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Building information modeling-based integration of MEP layout designs and constructability

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ABSTRACT

Building information modeling (BIM) has demonstrated its advantages in improving a mechanical, electrical and plumbing (MEP) layout in the design stage. Unfortunately, BIM applications normally stop prior to the construction stage. The MEP layout design may no longer fit properly during the installation process when there are as-built deviations between structures and the MEP layout. The purpose of this paper is to develop a practical BIM framework for integrating the MEP layout from preliminary design to construction stage. In this framework, BIM models were categorized into five levels of details: 3D MEP preliminary design model, 3D MEP detailed design model, 3D MEP construction design model, MEP construction model and MEP prefabrication model. Four types of coordination steps have been formulated to solve the design and constructability issues. A case study was adopted to validate the practical BIM framework. The results are very encouraging and demonstrate the significant value of the proposed BIM approach. In addition, one issue of collision detection is discussed because 78% collisions are ineffective when using the BIM tools for collision detection; and a significant number of effective collisions (102 collisions) are still detected by the designers and contractors manually. Ultimately, the research renders a practical insight into improving the MEP design and constructability using the developed BIM framework.

1. Introduction

Fragmented working environment is common in a traditional construction practice. Building information modeling (BIM) intends to solve the problem and serve as a collaborative platform, yet the technology is still relatively young and more efforts are required for the actual collaborative culture. This is particularly vital as mechanical, electrical, and plumbing (MEP) systems have become more complex to encompass sophisticated designs and needs of a building, which require more space and coordination for the installation. Conversely, the available space in buildings is limited due to the economic and energy-efficient considerations. Therefore, the coordination of MEP systems has become a major challenge particularly in complex properties such as high-rise commercial buildings and large-scale infrastructures [1,2]. It involves locating equipment and routing heating, ventilating, and air conditioning (HVAC) duct, pipe, and electrical raceway in a manner that satisfies many different types of criteria [3]. In the current MEP coordination process, designers among mechanical, electrical, and plumbing disciplines generally lack cooperation and many collisions are bound to occur. The traditional MEP coordination uses a process of sequentially overlaying and comparing drawings for multiple systems to detect and eliminate spatial and functional interferences among MEP systems [4]. Such multi-discipline efforts are time-consuming and expensive [3,4].

With the emergence of BIM, many BIM researches have been conducted to unleash its full potential. In the last 10 years (as shown in Table 1), considerable efforts have been made to use BIM for MEP coordination. The previous studies can be divided into four main categories:

Category 1: The studies focused on knowledge and reasoning for MEP coordination based on BIM/3D CAD;
Category 2: The studies demonstrated how BIM/3D CAD can improve the MEP coordination process and provide foundations for revised work process;
Category 3: The studies developed some tools or methods to support MEP coordination automatically and intelligently; and
Category 4: The studies investigated the state of practice of BIM/3D CAD in MEP coordination and its improvements.

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Table 1
Relevant work of MEP coordination based on BIM/3D CAD.

Author (date)	Domain	Technology	Contribution
Korman et al. [5]	Category 1	CAD	• Identified a knowledge framework and reasoning structure that integrate design, construction, and operation and maintenance knowledge of the building systems.
Tabesh and Staub-French [6]	Category 1	3D CAD	• Documented the 3D modeling and coordination; • Identified the design and construction knowledge used to create a coordinated and constructible design; • Evaluated the 3D coordination process.
Korman and Tatum [7]	Category 3	3D CAD	• Developed a knowledge-based 3D tool to improve the MEP coordination process.
Speidel et al. [3]	Category 2	BIM	• Demonstrated how BIM can improve the MEP coordination process in buildings; • Provided a foundation for a revised work process.
Khanzode et al. [8]	Category 1	BIM VDC	• Discovered some benefits for architects, general contractor, specialty contractor; • Summarized lessons related to the organization of team members, use of BIM/VDC tools and level of details in the models.
Dossick and Neff [9]	Category 1	BIM	• Found that while BIM makes visible the connections among project members, it is not fostering closer collaboration across different companies; • Discovered that organizational forces and structures must be accounted for in order for BIM to be implemented successfully.
Haiyan et al. [10]	Category 2	BIM	• Utilized the flexibility of the BIM MEP systems to protect occupant health and improving employee productivity, as well as reducing waste, pollution and environmental degradation of buildings.
Lu and Korman [11]	Category 2	BIM	• Demonstrated how BIM tools can be utilized to further innovation and increase the opportunities for prefabrication of MEP systems for modular construction projects.
Seo et al. [12]	Category 2	BIM	• Discovered problems and improvement opportunities for the clash detection process in an objective manner; • Described the concepts of IPD and lean construction and relationship with the BIM model; • Developed a clash detection process.
Boktor et al. [13]	Category 4	BIM	• Found that 58% of mechanical contractors have less than 3 years of BIM experience and consider themselves as beginners in the use of BIM; • Found that BIM implementation cost for these contractors is 1 to 2% of their total project cost estimate; • Found that more than 70% of mechanical contractors agree that BIM reduces field conflicts and improves coordination.
Hanna et al. [14]	Category 4	BIM	• Found that 59% of mechanical and electrical contractors that use BIM have three years or less of BIM experience; • Found that contractors should employ one to three BIM staff members and add 1% to 2% of total project cost estimates to account for BIM implementation; • Found that more than 70% of mechanical and electrical contractors that have used BIM agree that BIM reduces field conflicts and improves coordination.
Yung et al. [15]	Category 2	BIM	• Demonstrated how design institutes without 3D modeling capabilities could work with modelers to perform MEP coordination with BIM; • Found that BIM might not save overall design time as traditional 2D design; • Found that BIM could 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.
Lee and Kim [16]	Category 1	BIM	• MEP coordination productivity varies greatly depending on a coordination strategy; • The sequential coordination strategy performed three times faster than the parallel strategy; • The sequential coordination strategy reduced the concentration of information.

Although a significant amount of research efforts was focused on implementing BIM/3D CAD in design stage or construction stage individually, there is yet an integrated process from preliminary design stage to construction stage for the MEP coordination, which is the critical research gap to explore benefits of BIM to the full extent. With the selected case study of Shanghai Disaster Control Centre, this paper presents a practical BIM framework to integrate the MEP layout from preliminary design to construction phase. Finally, a detailed evaluation is carried out to validate the proposed BIM framework.

The structure of the paper begins with the proposed framework as the research generally adopts inductive reasoning approach. The framework presents the inductive logical argument that indicates the needs for the integrated process for the MEP layout from preliminary design to construction stage, and subsequently to improve the constructability of the project. Next, Shanghai Disaster Control Centre in China is selected as the case study to validate the proposed framework. After that, the data is analyzed and discussed. Finally, the paper concludes with recommendations for future studies.

2. Research method

In this paper, the development of the framework started with the reference and literature analysis of MEP coordination from previous studies. Subsequently, interviews were conducted with local BIM experts to fine-tune and finalize the framework. Table 2 shows the profile of ten interviewees, eight of which come from industry and another two

Table 2
Profile of organizations participating in interviews.

Interviewee	Organization	Expertise	Years of experience
1	China Construction Design International (CCDI)	BIM-based MEP design and coordination	8
2	Shanghai Xian Dai Architectural Design Co., Ltd.	BIM-based MEP design and coordination	5
3	Tongji Architectural Design	BIM-based MEP design and coordination	3
4	Sichuan Southwest Project Management & Consultancy Co., Ltd. (SSPMC)	BIM-based MEP coordination	4
5	Shanghai Xian Dai Architectural, Engineering & Consulting Co., Ltd.	BIM-based MEP design and coordination	8
6	China Construction Eight Engineering Division. Co. Ltd.	BIM-based MEP coordination and installation	5
7	China Construction Six Engineering Division. Co. Ltd.	BIM-based MEP coordination and installation	3
8	Shanghai Construction Group	BIM-based MEP coordination and installation	6
9	Tongji University	BIM process and organization research	7
10	Chongqing University	BIM-based MEP construction research	6

from academia. They all have BIM capability and had been involved in several real projects related to MEP layout design and constructability in the last few years. Finally, a real case was selected to test and evaluate the framework.

