

A BIM-ENABLED MEP COORDINATION PROCESS FOR USE IN CHINA

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SUMMARY: Mechanical, Electrical, and Plumbing (MEP) coordination is an important part of constructability review process. The rapid development of Building Information Modelling (BIM) could substantially facilitate this process by affording a visual and collaborative manner. However, BIM adoption in China has been hindered by the low management commitment and knowledge level. There is a need to develop a model to utilize BIM in China taking into consideration this current situation. This paper reports how design institutes without 3D modelling capabilities can work with modellers to perform MEP coordination with BIM. A BIM-enabled MEP coordination process for use in China is documented and further developed as one of the primary findings. IDEF0 language is used to illustrate the process in detail. It is found in the case study analysis that the use of BIM may not save overall design time as traditional 2D design was still used. However, it can reduce the costs of manual MEP coordination, the expected number of change orders, chance that significant number of change orders may occur, as well as MEP coordination related change orders as a percentage of total change orders.

KEYWORDS: MEP Coordination, constructability, Building Information Modelling, IDEF0, China

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1. INTRODUCTION

The US Construction Industry Institute (CII) defined “constructability” as “the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives” (CII 1987). Mechanical, Electrical and Plumbing (MEP) coordination is one critical activity for constructability review. In fact, many construction industry professionals have cited MEP coordination as one of the most challenging tasks encountered in the deliver process for construction projects (Korman et al. 2003).

Traditional MEP coordination is conducted through a time consuming manual process known as “sequential comparison overlay process” (Riley et al. 2005; Khanzode et al. 2008; Korman and Speidel 2010). The rapid development of Building Information Modelling (BIM) could substantially facilitate this process. However, the literature on 3D and 4D BIM has focused on modelling technologies and application examples. Little emphasis was placed on the integration of BIM supported knowledge communication and generation into ongoing construction working processes (Hartmann and Fischer 2007).

Furthermore, the use of BIM in China has been hindered by low levels of management commitment and knowledge. There is a need to develop a process that can facilitate the use of BIM in China given the lack of expertise on BIM in local design institutes. This paper seeks to make a contribution by documenting and further developing a BIM-enable MEP coordination process model based on the IDEF0 language. The model is largely based on US practice, taking into account the local practice in China. A 2D design step, although not recommended in any BIM guidelines, is still included in the process, as few local design institutes have 3D modelling capabilities. The proposed process is particularly suitable for current local industry, but where designers have modelling capabilities, the 2D design step shall be removed. The model describes in detail the input, control, mechanism and output of each procedure in each design phase so that the practitioners could easily apply the process onto the real projects. A high-rise building case was chosen as a demonstration of the process. It can also be easily adapted to suit other cases with different project organizations. The paper will also evaluate the cost and potential benefits of using the proposed BIM-enabled MEP coordination process.

1.1 Constructability Review

Constructability has gained acceptance throughout the construction industry (Pocock et al. 2006). A similar term “buildability”, but with narrower scope (it focuses on design stage only), has been used in the UK (Wong et al. 2007). Extensive research has been conducted since the definition of Constructability by CII in 1987.

A lot of benefits with improved constructability have been identified in the literature. They are summarized as follows:

- Reducing project cost (Griffith and Sidwell 1997; Eldin 1999; Francis et al. 1999; Jergeas and Put 2001; Trigunarsyah 2004a; Pocock et al. 2006);
- Reducing project duration (Griffith and Sidwell 1997; Eldin 1999; Francis et al. 1999; Low and Abeyegoonasekera 2001; Ford et al. 2004; Trigunarsyah 2004a, b; Pocock et al. 2006);
- Enhancing project quality (Eldin 1999; Francis et al. 1999; Low 2001; Low and Abeyegoonasekera 2001; Trigunarsyah 2004c; Pocock et al. 2006);
- Increasing productivity (Poh and Chen 1998; Low 2001);
- Improving safety performance (Francis et al. 1999; Low and Abeyegoonasekera 2001; Trigunarsyah 2004a, c)
- Minimizing contract change orders and disputes (Pocock et al. 2006);

The major obstacles to constructability include lack of open communications between designers and constructors, inadequate construction experience, difficulty in coordinating disciplines, etc. (Pocock et al. 2006).

Previous studies have also identified tools for constructability review. For instance, Fisher et al. (2000) identified 27 basic constructability tools based on maturity, ease and cost of implementation, maintainability considerations, and impact on constructability process. Tools commonly used in design stage include design review by construction expert (Pocock et al. 2006), peer review (Arditi et al. 2002; Pocock et al. 2006), feedback

system (Arditi et al. 2002), constructability review (Pocock et al. 2006), brainstorming (Arditi et al. 2002), etc. Wong et al. (2007) also identified three commonly used approaches to improve constructability, namely, quantified assessment of design, constructability review and implementation of constructability programs. They suggested that quantified assessment of design (e.g. Buildable Design Appraisal System enforced in Singapore) is the most practical and achievable way among the three.

1.2 MEP Coordination

MEP coordination is an important area of constructability review. Three knowledge domains are required for MEP coordination, namely, design, construction, and operations and maintenance (Korman et al. 2003). Each domain consists of several knowledge areas (Table 1). It can be seen that other than design knowledge, a lot of construction, operation and maintenance related knowledge areas are required for MEP coordination.

TABLE 1: Knowledge areas for MEP coordination

Domain	Knowledge area	Author (Date)
Design Knowledge	<ul style="list-style-type: none"> • system function and performance; • material considerations; • support requirements; • aesthetic considerations; • insulation and clearance; 	Korman et al. (2003)
Construction knowledge	<ul style="list-style-type: none"> • sequencing considerations; • fabrication considerations; • installation considerations; • safety requirements; • start-up and testing requirements; • tolerance and variance; • productivity 	Korman et al. (2003); Tabesh and Staub-French (2006)
Operations and maintenance knowledge	<ul style="list-style-type: none"> • accessibility requirements; • expandability and retrofit requirements; • safety considerations; • connection considerations; • performance; • space 	Korman et al. (2003); Tabesh and Staub-French (2006)

Korman et al. (2003) classified interferences in MEP systems/components into 5 types, namely, actual, extended, functional, temporal and future. Actual interference refers to physical interference, also known as “hard clashes”. Extended interference refers to the interference of the extended space (such as access path). An example of functional interference is a pipe blocking light from a fixture. Future interference occurs when space for routine operations, maintenance or future expansion is not allowed. It seems these three types match the meaning of “soft clashes” in the literature. Temporal interference refers to the prevention of efficient construction sequencing and scheduling.

Traditionally MEP coordination is conducted through a “sequential comparison overlay process” (Riley et al. 2005; Khanzode et al. 2008; Korman and Speidel 2010). In this process, the functional design is prepared by a consultant engineer, while the detailed design for each trade is developed by specialty contractors. The specialty contractors sequentially compare their shop drawings of the same scale on a light table and try to identify potential conflicts.

