AN APPROACH OF UTILIZING BUILDING INFORMATION MODELING TO OPTIMIZE MEP LAYOUT

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ABSTRACT

Building Information Modelling (BIM) has demonstrated its advantages in improving Mechanical, Electrical and Plumbing (MEP) layout in such as preliminary design and detailed design stages. Unfortunately, BIM applications normally stop prior to the construction stage, and the downstream stages have seldom become the arena of BIM applications. Therefore, the MEP layout optimal design from BIM will no longer fit properly to the installation space if there are as-built deviations in the construction of these spaces. This paper presents an approach of utilizing BIM to optimize MEP layout from preliminary design into construction phase. In this framework, BIM models are developed at five level-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 optimization methods have been developed to demonstrate solving constructability issues. A case study is implemented to validate this BIM approach framework. The results show that BIM can efficiently improve MEP layout and reduce cost, and construction preparation stage and construction stage should be paid more attention so as to insure MEP installed successfully.
Keywords: BIM; MEP; layout; optimization

1. INTRODUCTION

Nowadays, Mechanical, Electrical, and Plumbing (MEP) systems become more complex in design and design coordination which requires more space available for installation. Conversely, the available clearance space in buildings is limited due to the economic and energy-efficient consideration. Therefore, the coordination of MEP systems has become a major challenge particularly in complex properties such as high-rise commercial buildings, large-scale public buildings and infrastructure. MEP coordination 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 (Speidel, Simonian et al. 2008). In the current MEP coordination process, designers among mechanical, electrical, and plumbing are generally lack of cooperation, so as many collisions to occur. The traditional MEP coordination practice uses a process of sequentially overlaying and comparing drawings for multiple systems, during which representatives from each MEP trade work together to detect and eliminate spatial and functional interferences among MEP systems (Korman and Tatum 2006). Such multi-discipline effort is time-consuming and expensive (Korman and Tatum 2006; Speidel, Simonian et al. 2008).

With the emergence of Building information modelling (BIM), current MEP coordination process is now able to evolve with this technology. In the last 10 years, considerable efforts have been made to use BIM for MEP coordination. Those works can be divided into four main categories:

(1) Knowledge and reasoning for MEP coordination based on BIM/3D CAD (Korman, Fischer et al. 2003; Tabesh and Staub-French 2005; Tabesh and Staub-French 2006);
(2) Demonstrate how BIM/3D CAD can improve the MEP coordination process and provide foundations for revised work process (Khanzode A 2008; Speidel, Simonian et al. 2008; Dossick and Neff 2010; Haiyan, Tramel et al. 2011; Lu and Korman 2011);
(3) Develop some tools or methods to support MEP coordination automatically and intelligently (Korman and Tatum 2006; Seo 2012); and
(4) Investigate the state of practice of BIM/3D CAD in MEP coordination and suggest improvements (Boktor, Hanna et al. 2013; Hanna, Boodai et al. 2013).

Significant amount of research efforts have been focusing on implementing BIM/3D CAD in design stage. The optimal MEP layout cannot be fully realized in its installation because of the actual as-built deviations in the space that hosts the MEP systems. For example, with BIM, designers may find 4000 errors in a MEP layout in the design stage, and one million dollars would have been saved if every error had been solved correctly. However, due to designers' limited construction knowledge and expertise, the final MEP layout scheme may be found another 1000 incorrect issues in the real installation environment. Furthermore, after entire design errors are found and solved, potential problems still exist if regardless of construction deviations which impact MEP installation. Hence, previous evaluation and coordination process about BIM based MEP layout optimization are inappropriate. With the selected case study of Shanghai Disaster Control Centre, This paper presents an approach of utilizing BIM to optimize MEP layout from preliminary design into construction phase. In this framework, BIM models are developed at five level-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 optimization methods have been developed to demonstrate solving constructability issues. A case study is implemented to validate this BIM approach framework.