3. Framework for BIM-based MEP layout design and constructability

As highlighted in previous studies, there is a need for integrating the MEP coordination from preliminary design to construction stage. A practical BIM-enabled MEP layout framework was developed based on the inductive reasoning to address the research gap as illustrated in Fig. 1. It consists of five different level-of-detail MEP models and four consecutive steps of coordination in the overall MEP layout design process. The models explain different coordination processes throughout the MEP design development.

The first three models are a common practice in the initial coordination for the MEP design in BIM model development. For instance, the first model defines early project configuration, such as schematics, diagrams, and layouts of the project. MEP designers can automatically calculate each MEP system load and design system layout based on the 3D MEP preliminary design model. Next, the 3D MEP detail design model explains all of the design elements of the MEP system that should be modeled except some small elements which would not impact the MEP layout, such as wires and sprinklers. Then, the architecture and structure models will be incorporated into the 3D MEP detail design model. At this stage, MEP designers are able to search unreasonable design scheme and fine-tune the clashes and issues with some optimizations and coordination based on their experience and available BIM tools in the software.

After that, the framework begins a deeper coordination on the constructability aspect. This coordination would integrate the model from the design stage to the construction stage. It highlights a practical practice that can be applied in BIM projects. The 3D MEP construction design model is the fourth model, which is created based on design drawings, design specifications, construction specifications and construction expertise. In the 3D MEP construction design model, pipe insulation and permanent and temporary support structures (e.g., pipe supports and scaffoldings) will be added to the earlier design model at this stage. Then, the MEP construction model is able to identify the deviations of structural and MEP components that can affect the realization of the MEP layout design especially in certain complex nodes. The model should be the result of the MEP construction design model, which has been synchronized based on the as-built deviations from the site situation, for example, the constructed structures of the building. This process is imperative as certain coordination or clash detection in the software could not accommodate the actual onsite situation, where the small or tolerable deviations of the structures could become a big constructability issue when carrying out the MEP installations.

The last model is MEP prefabrication model, which is created based on the MEP construction model and manufacturer-specific knowledge.

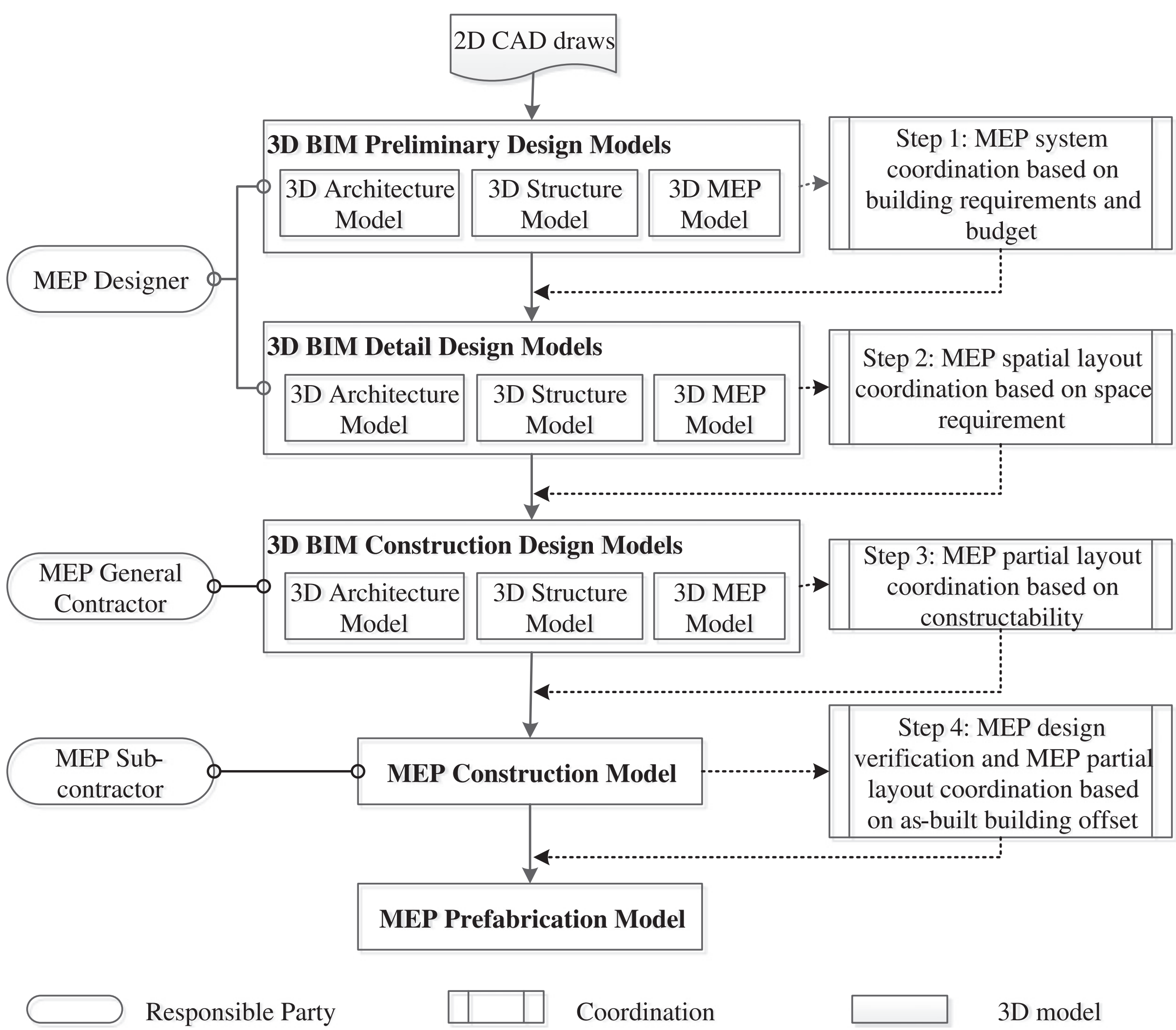


Fig. 1. Framework for BIM-based MEP layout design and constructability.

The model contains all the manufacturing information which can help generate more accurate estimates, create better building systems, and directly guide the MEP fabrication. The details of the MEP fabrication will benefit manufacturers, designers and contractors of the project.