Obviously this manual method is costly, time consuming and inefficient. Riley et al. (2005) surveyed 12 project managers in the US and found that MEP coordination cost for research labs or hospitals ranged from \$0.4-\$1.89/ft², which is about 0.8-2.7% of the total MEP cost. The cost of MEP coordination depends on MEP density (MEP cost per ft²) and plenum height. With the rapid development of BIM technology, constructability review or MEP coordination process could be greatly facilitated.

1.3 BIM and Constructability Review

A number of studies have used BIM for constructability improvements. For instance, Ganah et al. (2005) reported a prototype visualization system called “VISCON” to clarify and communicate constructability information. The system was tested on two real projects and found satisfactory by a group of academia and practitioners. Hartmann and Fischer (2007) developed a process that facilitates constructability review with 3D/4D modelling. It was suggested that BIM was useful for the communication and generation of design, sequencing, schedule and constructability knowledge. Navon et al. (2000) developed a prototype rebar constructability diagnosis system that can detect potential constructability problems in the early phases.

Haque and Rahman (2009) developed a 4D CAD model to detect time-space conflicts, although they have not evaluated the model. Others have used 4D models to detect site layout collisions, e.g., Lai and Kang (2009), Zhang and Hu (2011) and Hu and Zhang (2011).

Korman et al. (2010) suggested the use of BIM software for clash detection and interference checking, and argued that BIM allows a mechanism for dialogue between specialty contractors and design engineers. Nonetheless, only a limited number of studies have focused on BIM facilitated MEP coordination. For instance, Staub-French and Khanzode (2007) and Khanzode et al. (2008) reported a healthcare project that used BIM for MEP coordination. In their case the specialty contractors modelled their own trade, making communication and coordination more difficult. Therefore their recommendation was that all specialty contractors should work side-by-side in one big room. Staub-French and Khanzode (2007) further reported the use of BIM-enabled MEP coordination in a plant facility. Tabesh and Staub-French (2006) reported a university building case where the about 800m² of laboratory and corridor parts were modeled. Ghanem and Wilson (2011) reported an art performing center in California where the construction manager modelled the project to facilitate constructability and clash detection. A controlled experiment conducted by Santos and Ferreira (2008) revealed that 3D based design coordination was almost 30% more time efficient than the traditional 2D method. The organization and benefits of the above cases have been summarized in Table 2.

TABLE 2: A comparison of cases with BIM enabled MEP coordination

Author (Date)	Project Details	MEP design and modelling organization & roles	Benefits of BIM enabled MEP coordination
Staub-French and Khanzode (2007); Khanzode et al. (2008)	A 3-storey 250,000 ft ² medical office building and a 2-storey 1,400 space parking garage in California; contract value \$96.9M; floor to ceiling height: 2.74-2.90m.	Procurement method: “Design-Assist”; MEP functional design by consultant engineer; MEP coordination facilitated by general contractor; MEP detail design, modelling, and coordination by specialty contractors (led by HVAC contractor)	For owner: No RPIs or change orders related to field conflicts of modeled part, saving of \$9M and 6 months; For consultants: spent less time during construction phase; For general contractor: spent less time in resolving field conflicts, better safety performance; For specialty contractors: all trades finished ahead of or on schedule, higher field productivity, more pre-fabrication, less rework.
Staub-French and Khanzode (2007)	A 1-storey plant facility of 20,000 ft ² in California; contract value \$6M.	Procurement method: Design and build; MEP functional design by consultant engineer; design coordination by general contractor; MEP detail design and modelling by specialty contractors.	Most design conflicts/errors identified before construction; productivity significantly improved; less rework; increased opportunities for pre-fabrication; fewer request for information; fewer change orders; ability to build the system with less skilled labor force; improved safety performance; better cost control
Tabesh and	A 6-storey 11,427m ² (123,000	Procurement method: CM at risk	Identified 25 design errors, omissions and inconsistencies; avoided 25 MEP

Staub-French (2006)	ft ²) teaching research space in Vancouver	Chem-Bio and space in	MEP functional design by consultant engineer; only about 800m ² of laboratory and corridor space were modeled by university researchers	coordination issues or conflicts.
Ghanem and Wilson (2011)	A 168,000 ft ² art performing center in California; contract value \$100M		Procurement method: CM at risk with GMP; MEP design (from schematic to construction documentation) by consultant engineer, Constructability review by CM; modeled by CM (cost \$80,000)	More subcontractors were willing to bid and the lowest bid was within budget; 2000 clashes identified and cost avoided was estimated to be \$5M
Santos and Ferreira (2008)	A (including 3 basement car park levels) 17,400m ² apartment building	32-storey	A controlled experiment was conducted where one designer used traditional 2D coordination while the other used 3D coordination.	3D based method is almost 30% more time efficient; In traditional 2D method about 1/3 of time is devoted to non-value-adding checking and correction; Some interferences could only be detected with 3D method.

To summarize, little emphasis was placed on the integration of BIM supported knowledge communication and generation into ongoing construction working processes (Hartmann and Fischer 2007). Our literature review found very little academic work in the past 5 years. Moreover, there was no evidence of systematic incorporation of BIM into decision making process to enable optimum use of construction knowledge in previous studies. This paper will contribute by developing an MEP coordination process based on the IDEF0 language.

1.4 BIM in China

Despite the size of the industry, implementation and practice of BIM in the construction industry in China is still limited (Liu and Zhang 2014), although it is getting popularity since 2008 (Zhang et al. 2014). A survey done in China in 2011 showed that 73% of surveyed construction professionals had never adopted BIM, and only 22% of them considered themselves as being familiar or very familiar with BIM software (Zhang et al. 2014). The survey also found that a lot of projects which eventually gave up BIM because the participants knew little about BIM. Two factors contributing to the low adoption rate of BIM were identified as lack of management level commitment and knowledge.

Liu and Zhang (2014) analyzed 10 large-scale projects where BIM was used and found that BIM were not used in all stages. In those projects, BIM was mostly used in the preliminary design, detail design stages and construction stage. Fewer projects used BIM in planning stage or operation and maintenance stages.

Ideally designing with BIM shall start with 3D design from the beginning. However, given the low management commitment, knowledge level and adoption rate of BIM in China's construction industry, gradual transition measures are required to help adoption of BIM. We have therefore proposed a BIM enabled MEP coordination process which includes both traditional 2D design stages and modelling stages.

2. METHODOLOGY

The literature details the needs for constructability analysis, MEP coordination and a transition process for BIM application in China. The next step is to document and develop the process and conduct a case study. We shall use IDEF0 language to describe the process. IDEF0 does not itself improve the MEP coordination process, but it is a very good tool to present our proposed process specifically designed for transition into BIM usage.

