress is essential to identify process inefficiencies and bottlenecks. Also, recording coordination team's production rate across different projects over a period of time provides AEC companies with a baseline to compare their teams' performance against. Thus, the respondents were asked whether their companies have a procedure in place to track coordination progress on team and individual trade's level. The respondents were requested to provide utilized metrics if such procedures existed. 65% of the respondents (31 out of 48) reported that their companies track their coordination team's production. However, only 52% (25 out of 48) survey participants stated that their firms measure coordination production separately for different trades. Such difference is believed to be due to the complications of collecting coordination production data for separate trades. The top five production rate metrics cited by the respondents in descending order are:

- Coordination time per building area (Days/ft^2)
- Building area coordinated per meeting (ft^2/Meeting)
- Number of clashes resolved per coordination meeting
- Number of coordination meetings per number of coordinated component
- Building area (ft^2) coordinated per number of coordination meetings per trade

3.5 Trade Coordination Time

The components of building systems are different in terms of design complexity. Such difference causes the trades to vary in terms of the time it takes them to coordinate their system components with the other trades' system components. Survey respondents were asked to rank trades according to their coordination time. As it can be seen in Fig. 5, the HVAC dry is the trade that takes the longest to coordinate. The large size of components that limits coordinators' abilities to move the equipment was cited as the main reason behind the long coordination time of HVAC dry system. The respondents stated that the large ductwork and VAV (variable-air-volume) boxes of HVAC dry system also restrict the available space for routing the equipment. Plumbing and HVAC wet follow HVAC dry in terms of coordination time. The HVAC wet equipment is tightly related to HVAC dry components and is coordinated based on HVAC dry system routing (Korman et al., 2008). This facilitates the coordination of HVAC wet components since the locations of HVAC dry components are already determined. On the other hand, the restricted remaining space makes it difficult for coordinator to route plumbing equipment around HVAC dry and wet systems. Thus, it is expected that plumbing system takes longer to coordinate compared to HVAC wet. Electrical and fire protection trades are faster to coordinate since their components are generally smaller and more flexible to reroute.

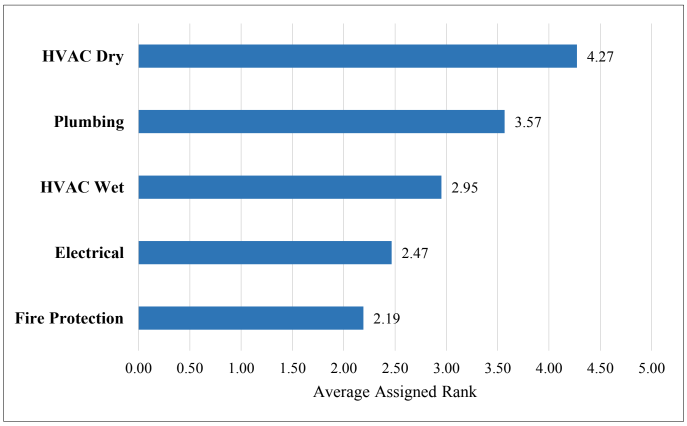

FIG. 5: Trades Ranking in Terms of Coordination Time

In addition to ranking trades based on coordination time, the survey participants were asked to specify trades that are believed as process bottlenecks. The results shown in Fig. 6 indicate that HVAC dry is a specialty trade that is most commonly thought as the bottleneck in the MEP coordination. While fire protection is the least time consuming trade, it was identified by more than 35% of the respondents as a trade that causes delays in the process. The lower familiarity level of fire protection representatives with BIM tools was reported to cause interruptions throughout the coordination process. Such trades usually lack in-house BIM capabilities. Thus, their BIM activities should be outsourced, which can introduce scheduling complications in the coordination process.

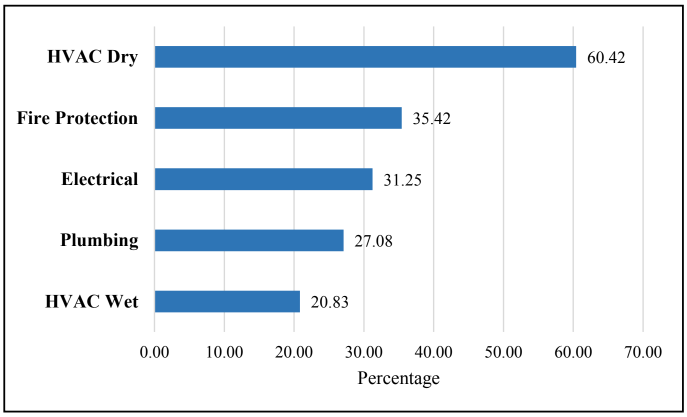

FIG. 6: Trades Believed as Bottlenecks

3.6 Information Items Collected to Monitor Coordination Progress

Systematic collection of progress information is essential to properly monitor coordination process. In the context of our research to study MEP coordination, information items refer to specific variables that are collected by the project management team to track progress of coordination process. These information items represent metrics related to the coordination team and the progress being made during their meetings. Project managers can potentially use this information to determine production rate of MEP coordination teams. The survey participants were asked to specify whether their companies collect the information items presented in Table 2. The respondents were also requested to specify if they collect data items other than the ones mentioned in the list.