Besides, the relationship of each model should be discussed. The framework describes four steps of coordination, namely:

1. *Step 1 MEP system coordination based on building requirements and budget*: In the MEP preliminary design stage, more than one alternative of MEP schemes might be provided. Designers can conduct sunlight analysis, indoor air quality simulation, energy analysis, ventilation simulation and so on. The best MEP scheme will be selected to satisfy cost budget and green building certification standards. The coordination of this stage focuses on the comparison between alternative MEP systems. For example, for lighting system: (a) to conduct detailed solar, lighting, and daylighting analyses; (b) to determine estimated energy use and implement choices to improve efficiency; and (c) to estimate and look for ways to reduce carbon emissions.
2. *Step2 MEP spatial layout coordination based on space requirements*: In the MEP detailed design stage, there are many collisions when integrating MEP systems with the architecture model and the structure model into one single platform. Currently, BIM tools have provided the feature to identify the clashes or conflicts (hard, clearance, duplicity, positioning and routing) in the model. In addition, the visualization capabilities enable the specialty trades, designers and coordinators to review and detect these conflicts faster, better and more accurately. When identifying possible solutions, one can instantly make the necessary changes into the BIM model, and also trace the effect of the suggested solutions on other components and systems.
3. *Step3 MEP partial layout coordination based on constructability*: Prior to installation, MEP contractors need to assess the constructability of the existing MEP design schemes based on their construction expertise. Some examples of construction expertise for the MEP layout optimization in this phase are as follows:
   - Access requirement, e.g., to provide path and halo (free space around system component) for construction craftsmen, materials, and construction equipment;
   - Configuration, e.g., to use standard materials and configurations, allow prefabrication offsite or in yard areas at the site; allow desired installation sequence, minimize fittings and field connections;
   - Construction method, e.g., to maximize prefabrication, allow efficient material handling, provide space and access for electrical cable pulling; and
   - Safety, e.g., to minimize exposure time and provide permanent scaffolding.
4. *Step 4 MEP design verification and MEP partial layout coordination based on as-built building offset*: This step is the most important works in the whole MEP design process. The critical works of this stage are measuring construction deviations especially in tight space area, updating existing BIM models in line with as-built building, analyzing deviations, and adjusting original design to satisfy construction requirement.

Last but not least, Table 3 summarizes and explains the details of the MEP models of the framework.

4. Case study

Having described the framework, it is necessary to conduct a case study to evaluate the proposed framework. Shanghai Disaster Control Centre was selected as the case study because of its relatedness to the research subject. The details are explained as follows.

Table 3
Comparative results of the five MEP models.

	3D MEP preliminary design model	3D MEP detailed design model	3D MEP construction design model	MEP construction model	MEP prefabrication model
Stage	Preliminary design	Detailed design	Preconstruction	Construction	Prefabrication
Model details and information	The model furnishes with approximate quantities, size, shape, location and orientation	The model is modeled as specific assemblies accurate in terms of quantity, size, shape, location, and orientation.	The model is suitable for construction simulation and installation. Construction equipment such as scaffolding, support and formwork is created in this model	This level of development is considered to be suitable for verifying constructability based on construction deviations. As-built building is created in this model	This level of development is considered to be suitable for fabrication and assembly in factory. The MEP prefabrication model contains all the manufacture information which can help generate better estimates, create more accurate building systems, and directly drive MEP fabrication
Model elements author	MEP designer	MEP designer	MEP contractor	MEP contractor	MEP prefabrication designer
Model checker	MEP chief designer	MEP chief designer	MEP chief designer	MEP chief designer MEP general contractor	MEP chief designer MEP general contractor
Model application	1. Calculating the indicators of as-designed MEP system in order to verify optimal; 2. Determining the MEP system general layout; 3. Holding communication meeting with other participants to find potential problems.	1. Determining each MEP system general layout; 2. Solving collision detections between different disciplines; 3. Coordinating MEP layout and improving building space utilization rate.	1. Determining each MEP system precise plane position and spatial layout; 2. Checking out accuracy of design drawings and verifying constructability of equipment installation method and elevation of pipes and ducts; 3. Determining pipeline and equipment support form; 4. Reserving the holes and embed pipes in the building accurately, avoiding chiseling any cave on the walls; 5. Coordinating MEP layout and improving building space utilization rate based on constructability.	1. Verifying constructability based on construction deviations; 2. Coordinating MEP layout based on as-built building deviations; 3. Guiding the construction activities accurately.	1. Generating more accurate estimates; 2. Creating more accurate building systems; 3. Driving MEP fabrication directly.

Firstly, the MEP system used by this case was extremely complex. Fifteen-five large systems were divided by different disciplines that needed to be installed; such as water supply and drainage system (WSDS), vacuum reducer valve air conditioning system (VRVACS), mechanical smoke extraction system (MSES), mechanical pressed air supply system (MPASS), urgent exhaust system (UES), air conditioning and fresh air system (ACFAS), water cooling system (WCS), and water freezing system (WFS). Furthermore, each system consisted of more than twenty subsystems. Therefore, it was difficult to plan the MEP systems in the limited space just using the traditional 2D CAD tool.

Secondly, the participants involved in this case showed significant interests in BIM and promised to give full support for BIM implementation. The owner was also willing to spend extra cost to employ an experienced BIM consultant company to plan the overall BIM execution and provide BIM training for the whole project team, especially MEP design and construction.

Thirdly, the proposed framework was fully implemented in this case. The five different level-of-detail MEP models were created to fulfill the requirements. Four consecutive steps of coordination were also strictly followed by the project team.

Finally, the authors were directly involved in this case and were able to gather primary data for further analysis and evaluation.

The case consisted of five floors: one underground and four above the ground. The total investment of this project was about US$48 million (converted from 1 USD to 6.21 RMB) with a total gross floor area of 28,124 m^2. The integrated architecture and structure model (as shown in Fig. 2) was created by Autodesk Revit software. The MEP model (as shown in Fig. 3) was designed by MagiCAD, which was the leading software for HVAC and electrical system design.

4.1. Background of working environment

In China, because construction companies are required to submit 2D drawings for regulatory approvals, 2D CAD remains the dominant design tool. It is also still difficult for BIM tools to automatically generate 2D drawings in accordance with industry Chinese specifications [17]. Despite the size of the industry, implementation and practice of BIM within China is still limited, and is typically restricted to the design stage [18–20]. Contractors are still significantly less frequently involved in BIM use than designers [15,17,18]. A survey done in China in 2011 showed that 73% of surveyed construction companies had never utilized BIM, and only 22% of them considered themselves as being familiar or very familiar with BIM tools [18]. A sizeable proportion of projects eventually gave up BIM because of BIM knowledge shortage, immature collaboration culture, and conventional project delivery method [15,17].

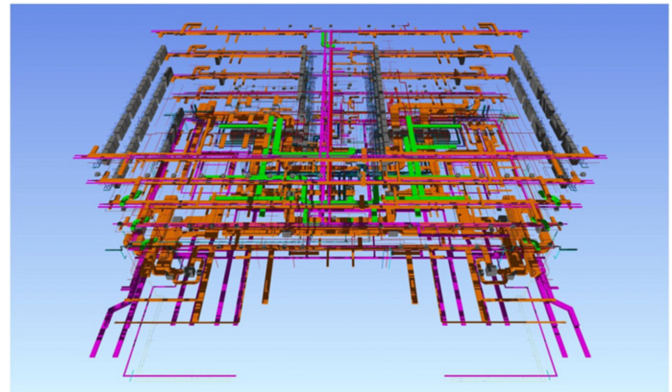


Fig. 3. The MEP model for Shanghai Disaster Control Centre.

Ideally BIM implementation should start with 3D design from the beginning. However, given the environment of Chinese construction industry, the work of transforming 2D drawings into 3D model is required to promote adoption of BIM. Therefore, the proposed framework for BIM-based MEP layout design and constructability includes both traditional 2D design stages and BIM modeling stages.

The use of BIM technology is often regarded as extra work by the designers with fixed fee contracts except extra pay by owners. In this case, in order to fully release BIM benefits, two types of design teams: 2D CAD team and BIM team had been employed to facilitate BIM implementation. They collaborated with each other throughout the whole implementation process.

The responsibilities of 2D CAD team were: (1) to design the MEP system with conventional 2D CAD tool; (2) to send the latest 2D drawings to BIM team; and (3) to support the BIM team for MEP coordination. The responsibilities of the BIM team were: (1) to create the 3D BIM models based on 2D design drawings, e.g., architecture model, structure model and HVAC model; (2) to conduct coordination meeting and detect MEP design errors and constructability issues with designers and contractors; (3) to coordinate the MEP layout design and system selection based on BIM simulation tools; and (4) to real-time track the statues of the errors and solve them before real construction.