2. FRAMEWORK FOR BIM-BASED MEP LAYOUT

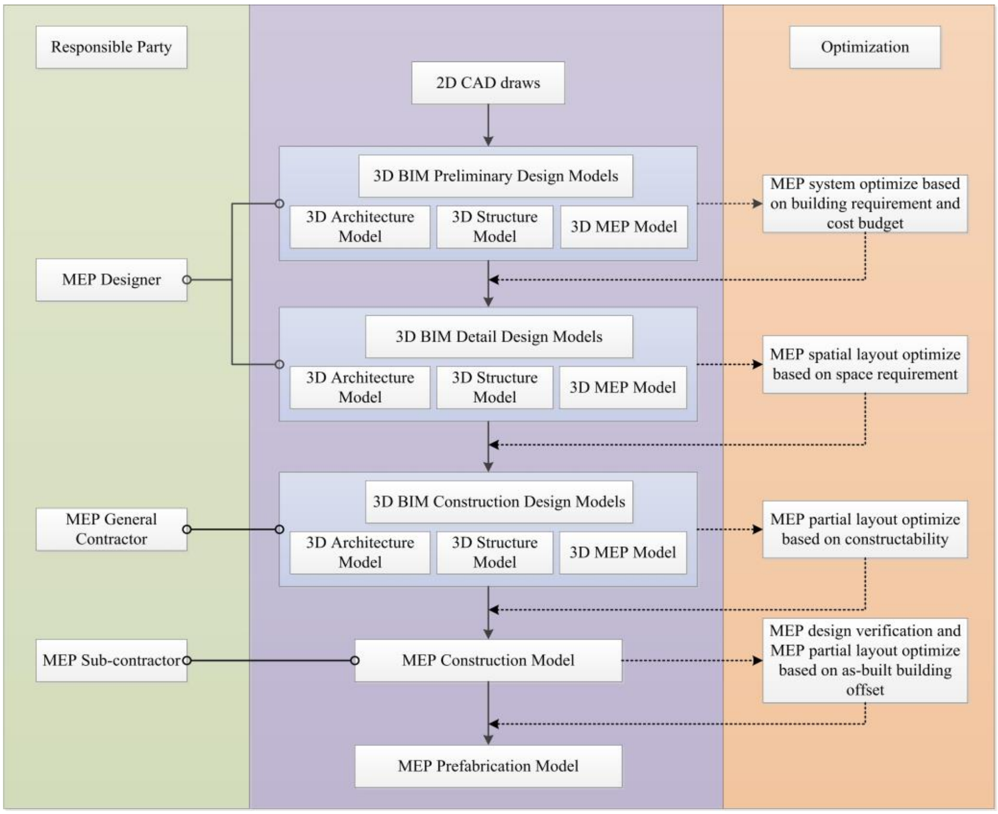


Figure1: Framework for BIM-based MEP layout optimization

This section describes a BIM enabled MEP layout optimization framework (as shown in Figure 1) which consists of 3D MEP Preliminary Design Model, 3D MEP Detailed Design Model, 3D MEP Construction Design Model, MEP Construction Model and MEP Prefabrication Model.

There are four consecutive steps of optimizations in the overall MEP coordination process.

Step1: MEP system optimization based on building requirements and budget.

In MEP preliminary design phase, more than one alternative MEP schemes might be provided. Traditionally, designers cannot comprehensively analyse those schemes in order to appropriately solve problems based on 2D drawings. When using BIM, 3D MEP preliminary design model is already created. Designers can conduct sunlight analysis, Indoor Air Quality Simulation, energy analysis, ventilation simulation and so on. The best MEP scheme will be selected and optimized to a satisfied cost budget and green building certification standards. The optimization in this stage is focused on the comparison between alternative MEP systems. For example, lighting analysis contain 1) Design lighting while adhering to light level and performance requirements and minimizing embodied measures; 2) Base lighting design on optimized daylighting; 3) Minimize lighting pollution by ensuring indoor lighting does not appear externally, or plan for auto-control lighting for after hours; and 4) Optimize outdoor and facade/landscape lighting. The achieve goals for lighting is 1) Conduct detailed solar, lighting, and daylighting analyses; 2) Determine estimated energy use and implement choices to improve efficiency; and 3) Estimate and look for ways to reduce carbon emissions.