Table 2: Description of Information Items Collected to Monitor Coordination Process

Information Item	Description
Number of meetings per week	Total number of coordination meetings held per week.
Number of meeting hours	Total number of coordination meeting hours per week.
Experience level of team members	The years of experience team members have in MEP coordination.
BIM knowledge of team members	The years of experience team members have using BIM tools for MEP coordination.
Number of clashes approved	Number of clashes approved as acceptable in each coordination meeting.
Number of clashes resolved	Number of clashes resolved in each coordination meeting.
Number of people attending meetings	Number of team members attending each coordination meeting.
Number of trades attending meetings	Number of trades whose representatives attend each coordination meeting.
SF coordinated in each meeting	Square footage of the area coordinated over each coordination meeting.

FIG. 7 shows the relative ranking of collected information items based on the number of times they were cited by the survey participants. Number of clashes resolved, BIM knowledge of team members, number of trades attending meetings, and experience level of team members were cited as the most commonly collected information items. Number of generated drawings is another information item that was mentioned by one of the survey respondent.

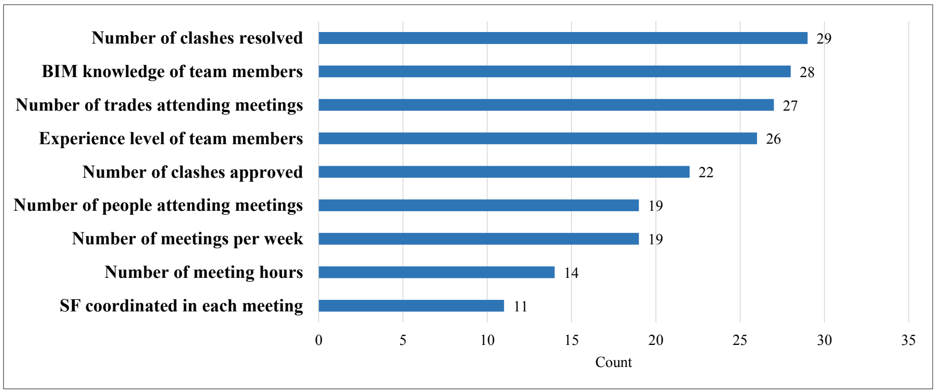

FIG. 7: Information Items Collected to Track Coordination Progress

3.7 Factors Affecting MEP Coordination Team's Production Rate

Identifying the factors that affect coordination is particularly important in helping practitioners anticipate and avoid possible delays and interruptions. To capture the industry perspective on this matter, an initial list of factors that potentially affect coordination was provided in the questionnaire. The survey respondents were asked to assign a score on the scale of one (not important) to four (very important) based on the impact of the identified factors on production rate of the coordination team. The presented factors and their effects on coordination process are discussed in table 3.

Table 3: Description of Factors Affecting Coordination

Factor	Description	Effect on MEP Coordination
BIM Knowledge of Team Members	The years of experience team members have using BIM tools for MEP coordination.	Designers with more experience using BIM are more productive (Sacks and Barak, 2008)
Building Type	The type of the building under construction.	Some projects, such as research labs and hospitals are typically more MEP intensive compared to other building types. As a result, more time needs to be spent to coordinate such buildings (Riley et al., 2005).
Interoperability Issues	The interoperability issues in BIM resulting from the use of different applications.	Interoperability is critical for the success of coordination, since there are many different interactions between the various participants (Grilo and Jardim-Goncalves, 2010)
MEP System complexity	The higher difficulty level of designing more dense and complex MEP systems.	MEP system complexity varies with the facility type and its unique system requirements. More complex systems require more extensive coordination efforts (Tao and Janis, 2001).
Preliminary Design Quality	The quality of BIM models generated separately by specialty contractors to initiate coordination.	Lower quality models have more clashes and take longer to coordinate (Lam et al., 2008)
Project Delivery System	The delivery method of the project (e.g., Design-Bid-Build, Design-Build, Integrated Project Delivery (IPD))	The close collaboration in IPD and Design-Build results in development of relatively compatible designs by trades and a faster coordination (El Asmar et al., 2013)
Team Experience Level	The years of experience team members have in conducting MEP coordination	Experienced modelers are more knowledgeable about building codes and systems. This knowledge enables them to conduct design more effectively and faster (Azhar, 2011)
Project Location	The remoteness of the project's location.	Projects in distant remote location face the problem of skilled workers' availability (Yi and Chan, 2014). Also, the limited access of the coordination team to the project site can potentially reduce coordination quality.
Public vs. Private Owner	The ownership type of the project.	Communications required for coordination are conducted faster in private sector projects compared to public ones (NAS, 2009).
Software Used for Coordination	The type of software packages used for coordination	To fully take advantage of advanced technologies, such as cloud computing, the required tool should be available to all coordination participants.