4.2. The creation of BIM model

Table 4 shows the level of detail (LOD) of each model element in the five types of MEP models. The definition of levels 100–400 came from the American Institute of Architects (AIA). Table 4 was created by a

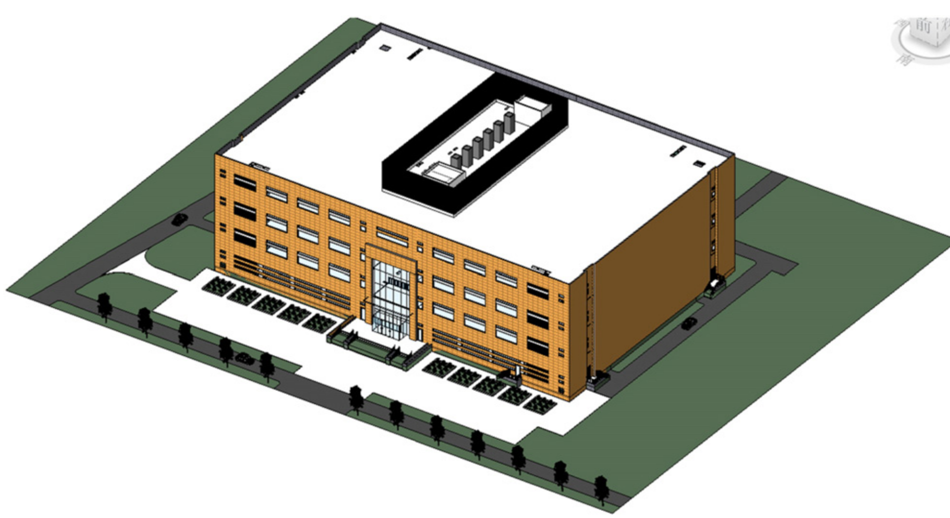


Fig. 2. The integrated architecture and structure model for Shanghai Disaster Control Centre.

Table 4
LOD of model elements in the MEP models of the BIM framework.

Model elements	Type of models: 3D MEP preliminary design model	3D MEP detailed design model	3D MEP construction design model	MEP construction model	MEP prefabrication model
Architecture (wall and ceiling)	LOD 200	LOD 200	LOD 300	LOD 300	–
Structure (wall, column, beam, floor and steel)	LOD 200	LOD 200	LOD 300	LOD 300	–
Cable tray	–	LOD 200	LOD 300	LOD 300	LOD 400
Conduit	–	–	LOD 200	LOD 300	–
Device	–	–	LOD 200	LOD 300	–
Lighting fixture	–	–	LOD 300	LOD 300	–
Pipe	LOD 200	LOD 200	LOD 300	LOD 300	LOD 400
Valve	–	–	LOD 200	LOD 300	–
Plumbing fixture	LOD 200	LOD 200	LOD 300	LOD 300	–
Sprinkler	–	–	LOD 200	LOD 300	–
Duct	LOD 200	LOD 200	LOD 300	LOD 300	LOD 400
Air terminal	LOD 200	LOD 200	LOD 300	LOD 300	–
Mechanical equipment	–	LOD 200	LOD 200	LOD 300	–

BIM consultant and approved by client, designers and MEP contractors. Fig. 4 illustrates the five types of MEP models' development process. Firstly, the 2D CAD team used the traditional way to design and deliver drawings to project owner. Then, the BIM team created the 3D BIM models based on design drawings in different stages. Thirdly, the two teams worked together to check as-planned BIM models and solved the problems in the MEP design. Finally, the BIM team updated their 3D models.

4.3. BIM-based MEP layout design and constructability

In Shanghai Disaster Control Centre, the proposed framework was fully performed. Table 5 shows the important degree of influential factors in different types of coordination. Each important degree was firstly decided by employed BIM consultants according to their experience and knowledge of previous BIM case studies. Then the draft results would be sent to the project stakeholders, namely, BIM consultants, client, MEP designers, MEP general contractor and subcontractors for further discussion so as to align the characteristics of this case. The final approved version would become a guideline for this case. Therefore, the data in Table 5 should be a little different among different cases because of different project environments. All the data recorded by the BIM consultants were also verified by the authors. Four typical examples were selected to demonstrate the four corresponding MEP coordination steps of the framework which are defined in Section 3.

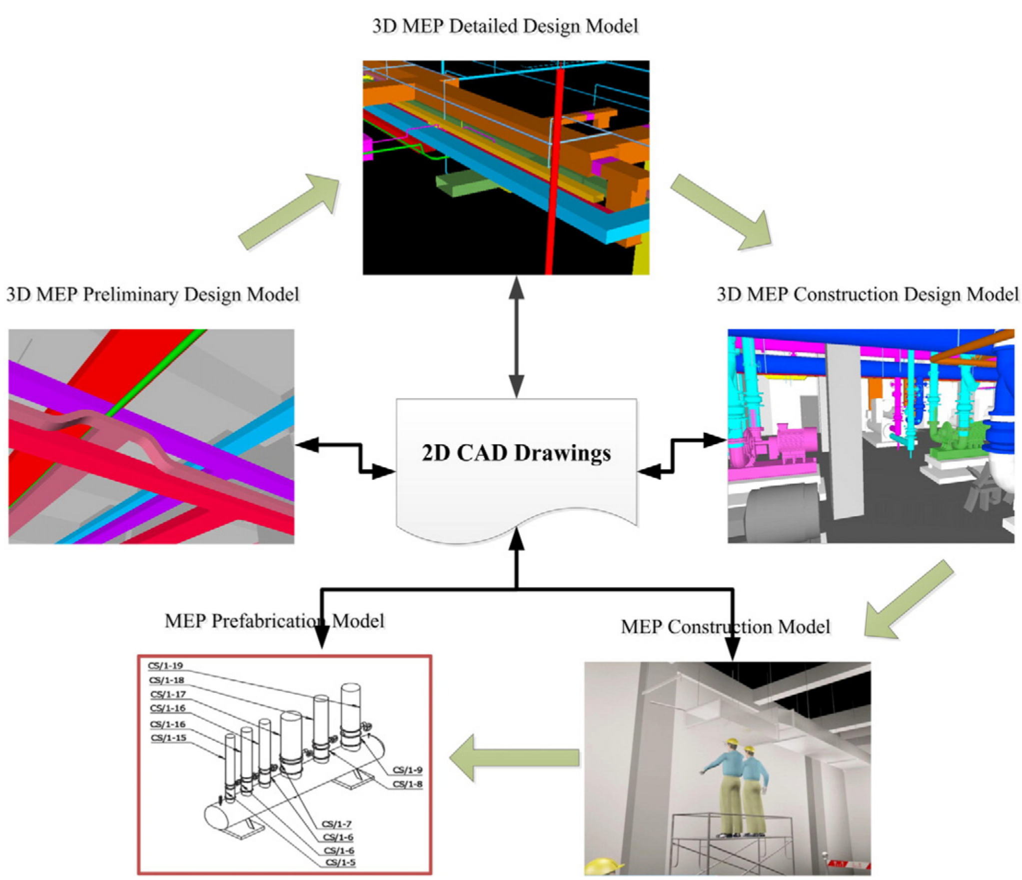


Fig. 4. MEP model development process.

Table 5
Importance degree of impact facts in different types of coordination.

Type of models						
Influential factors		3D MEP preliminary design model	3D MEP detailed design model	3D MEP construction design model	MEP construction model	MEP prefabrication model
Building requirement		5	5	2	2	2
Cost budget		5	3	2	2	2
Space requirement		3	5	5	5	5
Constructability	Thermal insulation layer	1	1	5	5	5
	Ceiling height	2	4	5	5	5
	Pipe type	1	1	5	5	5
	Pipe support	1	1	5	5	5
	Installation space	1	1	5	5	5
	Repair space	1	1	5	5	5
	Installation process	1	1	5	5	5
As-built building		1	1	1	5	5

"5" means "consider most", "1" means "not consider".