IDEF0 language is a modelling tool to specify business function in a simple diagram. The advantage of using IDEF0 for process analysis is that the subsystems in a process can be analyzed in detail.

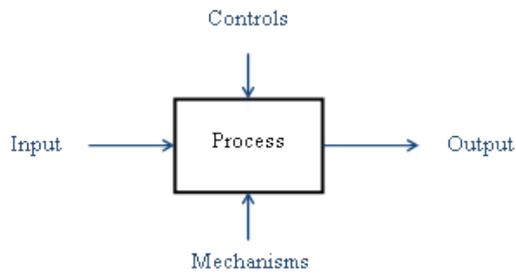


FIG. 1: Elements of an IDEF0 Model.

It consists of the following elements (as shown in Fig. 1):

- Input (arrows coming into the left of the function): the resource/information needed to perform the function;
- Control (arrows coming into the top of the function): the conditions/rules/information that governs the execution of the function;
- Mechanisms (arrows coming into the bottom of the function): the supporting mechanisms/tools, e.g. persons, physical devices, computer programs, etc.;
- Output (arrows coming out of the right of the function): objects/information produced by the function.

Construction projects need to incorporate different knowledge and experience from a number of different parties in certain sequence. Coordination and information flow have always been difficult areas in construction which cause a lot of problems. A formal process is needed as BIM is about provision of information, and those information must be utilized in the decision making process. IDEF0 language can best serve this purpose, as it details the input, output, knowledge, people, etc. of the process. This facilitates the flow and integration of information and knowledge as the process proceeds.

Examples of using IDEF0 or its modified version to represent design/construction process include Sanvido and Medeiros (1990), Austin et al. (1999, 2002), etc.

A case that utilizes the proposed MEP coordination process is reported. Cost benefit analysis will be used to evaluate the merit of BIM enabled MEP coordination process. The cost of 3D modelling will be compared with the potential benefits. They will also be compared with those reported in the literature. The potential benefits of BIM enabled MEP coordination to be measured, as advised in the literature, include:

- The extent to which BIM will shorten overall design time;
- The extent to which BIM will save manual MEP coordination time;
- The extent to which BIM will reduce the number of change orders and save costs.

It is extremely difficult, if not impossible, to design an experiment where the cases of using BIM or not can be compared. The reason is that BIM is mostly used in complex projects and for those projects, it would be impossible to find another project as a control. Since the client has decided to use BIM/3D modelling, the scenario of using BIM can be retrieved from company records, this include the design time and MEP coordination time. However, the construction has just begun and will take three years to complete. The number of change orders has to be estimated based on experience. The scenario of not using BIM is also estimated based on experience. One of the authors is a member of the project team, therefore the MEP design team leaders kindly spent a day to give an estimate as accurate as possible. A questionnaire was used to facilitate the process.

It can be argued that data from one case study might not be representative, as personal experience might be biased. However, since the results of this study would be compared with those in the literature, if they are consistent, the possibility of biasness would be very low. In addition, this case study shows how a design institute without 3D modelling capabilities can work with a modeller to use BIM for MEP coordination. It is particularly suitable for the current local construction industry where few designers have embraced BIM.

3. A NEW BIM-ENABLED MEP COORDINATION PROCESS

Based on US procurement practice, Staub-French and Khanzode (2007) suggested a 10-step process for 3D design coordination:

- Identify the potential uses of the 3D models;
- Identify the modelling requirements;
- Establish the drawing protocol;
- Establish a conflict resolution process;
- Develop a protocol for addressing design questions;
- Develop discipline-specific 3D models;
- Integrate discipline-specific 3D models;
- Identify conflicts between components/systems;
- Develop solutions for the conflicts identified;
- Document conflicts and solutions.

Other popular industry BIM guidelines are much more detailed, but still have very similar steps. We develop our MEP coordination process based on their suggestions. However, due to the different design practices in China and the fact that a lot of design institutes do not have 3D modelling capabilities, our process also includes a 2D design step to cater for the local situation. 2D design is not recommended in any published BIM guidelines, but it may be a necessary interim step for the local industry. While in the future when BIM is more widely embraced, this step shall be removed and the process revised accordingly. We have used an IDEF0 model to illustrate the important sub-processes.

The IDEF0 model is developed in levels. Level 1, the highest level, shows the six main functions of the BIM enabled design process (Fig. 2). Each function can be partitioned to show finer details in a separate diagram. All these diagrams make up Level 2 model, which could be further broken down into finer levels. Since the focus of our model is to demonstrate how BIM-enabled MEP coordination could be incorporated into the design process, our model stops at Level 2 which is sufficient to meet our requirements. To appreciate the complexity of design process, the readers are advised to read earlier works of Austin et al. (1999, 2002) where the design process was broken down into 4 levels consisting of 600 design tasks.

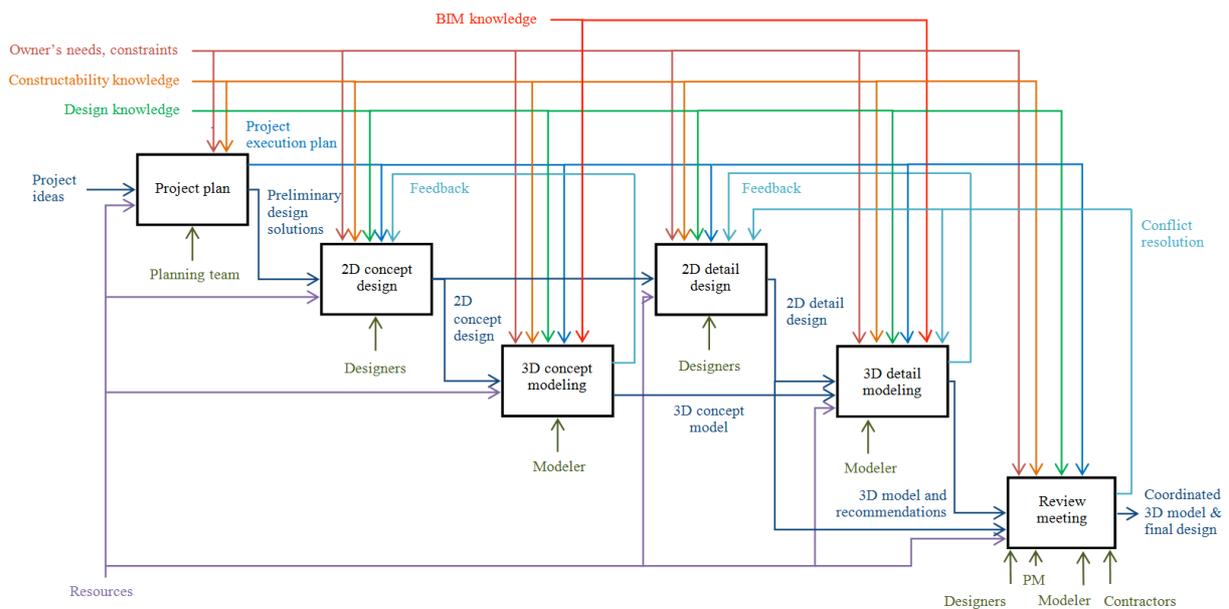


FIG. 2: Level 1 IDEF0 MEP coordination process model.