Step2: MEP spatial layout optimization based on space requirements

In MEP detailed design phase, there are many collisions when integrating MEP systems into one single platform. Conventionally designers overlay 2D drawings on a light table to identified clashes manually, it is time consuming and inefficient. Automatic clash detection can be easily realized by commercial BIM tools in MEP spatial layout optimization. For instance, considering the structure of large span, designers will make fire protection pipes through high beams to improve use space clear height. For vertical space tight area, designers also consider adding similar pipes to avoid cross way. For example in order to avoid waste pipe cross, waste pipe can be divided into two parallel, then merged into one pipe after entering into pipe-conduit shaft. These optimization methods effectively reduce the height of space requirement.

Step3: MEP partial layout optimization based on constructability

Prior to construction, MEP contractors based on final results from the MEP designers, but MEP designers need to be responsible for the whole MEP design. Construction knowledge is applied to assure the feasibility of building the system and to increase the efficiency of field operations. Examples of construction knowledge for the MEP layout optimization in this phase are 1) access requirement, e.g., provide path and halo (free space around system component) for construction craftsmen, materials, and construction equipment; 2) configuration, e.g., use standard materials and configurations, allow prefabrication offsite or in yard areas at the site; allow desired installation sequence, minimize fittings and field connections; 3) construction method, e.g., maximize prefabrication, allow efficient material handling, provide space and access for electrical cable pulling; and 4) safety, e.g., minimize high time, avoid exposure, provide permanent scaffolding.

Step4: MEP design verification and MEP partial layout optimization based on as-built building offset.

MEP design verification and MEP partial layout optimize based on as-built building offset are the most important work in the whole MEP design process. Because of the state-of-the-art procurement delivery system, project participants do not pay enough attention to this phase. If construction deviation is within a reasonable range, it does not matter when ignoring the work in this phase. However, in fact most of the time construction deviation is beyond the reasonable range for tight time and extensive management, and all the design work and optimization above will become no value if nothing is done to solve the deviation. The critical work of this stage are measuring construction deviation especially in tight space area and updating existing BIM models to reflect as-built design.

3. CASE STUDY

Shanghai Disaster Control Center is one of the important information infrastructures of the State Grid Corporation, China. The Center consists of five floors: one underground and four on the ground. The total investment of this project is 300 million RMB and total gross floor area is 28,124 square meters. Considering the need to host heaps of equipment and complex systems, it is difficult to plan the MEP systems in the limited space using the traditional 2D CAD. BIM was determined to be used in order to eliminate spatial and functional interferences among MEP systems. The MEP model (see Figure 2) was designed using MagiCAD, which is the leading software for HVAC and electrical design.