Example 1. MEP system coordination based on building requirements and budget.

Two different types of air conditioning systems had been assessed: conventional fan coil heat pump (CFCHP) and multi-variable refrigerant volume (MVRV). The former one was a traditional method which could only satisfy all the room to be cooled or be heated at the same time. The latter one was a new way which consisted of several indoor units and one outdoor unit. With BIM technology, it was effortless to conduct a comparison analysis of investment and annual operating cost between the two alternatives. In addition, energy consumption could be also calculated within the BIM tool. Based on the analysis, MVRV was selected because it could provide higher human comfort with lower energy consumption and life-cycle cost. Fig. 5 showed the final MVRV system in BIM.

Example 2. MEP spatial layout coordination for space requirement.

Fig. 6(a) illustrates some collisions of the MEP systems in original design. The design experience of the designers was mainly applied to solve the clashes:

(1) Gravity driven plumbing system was firstly considered because of limited space to adjust;
(2) HVAC system usually was secondly to be considered due to the large size of components and high price;
(3) Electrical system with large cables was thirdly considered due to inflexible routing and high price;
(4) Pressure driven plumbing system, fire protection, control system and other small systems were finally considered because of flexible routing; and
(5) Any other rules, such as a small pipe gave way to a big pipe and a cheap component gave way to an expensive component.

According to the rules above, the clashes of the MEP system were redesigned, where the smaller pipes were relocated below the gravity driven plumbing and large cables in the HVAC duct. Fig. 6(b) illustrates the result after eliminating clashes, and it also satisfied design specification and space requirement. However, sometimes after design coordination, the clash-free MEP layout design would not satisfy the space requirement. As shown in Fig. 7(a), the required clearance height was 3 m, however, the bottom of the pipe had already reached 3 m, when adding the ceiling, it was impossible to satisfy the requirement. In order to improve the clearance height, the under pipes were moved to the top and some conflicted pipes were moved to another space. Fig. 7(b) showed the final results after design optimization.

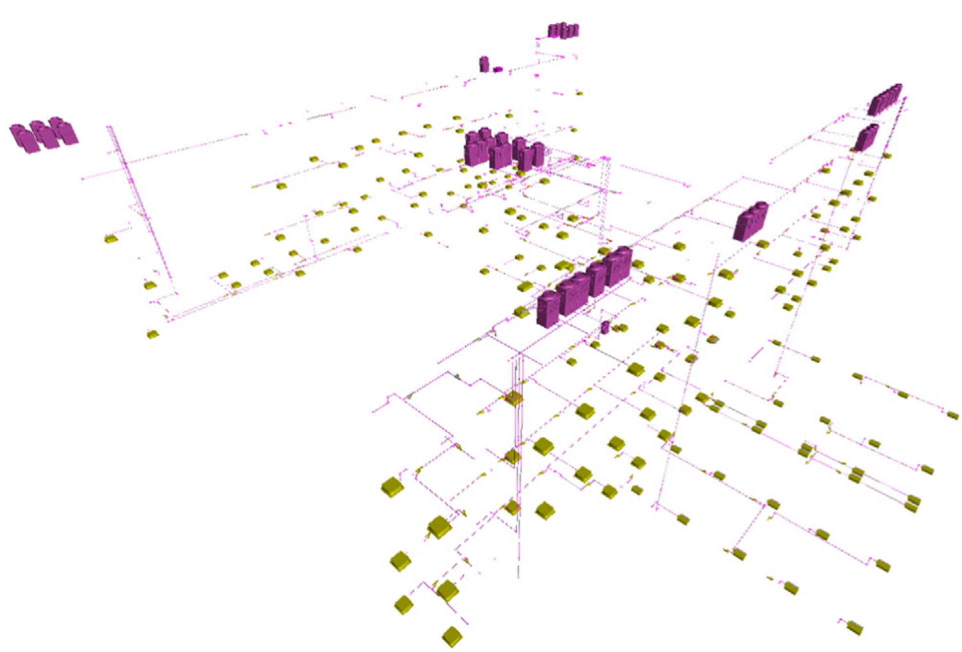
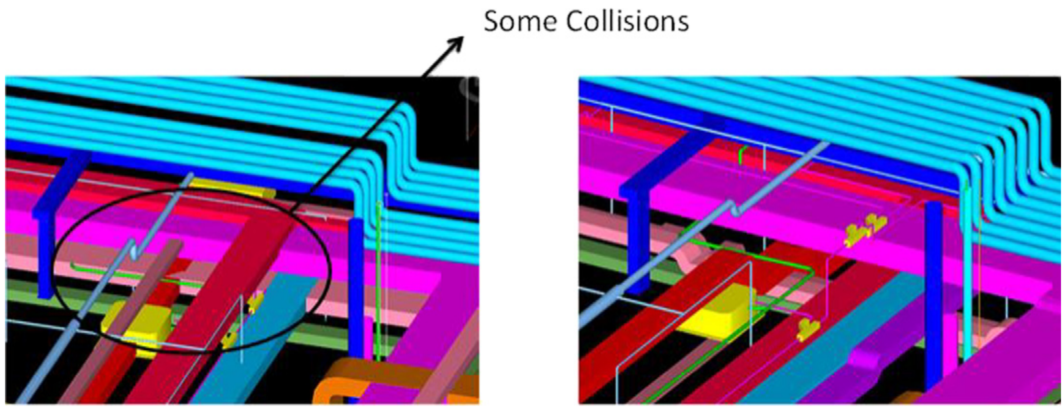


Fig. 5. 3D multi-variable refrigerant volume (MVRV) system in BIM.



(a) Original Design (b) After coordination

Fig. 6. MEP spatial layout coordination for eliminating collisions.

Example 3. MEP partial layout coordination for constructability.

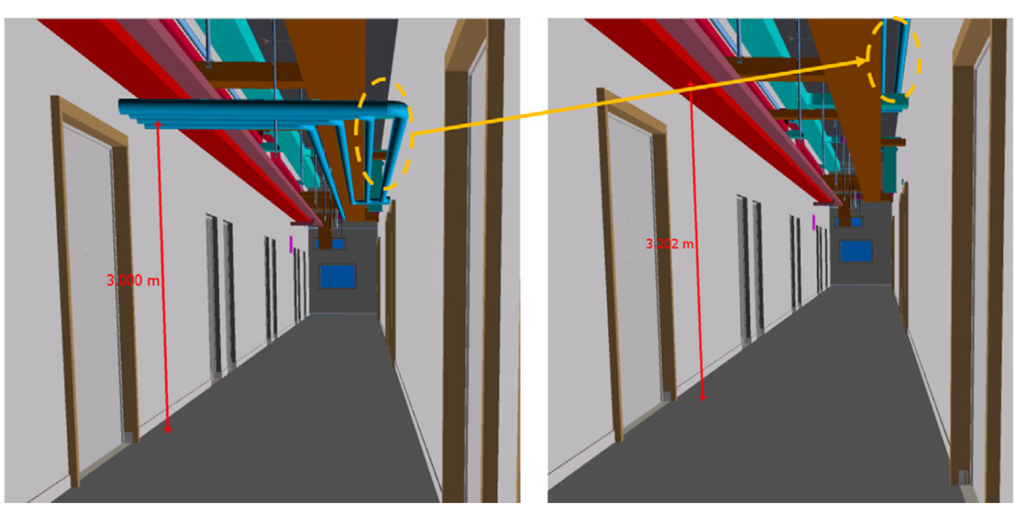
When the building space was narrow and tight, the construction sequence would affect the MEP installation. In this project, the MEP contractors had chosen thirteen (13) critical zones to simulate installation sequence in BIM. Fig. 8(a) illustrates a duct installation simulation, in view of construction method, installation space, access space, construction sequence and staff working face, the MEP contractors had conducted a more in-depth theoretical analysis and experimental study to verify the feasibility. Another kind of simulation is an equipment installation simulation. There were lots of large equipment in this project. Conventionally, designers took a little account of the equipment installation, where a number of potential risks would exist in construction, such as not enough space for equipment transportation and so on. Hence, how to install them correctly became very important to the MEP contractors. Fig. 8(b) illustrates an ice-storage cooling tank installation simulation.