Table 3 shows some differences in the design practices between US and China. Essentially in the US, a lot of firms are involved in the design process, while in China usually only one design institute will be involved. The effect is that coordination between firms is replaced with coordination within a firm. Whether this can save coordination cost is debatable and could be an area for further research.

TABLE 3: A comparison of design practices in US and China

	US	China
Design role	Usually the architectural, structural and MEP design will be done by separate designers (the architect, structural engineer, and MEP engineer respectively)	Usually all the architectural, structural and MEP design will be done by the same design institute.
MEP design	Usually the consultant MEP engineer only performs the functional design, the specialty subcontractors will provide detail design of each trade. MEP coordination usually led by HVAC subcontractor, facilitated by the general contractor	The design institute will provide detail design.

Fig. 2 shows the Level 1 IDEF0 model of the MEP coordination and constructability review process. Although this model reflects what this particular project has been doing, it is intended to be generally applicable to the industry, especially in China. Moreover, it could be easily adapted to the situations where the project organizations are much different.

Physical and human resources are the common inputs to all activities, and the owner's need, internal and external constraints are common constraints to all activities. Our model also shows some feedback loops, reflecting the iterative nature of design process.

The first function in Fig. 2 is the project plan, where the project idea is transformed into preliminary design solutions and project execution plan. The project execution plan should contain a variety of information such as the project execution schedule, budget, procurement method, etc. Regarding the 3D modelling and MEP coordination, it should also contain information on purpose and requirements of 3D model, and protocol for conflict resolution, etc.

The second function is the 2D concept design process, where the design solutions will be materialized into 2D concept design, including both 2D drawings and specifications. Note that this step is only necessary because a lot of local design institutes have not embraced BIM. While in the future when BIM is more widely used, this step shall be removed and the process shall be revised accordingly.

In this project as well as most Chinese projects, a design institute will perform this function. The design includes site investigation, architectural, structural (except the structural steel part in this project), and MEP design. The design institute in this project is not qualified for designing the structural steel part, and therefore this is done by a subsidiary of the main contractor. Where the architectural, structural and MEP designs are performed by different firms, as in the case of most Western countries, more entries could be added to the Mechanisms element of the IDEF0 model. Fig. 3 shows the Level 2 model of the 2D design process where it was broken down into three activities, namely, architectural design, civil and structural design, and MEP design. They could be further broken down into finer details, which is however beyond the scope of this paper.

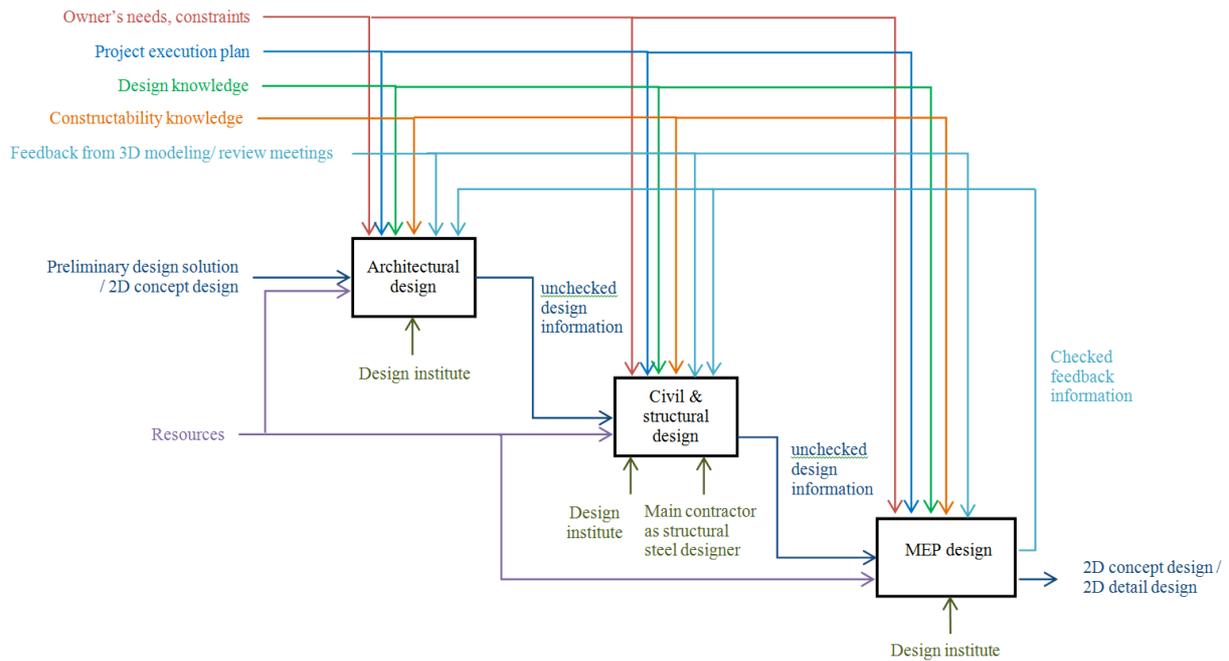


FIG. 3: Level 2 IDEF0 2D (concept / detail) design process model.

The third activity in Level 1 model is 3D concept modelling. The Input will be the 2D concept design and the Output will be the 3D concept model and layout feedbacks to 2D design. At this stage, the 2D concept design information may not have the required details for modelling, the modeller will identify this as an output of this function. Fig. 4 shows the Level 2 breakdown of this function. Discipline specific models will be built in parallel. They will be integrated into a full model. Finally the layout of disciplines will be optimized. This Level 2 model could of course be further broken down into finer details. However, this level is enough for the purpose of conceptually demonstrating how MEP coordination is performed with the use of BIM.