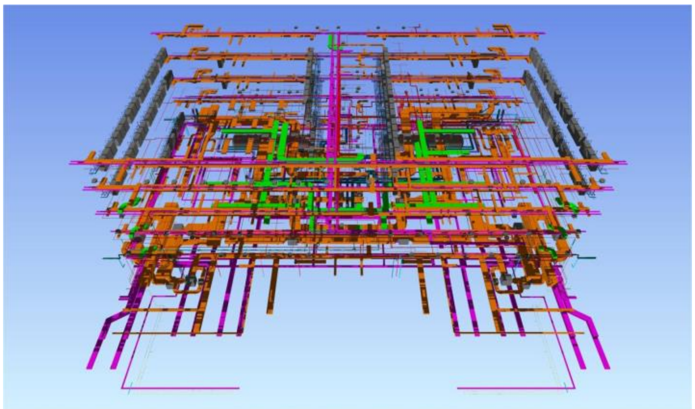


Figure 2: The MEP model for Shanghai Disaster Control Centre

3.1 BIM model development

Shanghai Disaster Control Center adopts the traditional design combined with BIM design to carry on the design. Project design team is divided into 2D CAD team and BIM team, and they collaboration with each other throughout the whole implementation process. BIM team mainly uses Autodesk Revit software to create Architecture and Structure models and MagiCAD to create MEP models. Figure 3 shows the MEP model development process, 2D CAD team use the traditional way to design and later BIM team create 3D BIM model based on its design drawings. Then, the two teams cooperation to do clash detection and optimization about MEP design and layout.

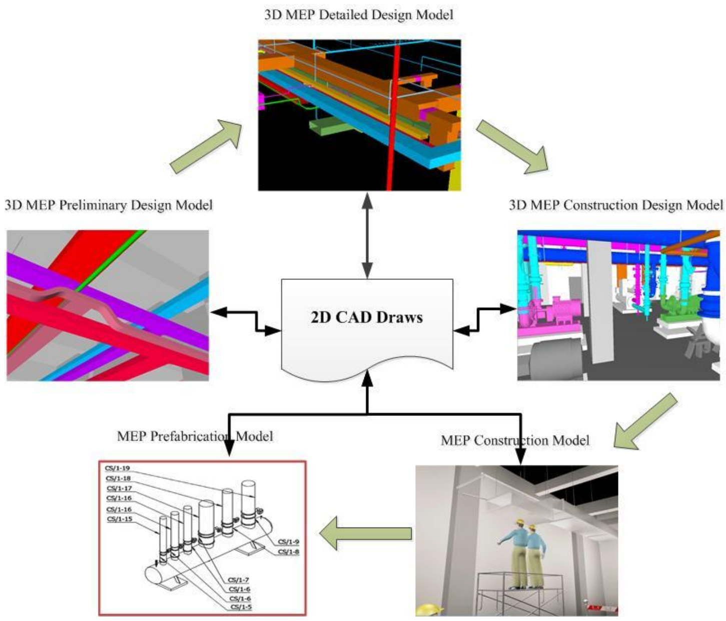


Figure 3: MEP model development process

3.2 BIM-based MEP layout optimization

In Shanghai Disaster Control Center, BIM-based MEP layout optimization is performed in every phase. There are almost 34 optimizations done by MEP designers and contractors in this project, and three typical examples are demonstrated as follow:

Optimization 1: MEP spatial layout optimization based on space requirement

Figure 4(a) shows some collisions among MEP systems in original design. There are some existing experience help designers 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 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 system were finally considered because of flexible routing;
(5) Any other rules such as small pipe give way to big pipe and cheap component give way to expensive component.

Figure 4(b) shows the result after design optimization, which satisfies to design specification and space requirement.