Example 4. MEP partial layout coordination based on as-built components' deviations.

In this project, the as-built components' deviations not only focus on structural components such as floors, ceilings, walls, beams and columns, but also the MEP components such as ducts, pipes and cables. Before each critical MEP component was installed, the following tasks were required to be conducted by the BIM team and the MEP contractors systematically:

(1) Collecting the data: according to predefined metrics (e.g., elevation, distance and orientation), the MEP contractors measured construction deviations of each relevant as-built components;
(2) Modifying the BIM models: the BIM team updated relevant virtual components in line with the as-built components based on the measured data;
(3) Analyzing deviations: the MEP contractors reassessed the constructability of the next step MEP installation program based on the modified BIM models;
(4) Adjusting the MEP layout design: if construction deviations were still impeded the next step MEP installation, the MEP designers would adjust again the MEP layout design to satisfy constructability. If not, the MEP contractors would install according to the earlier modified BIM models.

Fig. 9 illustrates the two freezing water pipes (external diameter was 529 mm) and fire pipelines (external diameter was 240 mm) had some conflicts with the two ducts (dimension sizes of 2000 mm and 630 mm) in the refrigeration room. The design drawings indicated that the



(a) Clash-free Design after coordination (b) After Design Optimization

Fig. 7. MEP spatial layout coordination for space requirement.

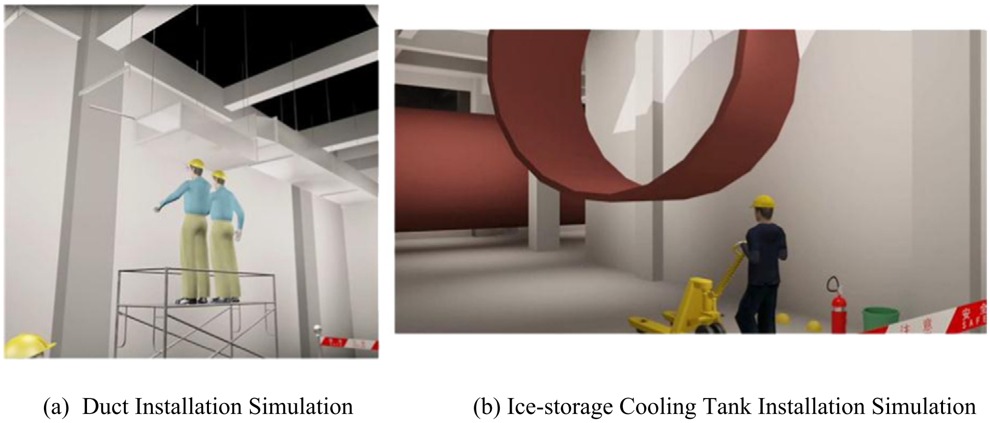


Fig. 8. MEP partial layout coordination for constructability.

elevations of the freezing water pipe center and fire pipeline should be about 4200 mm, and 6300 mm respectively. However, on one hand the elevation of the as-built freezing water pipe bottom was FL (floor level) about 4130 mm, which was 200 mm higher than the baseline and made the two ducts 200 mm higher; on the other hand the elevation of the exist fire pipeline that supports the bottom was about 5980 mm which made the two ducts 200 mm lower. Therefore, the two ducts could not have enough space to be installed if nothing would be changed in the design.

5. Results and discussions

The case study demonstrated the MEP designers and contractors had implemented the four steps of BIM-based MEP layout coordination

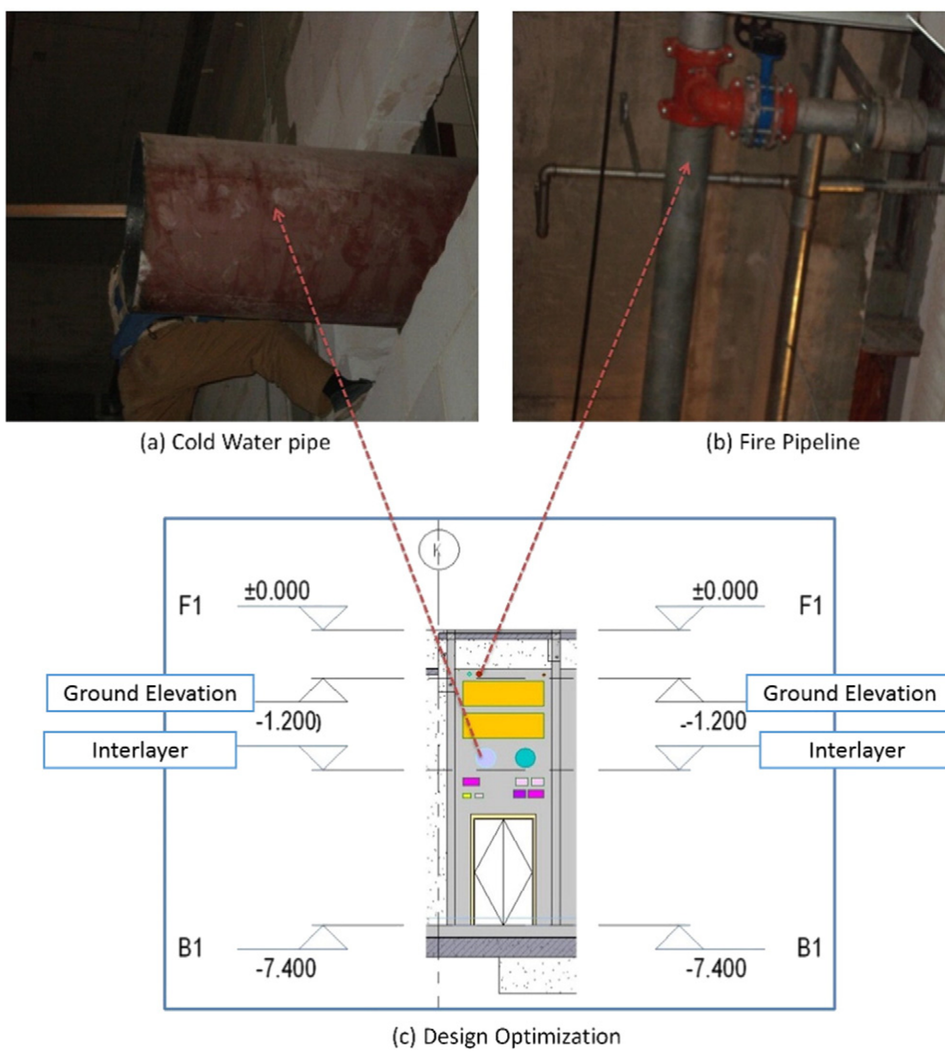


Fig. 9. MEP partial layout coordination based on as-built building offset.

based on the proposed BIM framework. One comparison study between CFCHP air conditioning system and MVRV air conditioning system was conducted in step 1. 121 MEP design errors were found in step 2, and 427 in steps 3 and 51 in step 4. Therefore a total of 599 critical errors were founded and they would cause project cost overrun from the extra materials required. In other words, it would save approximately US$ 201,133. The estimated cost was calculated using a preliminary estimate on all costs incurred on the items as per their standard length and area in meter run and meter square. The detailed statistic data could be found in Table 6.