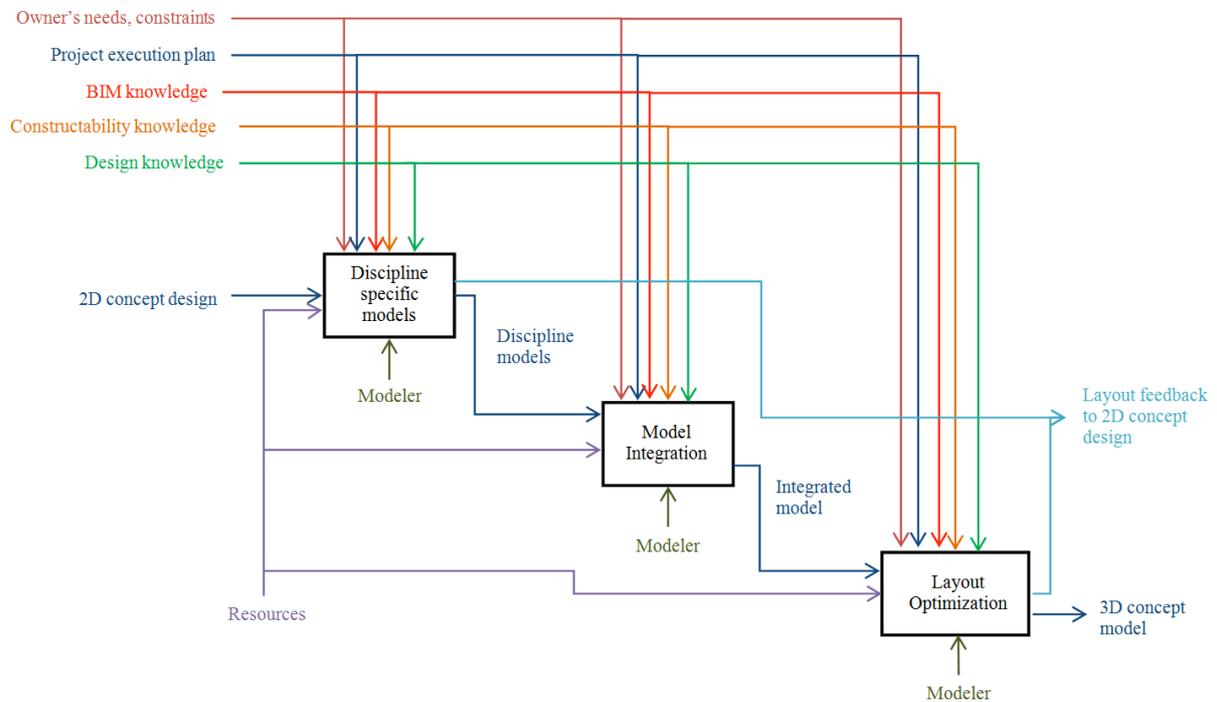


FIG. 4: Level 2 IDEF0 3D concept modelling process model.

3D modelling knowledge is required to build the model, but constructability knowledge is also essential. Tabesh and Staub-French (2006) reported a case where lengthy learning, communication and coordination processes were required if the modeller had only limited constructability knowledge. In a typical US case as reported in Staub-French and Khanzode (2007) or Khanzode et al. (2008), where the modelling of different trades is performed by different firms, more entries can be added to the Mechanisms element of the IDEF0 model. However, extensive coordination efforts are required. One way to facilitate coordination among the designers is to accommodate all of them in “one big room”, as suggested by Khanzode et al. (2008).

In our case, initially the client engaged a 3D modeller to produce a 3D model. Later the client employed a project management firm (PM) and found that they have the capability to produce 3D models as well. Therefore, the client engaged the project management firm to update the model and contribute to the constructability review and MEP coordination. The benefit is the easy and efficient integration of modelling knowledge and the constructability knowledge.

The fourth function in Fig. 2 is 2D detail design. It will convert the 2D concept design into 2D detail design. The Level 2 detail design process is very similar to that of concept design, therefore the same Fig. 3 can be used for illustration purpose.

The fifth function in Fig. 2 is 3D detail modelling. It uses the 3D concept model and 2D detail design as inputs, produces 3D detail models, conducts conflict detections and make recommendations on how conflicts can be resolved. Fig. 5 shows the Level 2 breakdown of this function. The difference between 3D detail modelling and concept modelling lies in the last Level 2 activity (conflict detection vs. layout optimization for MEP disciplines).

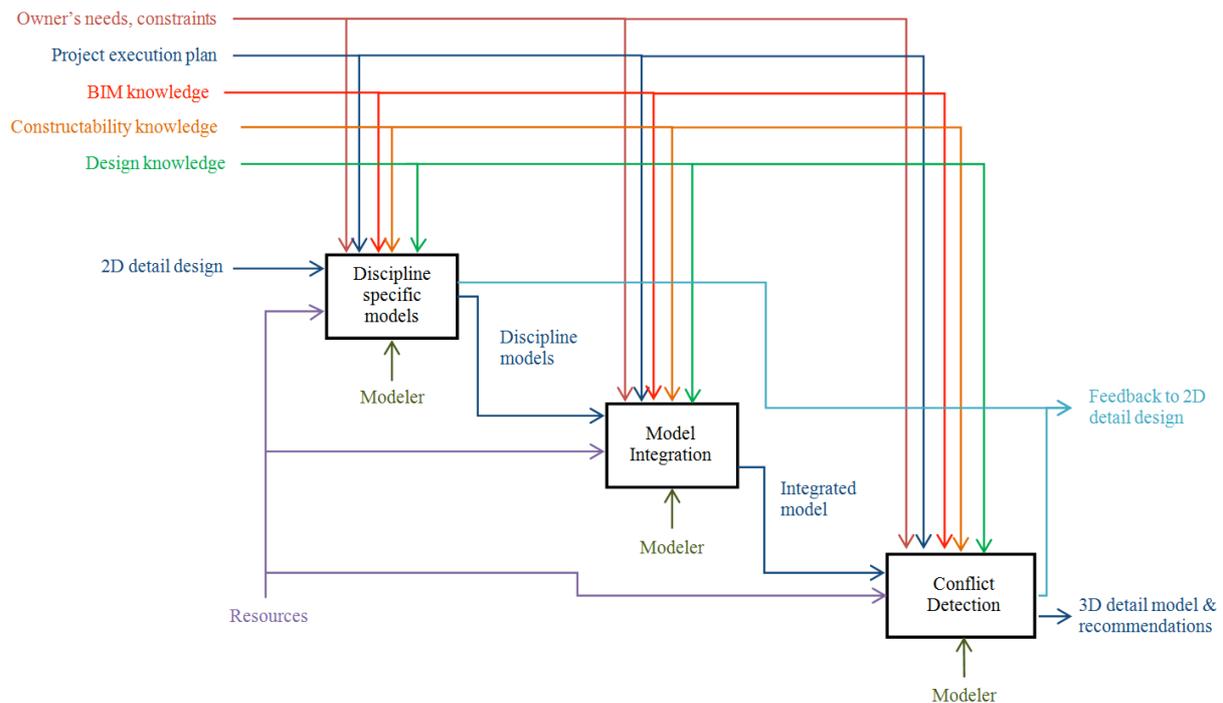


FIG. 5: Level 2 IDEF0 3D detail modelling process model.