Fig. 8 depicts the relative ranking of the identified factors based on the collected responses. According to the survey respondents, team experience level, preliminary design quality, and MEP system complexity members are believed as the major factors that impact coordination production rate. The findings of the survey are consistent with the existing literature. The fact that MEP coordination is a very experience-driven process justifies the high ranking of team experience level among affecting factors (Wang and Leite, 2014). Experience level of design coordinators is critical to the success of the whole process since all design, routing, and clash resolution tasks require extensive expertise, as well as familiarity with building codes. The quality of preliminary design has also been identified as an important factor that can affect the design process (Succar et al., 2012). The survey respondents reported cases through which preliminary deficiencies have caused scheduling issues. Another major factor that can potentially lengthen the coordination process is the complexity of MEP system (Tao and Janis, 2001). Research laboratories and hospitals are typically more restricted by available space compared to commercial and residential buildings and thus, typically require longer time for coordination.

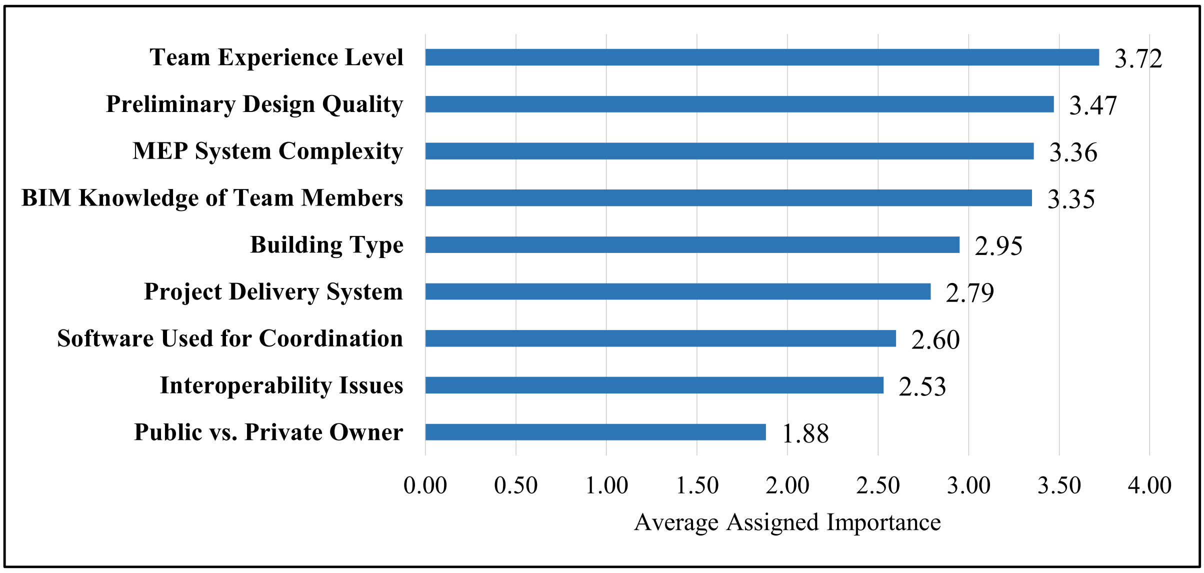

FIG. 8: Average Importance of Factors That Affect Coordination

3.8 Recommended Best Practices to Improve Coordination Efficiency

As the final part of the questionnaire, the respondents were asked to provide recommendations on how to improve coordination efficiency throughout the different phases of a project. The collected responses were grouped according to project phases' breakdown from a design perspective suggested by James Cummings (2010). The first category is primarily concerned with understanding requirements and developing program objectives for the project. In this phase, owners' expectations are captured and translated into project specifications. These specifications are used to develop concept design proposals and preliminary budget. Also, engineers visit the job site to ensure constructability of the conceptual design. The 3D models used to conduct coordination are developed in the design development phase. The model development task is usually performed by engineers/architects who have the required technical expertise, as well as the BIM knowledge. In addition, detailed cost estimation is conducted as project design and parameters are further developed.