5.1. Analysis of MEP design errors in four different steps

As discussed in the review of the literature [3–5,7,8,10,21–23], BIM had demonstrated its advantages in improving the MEP layout in different steps such as steps 1 and 2. However, other steps such as steps 3 and 4 had seldom been implemented during BIM applications. The benefits of BIM would be discounted as observed from the case study when:

(1) The designers had limited MEP installation expertise meanwhile only steps 1 and 2 were implemented. The final MEP layout design would have a lot of constructability issues;
(2) Large numbers of construction deviations occurred while only steps 1, 2 and 3 were implemented. The final MEP installation scheme would be impacted and could not be performed correctly; and
(3) Each step would not fully consider contractors' construction ability.

This paper presented some comparisons and analyses among three different scenarios:

Scenario 1: BIM was only implemented during steps 1 and 2;
Scenario 2: BIM was only implemented during steps 1, 2 and 3; and
Scenario 3: BIM was implemented from step 1 to step 4.

In order to satisfy these assumptions, some rules were defined to calculate the number of effective errors in different steps. For instance, one error would be counted in step 2 if the error was detected in step 2 and solved by designers, in addition, the same error was still not detected in step 3 by contractors by referring to their construction knowledge and did not occur in step 4 considering construction deviations. Otherwise, the error would be counted in step 3 or step 4.

Regardless of step 1, about 71% of errors were found in step 3 while 20% in step 2 and 9% in step 4 as illustrated in Fig. 10. Most MEP design errors occurred in step 3. However, 9% of the errors found in step 4 might affect the overall MEP installation, just liked a Chinese proverb as '*pull one hair and the whole body is affected*'. Fig. 11 illustrated the comparison results among the three different scenarios mentioned above. 458 errors had been detected in Scenario 1, however only 26% of errors could be solved correctly by designers because of limited field MEP installation knowledge and experience. In scenario 2, 599 errors had been found but still 9% of the errors could not be correctly solved because of construction deviations. In scenario 3, all the errors could be correctly solved. Hence, the MEP designers and contractors needed to put more effort in steps 3 and 4 so as to finish the MEP layout coordination loop and lock BIM value.

5.2. Cost-saving analysis

Data collection and analysis work in this paper were mainly compiled and recorded by the BIM consultant. Currently, the architectural, engineering and construction (AEC) industries were not ready to invest in BIM because of the lack of case study evidence on the financial benefit of BIM [24,25]. In this case, through the utilization of the proposed approach described in Section 3, an amount of US$ 201,133 had been saved.

Percentage of cost saving in units of cable, pipe and duct was demonstrated as illustrated in Fig. 12. It was calculated based on the rough estimate in Table 5, which included labor cost, material cost, equipment cost and extra time cost. Cable tray had contributed 61% to total saving, while duct was 23% and pipe was 16%.

Subsequently, percentage of cost was also compared with different pairs, namely, electrical–electrical, electrical–structure, electrical–HVAC, HVAC–structure, HVAC–HVAC, HVAC–plumbing, plumbing–plumbing, plumbing–structure and plumbing–electrical as illustrated in Fig. 13. 67% cost saving came up between electrical and HVAC while 14% between HVAC and plumbing and 9% between plumbing and plumbing, which meant that 90% cost saving happened in the top three items. These results reflected that there were more design errors in electrical design, and project managers should put more attention to electrical discipline in design and construction stages on other similar projects in the future.

5.3. Discussion: effectiveness of collision detection

During the BIM implementation in MEP layout design and coordination, one issue named collision detection faced in this project should be discussed, otherwise it would reduce the BIM benefits and work productivity. The collisions were caused from three sources in the case study, such as hard clashes, soft clashes and schedule clashes. A 'hard clash' is the overlapping of members of the BIM model in a space; while a 'soft clash' is a design error that was a failure to secure sufficient space for other parts, including access, insulation and safety [12]. Then, a 'Schedule clash' refers to scheduling clashes for work crews, equipment/

Table 6
Evaluation of BIM-based MEP layout coordination.

MEP layout design and constructability	MEP system comparison and selection in step 1	MEP design errors found in step 2	MEP design errors found in step 3	MEP design errors found in step 4	Increased quantity which caused by errors	Unit price	Increased total cost (US$)
Electrical–electrical	1 comparison study between CFCHP air conditioning system and MVRV air conditioning system	1	4	1	32 m of cable trays	136 US$/m	4352
Electrical–structure		3	11	5	11 m of cable trays	136 US$/m	1496
Electrical–HVAC		61	216	7	840 m of cable trays	136 US$/m	114,240
					132 m^2 of ducts	157 US$/$m^2$	20,724
Plumbing–electrical		4	17	3	20 m of cable trays	136 US$/m	2720
					18 m of pipes	111 US$/m	
Plumbing–structure		12	42	6	21 m of pipes	111 US$/m	2331
Plumbing–plumbing		10	33	10	157 m of pipes	111 US$/m	17,427
HVAC–plumbing		25	88	15	108 m^2 of ducts	157 US$/$m^2$	16,956
					96 m of pipes	111 US$/m	10,656
HVAC–structure		3	10	3	13 m^2 of ducts	157 US$/$m^2$	2041
HVAC–HVAC		2	6	1	43 m^2 of ducts	144 US$/$m^2$	6192
Total	1	121	427	51			201,133

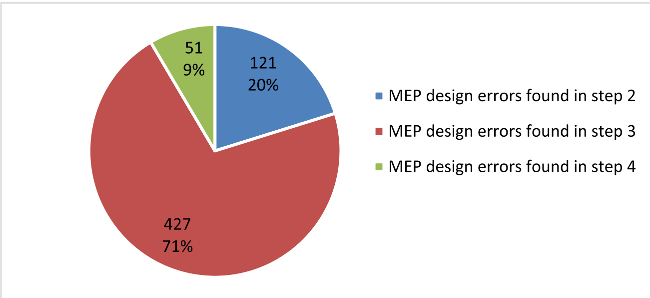


Fig. 10. Number and percentage of collisions which would be counted in different stages.

materials fabrication and delivery clashes and other project timeline issues.

Subsequently, the above clashes would classify into three common types of categories for solutions, namely effective clashes, ineffective clashes and untrue clashes. An 'effective clash' is a collision that will cause rework in construction. An 'ineffective clash' is a collision that can be solved effortlessly on construction site. And, an 'untrue clash' is a collision that will be assessed by BIM tools but not by a collision when judged by construction knowledge, for instance, a clash between column and beam.

In this project, the untrue classes were excluded from the clash analysis as the clashes were ignorable. Hence, the untrue clashes were not taken into account in analysis results. As shown in Table 7, more than 2000 collisions had been detected by BIM tools automatically in the original design, and analyzed one by one by the design team in coordination meeting. There were 497 important errors discovered, filtered from 2257 errors, which would cause a rework, which meant that 78% of collisions were ineffective. Furthermore, 27 additional valuable errors were detected by the designers manually and 75 additional valuable errors were detected by the MEP contractors manually. Fig. 14 illustrates the percentage of effective clashes among the MEP systems. 51% of effective clashes occurred between electrical and HVAC while 21% between HVAC and plumbing and 1% between HVAC and HVAC. It meant that 73% of effective clashes occurred relevantly with HVAC. The MEP designers should give more attention to HVAC design in practice.