The last function in Fig. 2 is constructability review meetings. The Input is the 2D detail design, the 3D model, coordination problems found and recommendations for improvements. The Output will be the conflict resolution ideas and finally coordinated 3D models and final design. Constructability knowledge is also required in this stage and essentially all members of the project team will jointly perform this function. In our case, this includes the design institute, the main contractor in the capacities of both main contractor and structural steel designer, the project management firm in the capacities of both project manager and 3D modeller, as well as the MEP subcontractors.

Since the project is a large scale one, it makes sense to divide it into portions. In our case, each level (basement floors, mechanical floors, typical apartment floor, and typical office floor) will go through the above-described IDEF0 process once. On average it takes about 3 weeks to go through one cycle.

Clash detection with computer software is one of the main benefits of 3D modelling. It replaces the time-consuming sequential comparison overlay process. Seo et al. (2012) suggested that in the construction documentation stage, the main purpose of clash detection is to identify “hard clashes” (physical clashes); while in the construction stage, the main purpose is to identify “soft clashes” (e.g. access/insulation space interference). We opine that “soft clashes” should not be left until construction stage, as it would be much more costly to rectify any problem in the construction stage.

Apart from those well-known constraints, such as ceiling height, dimensions of pipes, etc., some more points needed to be considered during MEP coordination for avoidance of soft clashes:

- Whether the pipes are covered with insulation and the thickness of insulation, as frequently in MEP drawings only the dimension of the pipes is shown;
- The material property of pipes, as different space is required for turning;
- Installation space and process;
- Maintenance space.

Some soft clashes can be detected with computer software by defining the extended space required for an element. For instance, there is only 50 mm between the cable tray and the HVAC pipe above, while 100mm installation space is required above the cable tray (Fig. 6a). Although there is no hard clash between them, modification is required. As it is impossible to move the HVAC pipe upward for 50mm, modifications to a number of pipes are required (Fig. 6b).

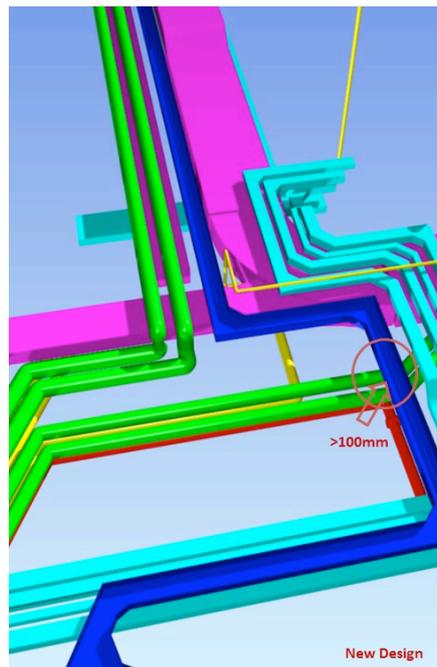
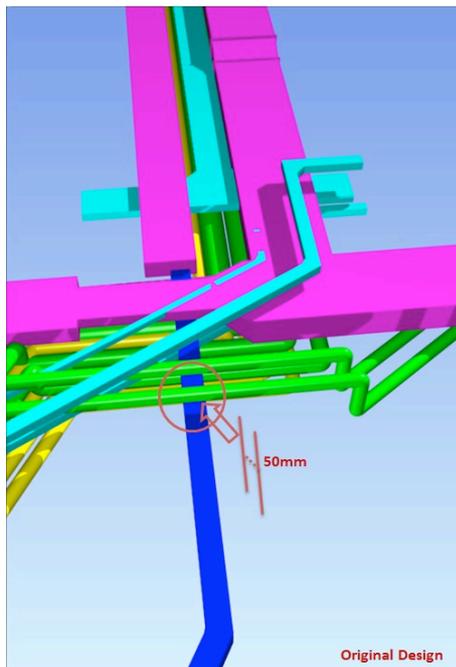


FIG. 6a: An example of soft clash.

FIG. 6b: Solution for the soft clash.

As to the sequence of MEP coordination, Korman et al. (2010) recommended the following: HVAC air ductworks, sanitary drainage system, HVAC process piping, fire protection piping, water distribution piping, electrical. The first one (HVAC air ductworks) is the hardest to relocate and need to be checked first, while the last one (electrical) is considered the most flexible). Essentially this sequence has been followed in our case. The structure has the highest priority (i.e., it should not be changed unless absolutely necessary), MEP coordination actually starts after the integration of architectural and structural models. The location of major plant and equipment need to be confirmed first, then comes HVAC system, then others.

4. CASE STUDY

Having described the process, it is necessary to conduct a case study to evaluate the proposed process. Case study is the best approach due to the exploratory nature of this study. The chosen case is a high-rise building project in the CBD of Chengdu, China. It consists of a 202m high 58-storey apartment tower, a 48-storey office tower of the same height, and a 3-storey basement. The total floor area is about 167,895m². The construction commenced in 2012 and it is expected that it will be completed in 2015. The construction cost is about RMB 1000 million (US\$161.3 million), of which RMB400 million (40%) is for MEP.

The 3D modelling and design coordination were performed by two firms. Initial 3D modelling was performed by a modeller from May 2011 to August 2011. The cost was RMB 1 million. When a project management firm was engaged in 2012, a separate contract of RMB 0.7 million was awarded to update the 3D model and conduct clash detections and make recommendations for improvement. Therefore, the total cost of 3D modelling was RMB 1.7 million, equivalent to only 0.17% of total construction cost, or 0.43% of MEP cost.

Four MEP design team leaders in the design institute were asked to provide information (Table 4). One was in charge of high voltage electrical design, one was in charge of low voltage electrical design (e.g. telephone, network, security monitoring system, etc.), one was in charge of both fire services and plumbing design, and the last in charge of HVAC design. All of them had 9 or more years of project experience. The actual design time and MEP coordination time have been retrieved from company record, while the number of change orders and the scenario of not using BIM have to be estimated based on experience.

The first potential benefit involves overall design time. All the design team leaders were able to estimate the design working days required for their respective trade. However, only one provided the hypothetical design time if BIM was not used in this project. He indicated that the design time without BIM would be the same, as 2D design is still used in the process. Upon communication with other project team members, it is confirmed that the client would require the same design period regardless of BIM application.

The second potential benefit is the saved manual MEP coordination works. The respondents indicated that manual MEP coordination would take: 20 days for high voltage electrical works; 50 days for low voltage electrical works; 60 days for fire services and plumbing; and 90 days for HVAC (Table 4). The manual coordination time as a percentage of total design time would be 20% for high voltage electrical; 42% for low voltage electrical; 50% for fire services and plumbing; and 38% for HVAC. The overall estimate for all trades is consistent with an experiment reported by Santos and Ferreira (2008) where the checking and correction of 2D drawings were found to be slightly over one third of total design time.