MEP coordination is conducted during the construction documents phase. Virtual models developed by different designers and engineers are collected and combined into a single integrated model. The integrated model is subsequently analyzed to identify and resolve existing system interferences. The products of this phase are shop drawings that will be used to fabricate and install building systems. Also, the detailed cost estimation is updated to develop bidding documents. During bid phase, a list of potential bidders is developed and reviewed to ensure companies that are awarded the contracts are capable to meet project requirements. The submitted bids are compared to one another to select winning subcontractors. In the final phase, construction administration, design documents are regularly updated to match existing site conditions. Also, the contractors' submissions are reviewed for compliance with the intent of design and the contract. This categorization of project phases was used to classify the BIM-based MEP coordination best practices recommended by survey participants.

Survey respondents identified several strategies that have the potential to enhance the efficiency of the overall BIM-based MEP coordination process. A summary of these strategies is provided as a set of recommended best practices in Table 4. The procedures recommended for schematic design phase are concerned with establishing a detailed workflow for coordination process and determining participating parties' responsibilities. The survey respondents also suggested breaking down large projects into smaller sub-projects to facilitate the coordination process. In such cases, the sub-projects are assigned to different coordination teams that simultaneously design building systems. The Level of Development (LOD) established in the schematic design phase provides the coordination team with guidelines required for developing 3D models. To develop more reliable virtual models, it is recommended that general contractors make sure all trade representatives have sufficient knowledge on the division they are handling and are familiar with local building codes. Also, the modelers should be held to the required LOD established in the initial phase. The details added to the models are instrumental in identifying micro-level changes.

Table 4: Recommendations to Improve Design Coordination Efficiency

Project Phase	Recommended Best Practices
Schematic Design	• Establish a detailed workflow for coordination process • Clarify the roles and responsibilities that the general contractor and trades must take on through modeling and coordination processes • Break down the project into smaller sub-projects based on the project size, MEP system density, and bid package priorities • Define the extent to which the models should be detailed and coordinated
Design Development	• Utilize the same software platform among coordination team to avoid interoperability issues • Invest as much effort as possible on developing BIM models (Models with higher LOD allow the coordination team to address micro level conflicts.) • Make sure modelers/engineers have the required expertise on the division they are handling and are familiar with local building codes.
Construction Documents	• Make sure coordination team members are competent in both coordination and modeling • Initiate coordination by trades with larger components and continue to the ones with smaller equipment • Identify high-priority and outstanding clashes before each meeting • Categorize clashes that belong to similar geometrical units into clash batches • Record and document discussions, ideas, and solutions during coordination meetings • Hold weekly or biweekly meetings with designers to review issues that require immediate attention
Bid	• Ensure accuracy of 3D models and drawings for quantity take off • Make sure subcontractors have in-house BIM capabilities so they can keep models up-to-date
Construction Administration	• Check constructability of the developed shop drawings • Provide field staff with quick access to the most updated models • Record and report change orders and RFIs in an organized format

The survey participants suggested starting coordination with trades with large system components (e.g., HVAC dry and HVAC wet) and continuing to smaller equipment. This approach is consistent with the ones indicated in the literature (Korman et al., 2008). To expedite coordination even further, the meeting facilitators should review and identify major clashes before meetings. This way, only major clashes are discussed and unproductive hours are reduced. The resolution of major clashes can be conducted faster if architect's representatives attend the meetings regularly. The survey participants also recommended that coordination moderators record meeting discussions to document ideas for clash resolution. It was stated that such documents can be beneficial to train less experienced coordinators, as well as resolving similar issues encountered in future projects.

The models and drawings used during the bid phase should be highly accurate as they are the bases of the detailed cost estimation used for bidding. It was recommended that the contracts be awarded to companies that have in-house BIM capabilities. Relying on third-party BIM service providers was considered a cause delays in the process, particularly in cases when several design modifications are required. Finally, it was recommended that the constructability of the developed system designs should be regularly reviewed during the construction administration phase. In case of a constructability conflict, the coordinated building systems' models should be updated in a timely manner to avoid delays. Also, it was recommended that the field personnel have immediate access to the most updated models to avoid reworks that can arise from last minute changes to the design documents.

4. DISCUSSION

The deployment of BIM along with the growing use of remote connection and cloud computing technologies has resulted in various forms of MEP coordination processes, such as parallel, remote, and cloud computing-based coordination approaches. The popularity of each approach is subject to different factors ranging from project complexity and schedule to the availability of proper software tools among coordination participants (Korman, 2008). Survey results showed that remote coordination and regular coordination are the top two most commonly used coordination approaches. The popularity of remote coordination is attributed to the instrumental capability of remote connection tools to facilitate communications among participating parties (Kam et al., 2013). Being able to attend coordination meetings in the convenience of their own offices, and easily contacting and discussing minor issues with other team members during modeling periods were cited by survey respondents as the main reasons behind the popularity of remote connection tools among practitioners.