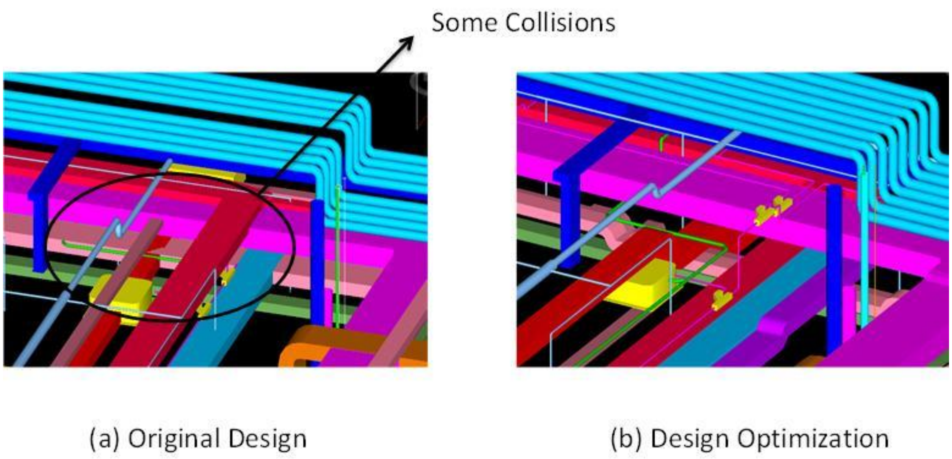
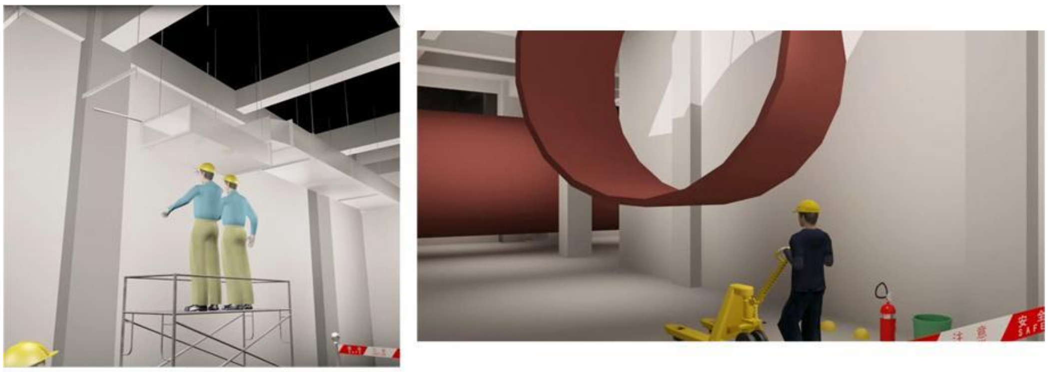


Figure 4: MEP spatial layout optimize based on space requirement

Optimization 2: MEP partial layout optimization based on constructability

After architects and MEP engineers used BIM in the design of a complex building, it is necessary for MEP contractors to implement constructability review. Sometimes MEP installed successfully largely depends on a very specific installation sequence when the design scheme is extremely tight fit. For this project, MEP contractor had chosen 13 critical zones to simulate installation in BIM. Figure 5(a) shows duct installation simulation, in view of construction method, installation space, access space, construction sequence and staff working face, MEP contractor has done a more in-depth theoretical analysis and experimental research to verify the feasibility. There is a lot of large equipment in this project, and how to install them correctly become very important to client. Designers take a little account to equipment installation, so there is some potential risk in construction, such as not enough space for equipment transportation. Figure 5(b) shows ice-storage cooling tank installation simulation.



(a) Duct Installation Simulation

(b) Ice-storage Cooling Tank Installation Simulation

Figure 5: MEP partial layout optimize based on constructability

Optimization 3: MEP partial layout optimization based on as-built building offset

At the beginning of MEP installation, the quality of the related building structure is not clear, which imposes risks on MEP systems if plans are based upon incorrect data (as built the final building), there will appear significant issues while integrating a MEP design model. At worst the restart of building structure has to be moved after all. To minimize this risk, in preparation of the planning, data verification takes place. Thereby the current status of a building is analysed and compared to the existing virtual information. The goal is to verify the positions of the MEP system, but it also has to be evaluated if there is any additional equipment within the workspace.

Figure 6 shows the two freezing water pipes (external diameter is 529mm) and fire pipelines positioned in the refrigeration room conflict with the two ducts (size 2000*630). The design drawings indicate the elevation of the freezing water pipes centre should be +4200, and the fire pipelines should be +6300. However, on one hand the elevation of the as-built freezing water pipes bottom are FL (Floor Level) + 4130, which is 200mm higher than baseline and make the two ducts 200mm higher, on the other hand the elevation of the exist fire pipeline supports are +5980 which make the two ducts 200mm lower. So the two ducts cannot have enough space to be installed if nothing changed in the design.