TABLE 4: Questionnaire results

Ref.	Description	Electrical High Vol.	Electrical Low Vol.	Fire services + Plumbing	HVAC
1.	Years of experience	13	9	10	14
2.	Design cost				
2.1	Number of working days required for completion of design (with BIM)	100	120	120	240
2.2	Cost of one designer per working day	400	400	400	400
2.3	Number of designers required per working day	6	3	7	5
2.4	Total design cost in RMB (2.1x2.2x2.3)	240,000	144,000	336,000	480,000
3.	Number of working days required for completion of design (if there was no BIM)	N/A	120	N/A	N/A
4.	Manual MEP coordination				

4.1	Number of working days required for manual MEP coordination if there was no BIM	20	50	60	90
4.2	Manual coordination as a percentage of total design time (4.1/2.1)	20%	42%	50%	38%
4.3	Manual coordination cost (4.1*2.2*2.3)	48,000	60,000	168,000	180,000
5.	Possible variations without BIM				
5.1	Possible number of change orders in the trade without BIM (minimum)	30	10	20	20
5.2	ditto (maximum)	100	30	80	50
5.3	Number of MEP coordination problems as a percentage of total change orders in the trade without BIM (minimum)	10%	10%	10%	40%
5.4	ditto (maximum)	20%	50%	50%	70%
5.5	Cost of MEP coordination related change orders as a percentage of construction cost of the trade without BIM (minimum)	N/A	N/A	N/A	5%
5.6	ditto (maximum)	N/A	N/A	N/A	10%
6.	Estimated variations with BIM				
6.1	Possible number of change orders in the trade with BIM (minimum)	10	5	10	10
6.2	ditto (maximum)	30	15	30	20
6.3	Number of MEP coordination problems as a percentage of total change orders in the trade without BIM (minimum)	5%	5%	5%	20%
6.4	ditto (maximum)	10%	20%	15%	30%
6.5	Cost of MEP coordination related change orders as a percentage of construction cost of the trade with BIM (minimum)	N/A	N/A	N/A	1%
6.6	ditto (maximum)	N/A	N/A	N/A	2%

The total manual coordination costs saved amounted to RMB 456,000, which is about 0.11% of total MEP cost (RMB400 million). The percentage is much lower compared with the range (0.8-2.7%) reported by Riley et al. (2005). There are two possible reasons for this. The first is that the ratio of labour price to material price is higher in the US. Since MEP coordination is very labour intensive in nature, while a lot of MEP construction cost comes from plant and materials which could be produced in countries with cheaper labour. The second possible reason is that MEP coordination within the same firm (design institute) is more efficient than among different firms. We do not have sufficient data to verify this, and hence it could be an area for further research.

The third potential benefit is the avoided change orders and their associated costs. The respondents are required to estimate the number of change orders with and without BIM. In the hypothetical case of not using BIM/3D

modelling, the minimum number of change orders ranges from 10 to 30 for each trade; while the maximum number ranges from 30 to 100 (Table 4). Out of these change orders, the percentages related to MEP coordination ranges from 10% to 70%. Only one respondent (HVAC design team leader) gave an estimate of the likely cost of MEP coordination related change orders, being about 5% - 10% of construction cost for the trade.

Since the construction would not be completed until 2015, the data for actual number of change orders is not available now. Therefore, the respondents are also required to estimate the likely number of changes orders, given that BIM/ 3D modelling has been used in this project. The minimum number of change orders ranges from 5 to 10 for each trade; while the maximum number ranges from 15 to 30 (Table 4). Out of these change orders, the percentages related to MEP coordination ranges from 5% to 30%. Again, only the HVAC design team leader gave an estimate of the likely cost of MEP coordination related change orders, being about 1% - 2% of construction cost for the trade.

Therefore from the estimations, it is concluded that the use of BIM/3D model will potentially

- Reduce the number of change orders (including the MEP coordination related change orders);
- Substantially lower the chance that lots of change orders occur (the maximum possible number of change orders substantially reduced);
- Reduce the MEP coordination related change orders as a percentage of total change orders.

The total cost of MEP is estimated to be about RMB 400million. If the avoided MEP coordination related change orders amounted to 5% of the MEP construction cost, the cost saving will be RMB20 million, which is much higher than the total modelling cost (RMB 1.7 million).

5. CONCLUSION

This paper documents and further develops a BIM-enabled MEP coordination process based on IDEF0 language, which is particularly suitable for China construction industry where few design institutes have embraced BIM. A 2D design step is included in the process to cater for local circumstances. However, in the future when BIM is more widely adopted, the 2D design step shall be removed and the process revised accordingly.

The motivation of this paper comes from the lack of attention to this topic in the literature, despite of its importance. Previous works have concentrated on description of BIM technologies. There have been few discussions or evaluations on systematic integration of BIM-enabled MEP coordination onto design processes. The model presented in this paper provides a viable solution to use BIM for MEP coordination in local construction industry where the management commitment, knowledge and adoption level have been low. It uses the IDEF0 language to explain the inputs, controls, mechanisms and outputs of each sub-process in the BIM-enabled design process so that practitioners can easily adopt the model in real projects.

A case study was implemented to demonstrate the coordination process. The cost of 3D modelling has been compared with the estimated benefits. It is found that the use of BIM may not save overall design time as 2D design is still involved. However, it can save the costs of manual MEP coordination, potentially reduce the number of change orders, the chance that lots of change orders may occur, as well as MEP coordination related change orders as a percentage of total change orders. Overall, the benefits could be much higher than the cost.

It should be emphasized that one contribution of this paper is the development of a process that is suitable for adoption in China, given the low management commitment, knowledge level and adoption level. The one case study gives some evidence of the adoption of the process, more evaluations are necessary to verify the merits of the proposed process. Since this study has been based on only one case, and the scenarios were estimated based on experience which could be biased, care should be taken when interpreting the results of this study. Nonetheless, many of the results have been found consistent with the literature; therefore the possibility of biasness in personal experience is low. If in the future there are more cases with BIM-enabled MEP coordination, a possible further work would be the comparison of the general level of change orders in these projects with that of projects without BIM. This would provide a more reliable result because of larger sample size.