Even though cloud computing-based coordination ranked last among commonly used coordination approaches, this approach is expected to gain more popularity due to the growing use of cloud-based BIM management tools (Redmond et al., 2012). While employment of BIM has resulted in different coordination approaches, the sequence of trade involvement in the process is consistent with SCOP (Korman and Tatum, 2001). The survey respondents indicated that generally coordination starts with trades with larger and less movable items, such as HVAC dry and wet. Once the larger components are coordinated, electrical and fire protection trades design their system components. These trades have more flexibility in coordination as their systems components are smaller (Tabesh and Staub-French, 2006).

Proper measurement of coordination production rate is essential to identify process bottlenecks, as well as benchmarking coordination teams' performance across different projects and various clients (Kim and Huynh, 2008). Despite the importance of progress measurement, the survey findings showed the lack of a systematic method to capture information and measure coordination production rate in the AEC industry. While 65% of survey participants confirmed that their firms attempt to track coordination progress to some extent, only a few respondents provided quantifiable metrics to measure production rate. The cited metrics also lack uniformity not only across the industry, but also among respondents from the same companies. The issue of progress measurement has been found to be more severe when it comes to tracking production rate separately for different trades. This problem is believed to be due to the difficulty of recording individual data retrieved from each trade. Such difficulties arise especially when "coordination by trades" approach is used. In this case, some information items, such as time spent by drafters to coordinate, are almost impossible to be accurately collected.

Despite the difficulties in recording coordination time, the survey participants reported HVAC dry and HVAC wet as the longest trade to coordinate based on their qualitative observations. The large size of the system components that limit coordinator's ability to move the equipment vertically and horizontally is believed to be the main contributing factor to the long coordination time of HVAC trades (Hanna et al., 2013). While HVAC trades are the longest to coordinate, fire protection is recognized as one of the main trades that cause interruptions through the process. The survey respondents cited the lower familiarity level of fire protection drafter as the reason behind these interruptions. However, it was indicated that this issue is expected to be addressed as the utilization of virtual models to conduct coordination is becoming a norm throughout the AEC industry.

Calculating metrics to measure coordination progress is only possible if required information items are collected throughout the process. Number of clashes resolved in each meeting, BIM competency of team members, number of trades attending meetings, and experience level of team members were identified as the most commonly collected information items by survey respondents. While number of resolved clashes and number of trades attending meetings are quantitative measures, it is not clear how other items, such as BIM competency and experience level of coordinators, are quantified. Also, the variability among collected information items through different companies can be traced back to the lack of uniformity in the AEC industry regarding coordination progress management. The survey participants noted this issue as an area that further research is required to enhance the efficiency of current MEP coordination process.

Better understanding of the factors that potentially affect the MEP coordination process can be instrumental in improving coordination team's production rate (Liao et al., 2011). The survey participants indicated that team experience level and their BIM competency have major impacts on the progress of coordination process. These findings are consistent with studies that assess the impact of designers' expertise on conducting designing tasks (Waldron and Waldron, 1996, Wang and Leite, 2014). Most respondents indicated that the quality of preliminary design is among the top factors that affect the coordination time. The possible explanation is related to significant delays that may be caused by major modifications resulting from design deficiencies (Yang and Wei, 2010). Also, the added difficulty associated with the complexity and number of building systems in a facility justifies the high ranking of MEP system complexity among affecting factors (Riley, 1997).

The survey respondents also provided the research team with several best practices leveraged by their companies to improve the efficacy of their MEP coordination processes. The procedures recommended schematic design phase are generally concerned with determining trades' design and coordination responsibilities, as well as establishing a plan for conducting coordination. The plan set forth in the schematic design phase provides the coordination team with guidelines regarding the Level of Development required for developing 3D models. To develop more reliable virtual models, it is recommended that general contractors make sure all trade representatives have sufficient knowledge on the division they are handling and are familiar with local building codes.

The coordination sequence recommended by the survey participants is consistent with the SCOP approach suggested by the existing literature (Tatum and Korman, 2001, Korman et al., 2008). This approach requires coordinators to initiate the process by trades with larger equipment and continue to the ones with more movable system components. It was also suggested that in addition to general contractor and trades, designer's representatives attend the coordination meetings regularly to expedite the process. Immediate access to the designers facilitates resolving issues that can potentially interrupt coordination process. The survey findings also indicated that reviewing and grouping clashes into similar geometrical batches can significantly reduce unproductive discussions in the meetings and thus, increase coordination team's production rate. The survey participants also recommended that the field staff should have immediate access to the most updated shop drawings and BIM models to avoid potential rework and change orders.