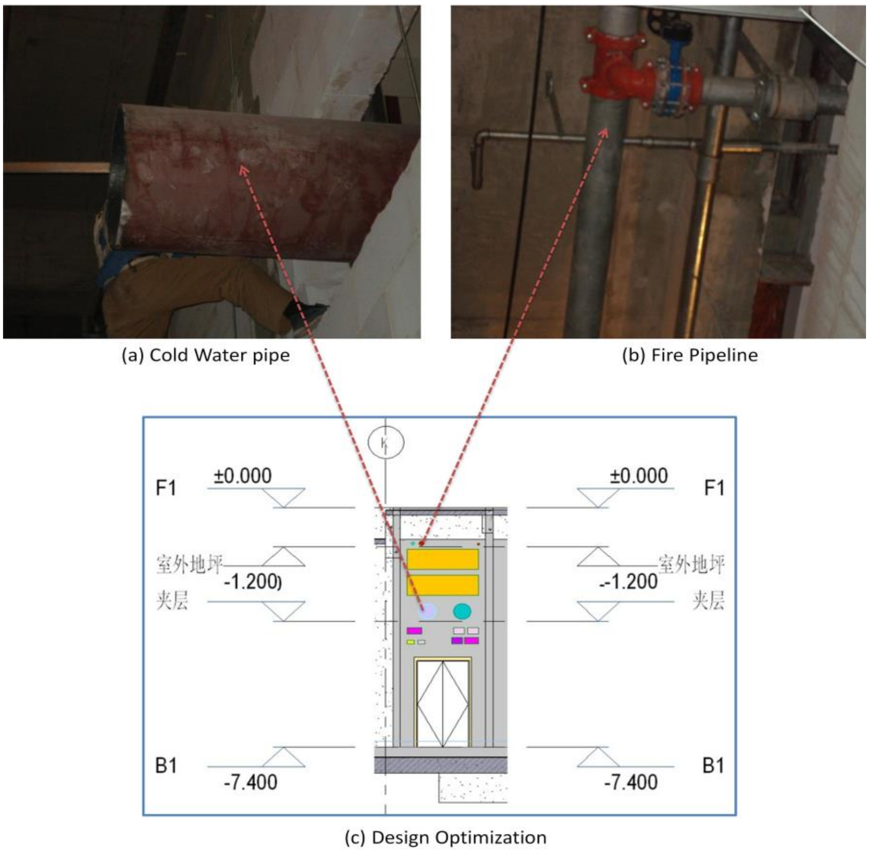


Figure 6: MEP partial layout optimize based on as-built building offset

3.3 Evaluation

The comprehensive applications of BIM have efficiently improved MEP layout design and installation in the above case study. Table 1 shows the evaluation in detail. MEP designers and contractor had done a lot of clash detections among Mechanical, Electrical, and Plumbing systems. More than 2000 errors had been found by BIM software automatically in the original design, and analysed one by one by project participants in coordination meeting. There were 497 important Collisions discovered, filtered from 2257errors, which would cause rework. What's more, 27 additional valuable collisions were detected by designers manually and 75 additional valuable collisions were detected by MEP contractors manually. Therefore a total of 599 critical collisions were founded and they would cause extra quantities such as extra materials and cost. Calculation results based on workers' experience and market price show that 1,250,527 RMB can be saved through using BIM. In addition, through optimizing the MEP layout and equipment installation, MEP contractor developed a more reasonable construction schedule, which reduced the potential risk and rework. Through the above measures, for example, the mechanical and electrical installation teams approached the construction site eight days ahead; the installation of air conditioners reduced from the original 81 days to 58 days; the fire protection engineering from 88 days down to 60 days, the civil structures from 273 days down to 200 days, the decoration engineering from 262 days down to 200 days, the drainage system installation from 252 days down to 187 days, the electrical system from 174 days down to 133 days, HVAC equipment installation from 58 days down to 48 days, UPS system installation from 47 days down to 36 days, the weak electricity system installation from 72 days down to 56 days, the ground facility room construction from 103 days down to 76 days, etc. As a whole, the construction schedule of the project "Shanghai Disaster Control Center" has been shortened for three months.