The purpose of the clash detection was to improve productivity in discovering design errors in the BIM project. However, it would become inefficient when a mass of ineffective clashes or untrue clashes was detected in practice since designers needed much time to filter them out. It had become critical on how to improve the effective rate of the clash detection in BIM tools. The reasons for poor clash detection rate could be concluded in three aspects. The first one was the use of immature BIM tools which could not provide ideal algorithm to detect the effective clashes [26]. The second one was lack of deep understanding of specifications related to MEP design and installation, therefore, the BIM team

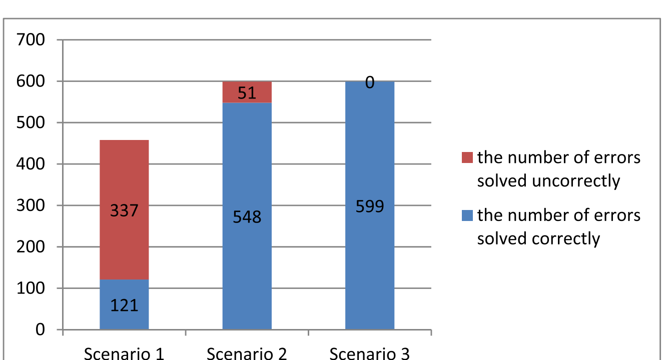


Fig. 11. Comparison results among the three different scenarios.

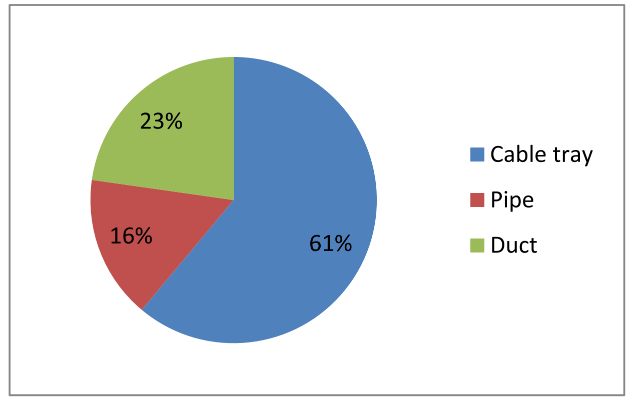


Fig. 12. Saving contribution of cable tray pipe, and duct.

could not define effective rules to filter ineffective clashes. The third one was an immature collaboration culture which prevented the real-time information sharing.

5.4. Limitation

The case study was mainly based on the BIM consultant's perspective and had less visibility to details regarding third party cost savings. Additionally, some of the data available is based on experience, such as the number of collisions which will cause a rework and the value of rework quantities. Hence, it is recommended to have a proper tracking by the team while the project progresses. The ideal methodology of measurement should refer to a case study in which both BIM and non-BIM projects under similar scopes of work are paid by the same employer and also constructed by the same contractors. Furthermore, the actual savings become proprietary due to the business nature of these transactions. Nevertheless, the case study was predicted on benefits that were quantifiable and realized by the BIM consultant.

6. Conclusions and future work

For a project trying to find how to best utilize BIM to support the MEP layout, a practical BIM framework was developed for coordinating the MEP layout from the preliminary design to construction stage. In the framework, the BIM models were classified into five level-of-detail models: 3D MEP preliminary design model, 3D MEP detailed design model, 3D MEP construction design model, MEP construction model and MEP prefabrication model. Four types of coordination steps were adopted to solve the design and constructability issues, namely: MEP system coordination, MEP spatial layout coordination, MEP

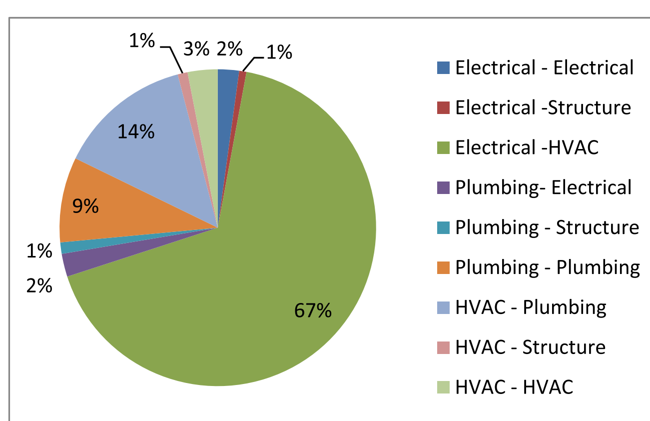


Fig. 13. Percentage of cost saving.

Table 7
Effectiveness of collision detection.

Collision detection	Collisions which detected by BIM tools automatically (a)	Collisions which will cause rework based on (a)	Additional valuable collisions which detected by designers manually	Additional valuable collisions which are detected by MEP contractors manually
Electrical–electrical	25	5	0	1
Electrical–structure	90	13	5	7
Electrical–HVAC	1026	252	8	11
Plumbing–electrical	92	18	3	5
Plumbing–structure	236	49	4	9
Plumbing–plumbing	198	38	6	15
HVAC–plumbing	495	103	1	21
HVAC–structure	57	12	0	4
HVAC–HVAC	38	7	0	2
Total	2257	497	27	75

constructability coordination, and MEP verification based on construction deviation.

Subsequently, the research also highlighted an important reference for the potential benefits of application of BIM in the MEP layout coordination. The findings indicated that (1) regardless of step 1, about 71% of errors were found in step 3 while 20% in step 2 and 9% in step 4; (2) 26% errors could be solved correctly in scenario 1, 91% in scenario 2 and 100 in scenario 3; (3) an amount of US$ 201,133 had been saved. Cable tray contributed 61% to total saving, while duct was 23% and pipe was 16%; (4) 90% cost saving happened in the top three items: 67% between electrical and HVAC while 14% between HVAC and plumbing and 9% between plumbing and plumbing; (5) only 22% collisions were effective when using BIM tools for automatic collision detection; and (6) 17% effective collisions were still detected by the designers and contractors manually as compared with 83% were detected by BIM tools automatically. In addition, through coordination the MEP layout and equipment installation, the MEP contractors had developed a more practical construction schedule, which was able to reduce the potential risk and rework.

Although BIM had significantly enhanced the MEP design and installation, there were some methods that could be improved. In this project, workers measured the construction deviations between as-planned and as-built building using tapes manually. There were three main challenges when utilizing this method in practice, such as:

(1) The measurement was time-consuming and labor-intensive;
(2) The quality of measured data was low; and
(3) The construction deviation report was too abstract and could not be understood easily.

As an emerging technology, Augmented reality (AR) integrates 3D virtual objects into the real world [27,28]. The technology could satisfy the goal of enhancing and accelerating the process of verifying the deviations [29–32]. The superimposition of the real facility with the related BIM models enables a visual comparison. Hence, the construction deviations can be immediately determined, and constructability of the next step MEP installation can be assessed accurately and effortlessly.

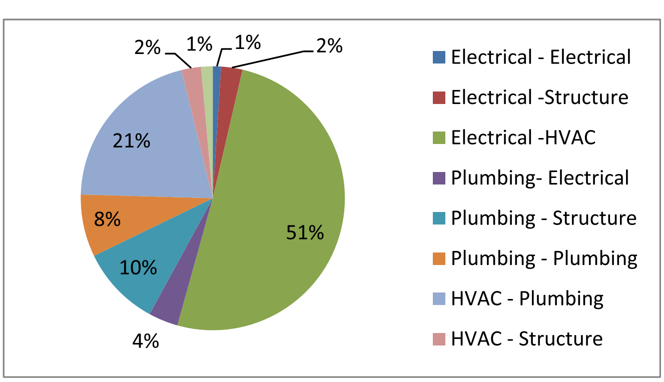


Fig. 14. Distribution of effective clashes among MEP system.

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