5. CONCLUSIONS AND FUTURE WORK

The deployment of BIM technology in design processes has resulted in new means and methods of conducting MEP coordination. The study results indicated that "remote coordination" and "regular coordination" are the most commonly used approaches among practitioners. The popularity of remote coordination is largely attributed to the tremendous capability of remote connection tools to facilitate communication among coordinators. Despite their current limited use, the popularity of cloud computing-based coordination approaches is on the rise. The shared online cloud databases provide coordination participants with real-time access to the most updated virtual models and design documents. Interestingly, it was also found that the sequence of trades' involvement in BIM-based coordination process is consistent with the order used through conventional coordination; the process starts with larger equipment and trades with smaller system components route around the already designed equipment.

Coordination time per building area, building area coordinated per meeting, and number of clashes resolved per meeting were found to be among metrics used by AEC companies to measure the production rate of their coordination teams'. However, the variation among the cited metrics across different companies suggests a lack of systematic method to track coordination progress in the AEC industry. Such variation existed not only among different firms but among respondents from the same companies. This lack of uniformity was also observed when the survey participants were asked to provide a list of information items their companies collect to monitor their coordination processes. Number of clashes resolved in each meeting, BIM competency of team members, number of trades attending meetings, and experience level of team members are the most frequently used information items among the surveyed firms.

The survey findings indicated that team experience level, preliminary design quality, and MEP system complexity are the most important factors that affect coordination progress. According to the survey responses, the recommended best practices to enhance the efficiency of MEP coordination can be classified under four general categories that represent different phases of the project. The procedures suggested for the initial phase are primarily concerned with planning the coordination process and allocating responsibilities among process participants. The developed plan is the cornerstone of the activities conducted through the remaining phases. The familiarity of drafters with BIM tools and local building codes is pivotal to develop reliable virtual models in the second phase. Through the third step, coordination facilitators are highly recommended to review and identify major clashes before each meeting. This way the meeting discussions will be limited to just major modifications and hence, the efficiency of the whole process will be improved. To fully realize the benefits of coordination, it is essential that the field personnel have immediate access to the most updated models.

The survey questions were developed through a close collaboration with experienced building systems' coordinators. Throughout the questionnaire development process, the research team refined the questions multiple times to ensure their objectivity and validity. Also, the results obtained through this study were presented to a panel of AEC industry professionals at the Digital Building Laboratory (DBL) Symposium held in May 2014. This panel consisted of architects, engineers, contractors, and subcontractors actively engaged in BIM related activities. The panel members represented a total of 17 domestic and international AEC companies. The panel generally verified the compatibility of the obtained results with the realities of MEP coordination practices. The provided comments were also recorded and used to further improve the results.

This study contributes to the body of knowledge in design engineering by enhancing our knowledge about the variations among different approaches of conducting BIM-based coordination. The findings of this study also benefit AEC firms by identifying metrics and information items required to systematically track and measure coordination progress. As future work, a proper framework should be developed to collect the information items required for measuring coordination progress across different projects in a systematic fashion. Such framework lays the foundation to quantitatively investigate the relationship among coordination duration and potential factors that may affect it.

ACKNOWLEDGEMENTS

The authors take this opportunity to thank Professor Charles M. Eastman, who leads Digital Building Laboratory (DBL) at the Georgia Institute of Technology, for his support of this research project. In addition, we are grateful to Mr. James P Barrett, Ms. Jennifer Downey, Mr. Pushkar Mahabaleshwarkar, Mr. Omar Martinez, and Mr. Chad C Bacote from Turner Construction Company, Mr. Oliver Smith, Mr. Jim Becker, and Mr. Mike Clark from Skanska, Mr. Frank Fralick and Mr. Silviu Stoian from Beck Group, Mrs. Valeh Nowrouzian from Whiting-Turner, Mr. Fred Gibson from Bechtel Construction, and Mr. Justin Schmidt from DRP Construction Company who kindly helped us throughout the progress of this study.

REFERENCES

Anumba C.J., Ugwu O.O., Newnham L., Thorpe A. (2002) Collaborative design of structures using intelligent agents, *Journal of automation in construction*, Vol. 11, 89-103

This paper is available electronically at http://dx.doi.org/10.1016/S0926-5805(01)00055-3

Azhar S. (2011) Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry, *Leadership and management in engineering*, Vol. 11(3), 241–252.

This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Becerik-Gerber B and Rice S. (2010) The perceived value of building information modeling in the US building industry. *ITcon,* Vol. 15, 185-201.

Boktor J., Hanna A., and Menassa C. (2014) State of practice of building information modeling in the mechanical

construction industry, *Journal of management in engineering,* Vol. 30, 78-85.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000176

Cummings J. (2010) Design process, A collaborative design group. 1-7.
This paper is available electronically at http://jamescummingsaia.com/jcaia-design%20phases.pdf

Eastman C., Teicholz P., Sacks R., and Liston K. (2008) BIM Handbook: *A guide to building information modeling for owners, managers, designers, engineers, and contractors*, John Wiley & Sons, Inc., Hoboken, NJ.