Table 1: Evaluation of BIM-based MEP Layout optimization

Clash Detection	Collisions which detected by BIM software automatically (a)	Collisions which will cause rework based on (a) (b)	Additional valuable collisions which detected by designers manually (c)	Additional valuable collisions which detected by MEP contractors manually (d)	Increased quantity which caused by rework (e)	Unit price which contained labour cost, material cost, mechanical cost and extra time cost (f)	Increased total cost (g)=[(e)*(f)]
Electrical - Electrical	25	5	0	1	Cable tray 32	846 RMB/m	27,072
Electrical - Structure	90	13	5	7	Cable tray 11	846 RMB/m	9,306
Electrical - HVAC	1026	252	8	11	Cable tray 840 Duct 132	846 RMB/m 973 RMB/m2	710,640 128,436
Plumbing-Electrical	92	18	3	5	Cable tray 20 Pipe 18	846 RMB/m 692 RMB/m	16,920 12,456
Plumbing - Structure	236	49	4	9	Pipe 21	692 RMB/m	14,532
Plumbing - Plumbing	198	38	6	15	Pipe 157	692 RMB/m	108,644
HVAC - Plumbing	495	103	1	21	Duct 108 Pipe 96	973 RMB/m2 692 RMB/m	105,084 66,432
HVAC - Structure	57	12	0	4	Duct 13	973 RMB/m2	12,649
HVAC - HVAC	38	7	0	2	Duct 43	892 RMB/m2	38,356
Total	2257	497	27	75	-	-	1,250,527

4. CONCLUSION AND FUTURE WORK

The evaluation of the project "Shanghai Disaster Control Center" provides evidence to support the potential benefits of application of BIM in MEP layout optimization. It is believed that BIM can efficiently improving MEP coordination by involving various roles of project participants such as contractor, civil engineers, structural engineers, mechanical and electrical engineers. One of the unique contributions of this study was that five levels 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, were applied to the real-life project, to discover a way of choosing appropriate MEP models in different design stage for different optimization purpose. Due to its simplicity, the 3D MEP preliminary design model was the best for MEP system optimize based on building requirement and cost budget. Meanwhile, a higher level of space requirement analysis was possible with the 3D MEP detailed design model, due to their level of detail of MEP elements. The 3D MEP construction design model is best for MEP partial layout optimize based on constructability because of their abilities to represent such detailed construction objects as the pipe support and thermal insulation layer. Nonetheless, the MEP construction model showed the best communication capacity among project participants when construction deviation is occurred. In addition, a detailed evaluation is provided based on the case study. The results show that 1,250,527 RMB has been saved and duration shortens for three months through BIM application.

In this project, construction deviations between as-plan and as-built building are measured by workers using steel tape. There are three challenges when utilizing this method in practice.

(1) Current measurement method is time-consuming and labor-intensive;

(2) Quality of manually collected and extracted data may be low; and

(3) Construction deviation reports are visually complex.

Augmented Reality (AR) creates an environment where digital information is superimposed into a real-world view. Wide variety of built environment applications for which AR systems are now being developed and tested (Wang, Kim et al. 2013). Wang and Dunston have selected some scenarios where AR can be potentially applied, such as working distantly and hazardously, construction and assembly, maintenance and renovation, inspection, safety and training (Wang and Dunston 2006). They further used AR as an assistant viewer for computer-aided drawing (Wang and Dunston 2006). In the future, integration of BIM and AR is becoming an innate feature of the measurement within the building industry (Wang, Love et al. 2013). AR enhances and to accelerates the process of verifying MEP design. The superimposition of photos of the real facility with the related BIM models enables a visual comparison. Based on this, the data quality can be determined immediately. AR helps to determine the deviations between real and virtual equipment exactly and to transfer this information into the BIM software in use.

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