6. REFERENCES

- Austin, S., Baldwin, A., Li, B. and Waskett, P. (1999). "Analytical design planning technique: a model of the detailed building design process." *Design Studies*, 20, 279-96.
- Austin, S., Newton, A., Steele, J., Waskett, P. (2002). "Modelling and managing project complexity." *International Journal of Project Management*, 20, 191-98.
- Arditi, D., Elhassan, A., and Toklu, Y. C. (2002). "Constructability analysis in the design firm." *Journal of Construction Engineering and Management*, 128 (2), 117-26.
- Construction Industry Institute (1987). *Guidelines for implanting a constructability program*, Publication 3-2, Austin, Tex.
- Eldin, N. N. (1999). "Impact of employee, management and process issues on constructability implementation." *Construction Management and Economics*, 17 (6), 711-720.
- Fisher, D. J., Anderson, S. D., and Rahman, S. P. (2000). "Integrating constructability tools into constructability review process." *Journal of Construction Engineering and Management*, 126 (2), 89-96.
- Ford, D. N., Anderson, S. D., Damron, A. J., de Las Casas, R., Gokmen, N., and Kuennen, S. T. (2004). "Managing constructability reviews to reduce highway project durations." *Journal of Construction Engineering and Management*, 130 (1), 33-42.
- Francis, V. E., Mehrtens, V. M., Sidwell, A. C., and McGeorge, W. D. (1999). "Constructability strategy for improved project performance." *Architectural Science Review*, 42, 133-138.
- Ganah, A.A. Bouchlaghem, N.B., and Anumba, C.J. (2005). "VISCON, Computer visualization support for constructability." *ITcon*, 10, 69-83.
- Ghanem, A. A. and Wilson, N. (2011). "Building Information Modelling applied on a major CSU capital project, a success story." 47th ASC Annual International Conference Proceedings, April 6-9, Omaha, N.E.
- Griffith, A. and Sidwell, A. C. (1997). "Development of constructability concepts, principles and practices." *Engineering, Construction and Architectural Management*, 4 (4), 295-310.
- Haque, M. E. and Rahman, M. (2009). "Time-space-activity conflict detection using 4D visualization in multi-storied construction project." In Zaman, H.B. (Ed.). *IVIC 2009, LNCS 5857*, 266-278.
- Hartmann, T. and Fischer, M. (2007). "Supporting the constructability review with 3D/4D models." *Building Research & Information*, 35 (1), 70-80.
- Hu, Z. Z. and Zhang, J. P. (2011). "BIM- and 4D- based integrated solution of analysis and management for conflicts and structural safety problems during construction, 2. Development and site trials." *Automation in Construction*, 20, 167-80.
- Jergeas, G. and Put, J. V. D. (2001). "Benefits of constructability on construction projects." *Journal of Construction Engineering and Management*, 127 (4), 281-90.
- Khanzode, A. Fischer, M., and Reed, D. (2008). "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, Electrical, and plumbing (MEP) systems on a large healthcare project." *ITcon*, 13, 324-42.
- Korman, T. M., Fischer, M. A., and Tatum, C.B. (2003). "Knowledge and reasoning for MEP coordination." *Journal of Construction Engineering and Management*, 129 (6), 627-34.
- Korman, T. M., Simonian, L. and Speidel, E. (2010). "How building information modelling has changed the MEP coordination process." In Ghafoori (Ed.) *Challenges, Opportunities and Solutions in Structural Engineering and Construction*, Taylor & Francis, London, 959-63.
- Lai, K. C., and Kang, S. C. (2009). "Collision detection strategies for virtual construction simulation." *Automation in Construction*, 18, 724-36.

- Liu, H., and Zhang, L. (2014) "Lessons Learned from Case Projects and Enterprises Where BIM Was Utilized", in J. Wang et al. (eds.), Proceedings of the 17th International Symposium on Advancement of Management and Real Estate, Berlin Heidelberg: Springer-Verlag, pp. 961-968.
- Low, S. P. (2001). "Quantifying the relationships between buildability, structural quality and productivity in construction." *Structural Survey*, 19 (2), 106-12.
- Low, S. P. and Abeyegoonasekera, B. (2001). "Integrating buildability in ISO 9000 quality management systems, case study of a condominium project." *Building and Environment*, 36 (3), 299-312.
- Navon, R., Shapira, A., and Shechori, Y. (2000). "Automated rebar constructability diagnosis." *Journal of Construction Engineering and Management*, 126 (5), 389-97.
- Pocock, J. B., Kuennen, S. T., Gambatese, J., and Rauschkolb, J. (2006). "Construability state of practice report." *Journal of Construction Engineering and Management*, 132 (4), 373-83.
- Poh, P. S. H. and Chen, J. (1998). "The Singapore buildable design appraisal system, a preliminary review of the relationship between buildability, site productivity and cost." *Construction Management and Economics*, 16 (6), 681-92.
- Riley, D. R., Varadan, P., James, J. S., and Thomas, H. R. (2005). "Benefit-cost metrics for design coordination of mechanical, electrical and plumbing systems in multistory buildings." *Journal of Construction Engineering and Management*, 131 (8), 877-89.
- Santos, E. T., and Ferreira, R. C. (2008). "Building design coordination, Comparing 2D and 3D methods." CIB W78 – 25th International Conference on Information Technology in Construction, July 15-17, Santiago, Chile.
- Sanvido, V. E., and Medeiros, D. J. (1990). "Applying computer-integrated manufacturing concepts to construction." *Journal of Construction Engineering and Management*, 116 (2), 365-79.
- Seo, J. H., Lee, B. R., Kim, J. H., and Kim, J. J. (2012). "Collaborative process to facilitate BIM-based clash detection tasks for enhancing constructability." *Journal of the Korea Institute of Building Construction*, 12 (3), 299-314.
- Staub-French, S. and Khanzode, A. (2007). "3D and 4D modelling for design and construction coordination, Issues and lessons learned." *ITcon*, 12, 381-407.
- Tabesh, A. R. and Staub-French, S. (2006). "Modelling and coordinating building systems in three dimensions, a case study." *Canadian Journal of Civil Engineering*, 33, 1490-504.
- Trigunarysyah, B. (2004a). "A review of current practice in constructability improvement, case studies on construction projects in Indonesia." *Construction Management and Economics*, 22 (6), 567-80.
- Trigunarysyah, B. (2004b). "Constructability practices among construction contractors in Indonesia." *Journal of Construction Engineering and Management*, 130 (5), 656-69.
- Trigunarysyah, B. (2004c). "Project owners' role in improving constructability of construction projects, an example analysis for Indonesia." *Construction Management and Economics*, 22 (8), 861-76.
- Wong, F. W. H., Lam, P. T. I., Chan, E. H. W. and Shen, L. P. (2007). "A study of measures to improve constructability." *International Journal of Quality & Reliability Management*, 24 (6), 586-601.
- Zhang, L., Wang, G., Chen, T., and He, G. (2014) "Survey of BIM Application Status and Characteristics in China", in J. Wang et al. (eds.), Proceedings of the 17th International Symposium on Advancement of Management and Real Estate, Berlin Heidelberg: Springer-Verlag, pp. 969-979.
- Zhang, J. P. and Hu, Z. Z. (2011). "BIM- and 4D- based integrated solution of analysis and management for conflicts and structural safety problems during construction, 1. Principles and methodologies." *Automation in Construction*, 20, 155-66.