El Asmar, M., Hanna, A., and Loh, W. (2013) Quantifying performance for the Integrated Project Delivery system as compared to established delivery systems, *Journal of construction engineering and management*, Vol. 139(11), 04013012.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000744

Grilo A. and Jardim-Goncalves R. (2010) Value proposition on interoperability of BIM and collaborative working environments*, Journal of automation in Construction*, Vol. 19, 522-530.
This paper is available electronically at DOI: 10.1016/j.autcon.2009.11.003

Hanna A., Boodai F., and El Asmar M. (2013) State of practice of building information modeling in mechanical and electrical construction industries, *Journal of construction engineering and management*, Vol. 139, 04013009.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000747

Hartmann T., Gao J., and Fischer M. (2008) Areas of application for 3D and 4D models on construction projects, *Journal of construction engineering and management,* Vol. 134, 776-785.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)0733-9364(2008)134:10(776)

Kam C., Senarantna D., Xiao Y., and McKinney B. (2013) The VDC scorecard: evaluation of AEC projects and industry trends, *Center for Integrated Facility Engineering (CIFE)*, Stanford University, Stanford, CA.
This paper is available electronically at http://cife.stanford.edu/sites/default/files/WP136.pdf

Kent D. and Becerik-Gerber B. (2010) understanding construction industry experience and attitudes toward integrated project delivery. *Journal of construction engineering and management,* Vol. 136, 815-825.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000188

Kim, S. Y., and Huynh, T. A. (2008) Improving project management performance of large contractors using benchmarking approach, *International Journal of Project Management*, Vol. 26(7), 758-769.
This paper is available electronically at http://dx.doi.org/10.1016/j.ijproman.2007.10.002

Korman T. M. and Tatum C. B. (2001) Development of a knowledge-based system to improve mechanical, electrical, and plumbing coordination, *Center for Integrated Facility Engineering (CIFE)*, Stanford University, Stanford, CA.
This paper is available electronically at http://cife.stanford.edu/sites/default/files/TR129.pdf

Korman T. M., Fischer M., and Tatum C. B. (2003) Knowledge and reasoning for MEP coordination, *Journal of construction engineering and management*, Vol. 129, 627-634.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)0733-9364(2003)129:6(627)

Korman T. M., Simonian L., and Speidel E. (2008) Using building information modeling to improve the mechanical, electrical, and plumbing coordination process for buildings, *Proceedings of Architectural Engineering Institute (AEI),* 1-10.
This paper is available electronically at http://dx.doi.org/10.1061/41002(328)10

Korman T. M. and Huey-King L. (2014) Industry input for construction engineering and management courses: development of a building systems coordination exercise for construction engineering and management students, *Practice periodical on structural design and construction,* Vol. 19, 68-72.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)SC.1943-5576.0000189

Lam E., Chan A., and Chan D. (2008) Determinants of successful Design-Build projects, Journal of construction engineering and management, Vol. 134(5), 333-341.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)0733-9364(2008)134:5(333)

Lee G. and Kim J. W. (2014) Parallel vs. sequential cascading mep coordination strategies: a pharmaceutical building case study, *Automation in construction,* Vol. 43, 170-179.
This paper is available electronically at http://www.sciencedirect.com/science/article/pii/S0926580514000569

Leite, F., Akcamete, A., Akinci, B., Atasoy, G., and Kiziltas, S. (2011). Analysis of modeling effort and impact of different levels of detail in building information models. *Automation in construction*, Vol. 20(5), 601-609.
This paper is available electronically http://dx.doi.org/10.1016/j.autcon.2010.11.027

Liao, P. C., O'Brien, W. J., Thomas, S. R., Dai, J., and Mulva, S. P. (2011). Factors affecting engineering productivity. *Journal of management in engineering*, Vol. 27(4), 229-235.
This paper is available electronically http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000059

McGraw-Hill Construction (2013) Information mobility: improving team collaboration through movement of project information, SmartMarket report, McGraw-Hill, New York.
This paper is available electronically http://enr.construction.com/engineering/pdf/News/Information_Mobility_SMR_2013.pdf

McGraw-Hill Construction (2014) The business value of BIM for construction in major global markets: how contractors around the world are driving innovation with building information modeling, SmartMarket report, McGraw-Hill, New York.
This paper is available electronically at http://i2sl.org/elibrary/documents/Business_Value_of_BIM_for_Owners_SMR_%282014%29.pdf

National Academies Press (2009) Advancing the competitiveness and efficiency of the US construction industry, *National Academy of Sciences*, Washington, DC, 19-25.

Redmond A., Hore A., Alshawi M., and West R. (2012) Exploring how information exchanges can be enhanced through Cloud BIM, *Automation in Construction*, Vol. 24, 175-183.
This paper is available electronically at http://www.sciencedirect.com/science/article/pii/S0926580512000180

Riley D. R. and Sanvido V. (1997) Space planning method for multistory building construction, *Journal of construction engineering and management,* Vol. 123, 171-180.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)0733-9364(1997)123:2(171)

Riley, D. R. and Horman, M. J. (2001) Effects of design coordination on project uncertainty, *Proceedings of the 9th annual conference of the International group for lean construction (IGLC-9)*, 129–136.

Riley D. R., Varadan P., James J., and Thomas H. (2005) Benefit-cost metrics for design coordination of mechanical, electrical, and plumbing systems in multistory buildings, *Journal of construction engineering and management,* Vol. 131, 877-889.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)0733-9364(2005)131:8(877)

Sacks R. and Barak R (2008) Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice, *Journal of automation in construction*, Vol 17, 439-449.
This paper is available electronically at http://dx.doi.org/10.1016/j.autcon.2007.08.003

Sacks R., Radosavljevic M., and Barak R. (2010) Requirements for building information modeling based lean production management systems for construction, *Automation in Construction,* Vol. 19, 641-655.
This paper is available electronically at http://dx.doi.org/10.1016/j.autcon.2010.02.010

Sacks R. and Barak R. (2010) Teaching building information modeling as an integral part of freshman year civil engineering education, *Journal of professional issues in engineering education and practice,* Vol. 136, 30-38.
This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)EI.1943-5541.0000003

Schaeffer N. C., and Presser S. (2003). The science of asking questions, *Annual Review of Sociology*, 65-88.

Simonian L. and Korman T. (2011) Building information modeling for electrical contractors: current practice and recommendations, *Proceedings of Architectural Engineering Institute (AEI) 2011*. 456-463.
This paper is available electronically at http://dx.doi.org/10.1061/41168(399)53

Staub-French S. and Khanzode A. (2007) 3D and 4D modeling for design and construction coordination: issues and lessons learned, *ITcon,* Vol. 12, 381-407.
This paper is available electronically at http://www.itcon.org/2007/26

Succar, B. (2009) Building information modelling framework: A research and delivery foundation for industry stakeholders, *Automation in construction*, Vol. 18(3), 357-375.

This paper is available electronically at http://dx.doi.org/10.1016/j.autcon.2008.10.003

Succar, B. (2010) The five components of BIM performance measurement, Proceedings of CIB World Congress, Salford.

Succar B., Sher W., and Williams A. (2012) Measuring BIM performance: Five metrics, *Architectural engineering and design management,* Vol. 8, 120-142.

This paper is available electronically at http://www.tandfonline.com/doi/abs/10.1080/17452007.2012.659506#.VLSIWCvF_YE

Tabesh, A. R., and Staub-French, S. (2006) Modeling and coordinating building systems in three dimensions: a case study, *Canadian journal of civil engineering*, Vol. 33(12), 1490-1504.

This paper is available electronically at http://www.nrcresearchpress.com/doi/abs/10.1139/l06-124#citart1

Tao W. K. and Janis R. R. (2001) Mechanical and electrical systems in buildings, Prentice Hall, Columbus, OH.

Tatum C. and Korman T. (2000) Coordinating building systems: process and knowledge, *Journal of architectural engineering,* Vol. 6, 116-121.

This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)1076-0431(2000)6:4(116)

Ugwu O.O., Anumba C.J., Newnham L., and Thorpe A. (1999) Agent based collaborative design of constructed facilities' in artificial intelligence in structural engineering—information technology for design, manufacturing, maintenance, and monitoring, *Proceedings of the 6th EG-SEAAI Workshop*, *Wierzba*., 199–208

Waldron M. B. and Waldron K. J. (1996) The influence of the designer's expertise on the design process, Springer-Verlag New York, New York, NY, 5-20.

Wang L. and Leite F. (2014) Comparison of experienced and novice bim coordinators in performing mechanical, electrical, and plumbing (MEP) coordination tasks, *Proceedings of Construction Research Congress* (CRC) *2014*, 21-30.

This paper is available electronically at http://dx.doi.org/10.1061/9780784413517.003

Yang J. and Wei P. (2010) Causes of delay in the planning and design phases for construction projects, *Journal of architectural engineering,* Vol. 16, 80-83.

This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)1076-0431(2010)16:2(80)

Yi J. and Chan A. (2014) Critical review of labour productivity research in construction journals, *Journal of management in engineering,* Vol. 30(2), 214-225.

This paper is available electronically at http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000194