Advances in Engineering Software 100 (2016) 215–230

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Construction and facility management of large MEP projects using a multi-Scale building information model

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ARTICLE INFO

Article history:
Received 30 March 2016
Revised 11 June 2016
Accepted 17 July 2016
Available online 2 August 2016

Keywords:
Construction management
Facility management
MEP
BIM
Multi-scale

ABSTRACT

Several challenges have been found in the current applications of building information modelling/model (BIM) technology in large-scale mechanical, electrical and plumbing (MEP) projects, such as the huge modelling workloads of MEP models and details, untapped potential in supporting cooperative construction management with multiple participants and insufficient functions for intelligent facility management. This paper proposes a multi-scale solution to address the insufficiencies of the current applications in the construction and facility management of MEP projects. Particularly, a practical multi-scale BIM consisting of several macro-, micro- and schematic-scale information models is described in detail with the required information of the MEP components according to the schema of industrial foundation classes. Based on this model, the paper presents a BIM-based construction management system to provide virtual construction scenes with appropriate scales for various participants to communicate and cooperate, as well as a BIM-based facility management system to share information delivered from previous phases and improve the efficiency and safety of MEP management during the operation and maintenance period. The application in a real-world airport terminal illustrates that the proposed model and two systems can support collaborative construction management and facility management with multi-scale functionalities among participants. This paper proposes a series of feasible models and techniques to promote BIM application in large MEP projects.

1. Introduction

Mechanical, electrical and plumbing (MEP) engineering represent a substantial part of a building and directly influence operating efficiency, safety and energy utilisation [1]. MEP engineering may consist of more than 10 subsystems, including heating, ventilation and air conditioning (HVAC), power distribution, telecommunication, automatic control, fire protection, and water supply and drainage. Each system is a complex combination of several components, such as equipment, pipes and wires, as well as a number of logic relationships among these components.

Particularly for large public buildings such as airport terminals and railway stations, the installation of MEP systems accounts for 20%–40% of the total construction cost and covers more than 50% of the total duration during the construction process [2]. In addition, MEP construction includes many interactive and parallel activities of multiple participants; thus, smooth communication and cooperation among these participants are essential for construction management (CM). Compared with the construction process, the operation and maintenance period takes most of the time within the lifecycle and consequently incurs the highest cost. Among the maintenance tasks, the operation management of MEP components has a critical role, and the cost could account for up to 60% of the total cost [3].

Building information modelling/model (BIM) systems provide all of the participants with a shared information source and several visualisation platforms. BIM systems effectively assist managers in conducting collaborative CM. Furthermore, the application of BIM can provide managers with structured information to support the rapid querying of required information on MEP assets and 2D/3D virtual scenes for facility management (FM) [4].

Although the BIM concept has been proposed for many years, several studies on their applications to the CM and FM of large-scale MEP projects point out some deficiencies in the current practices. For example, inconsistent/time-consuming manual modelling is one of the deficiencies to limit BIM Model development [5] and

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http://dx.doi.org/10.1016/j.advengsoft.2016.07.006
0965-9978/

the high LOD[1] is not compatible with current time and cost restrictions in the architecture, engineering, construction, facility management and deconstruction (AEC/FM/D) engineering [6]. The chosen LOD for a given task should be determined by the purpose of its usage, considering the impacts as well as benefits of a LOD [7]. Generally speaking, the MEP engineering of a large public building includes more than 10 systems, each of which has dozens of thousands of components. Modelling all of these components in detail and importing them into a single system for visualised CM or FM are impossible because of the numerous elements embodied in MEP systems. In fact, modelling the entire details for all of the components is always unnecessary because in certain cases, a schematic or rough model is adequately informative and lightweight to assist CM and FM. Another deficiency limiting the application of BIM is the lack of functions to support remote collaboration [8]. More than 10 constructors may be involved in a large-scale MEP project and thus work synchronously in the same area. In addition to quick modelling functions, facilitating communication and cooperation among participants is crucial to avoid construction conflicts and other problems. Finally, though BIM normally comprises building geometry, spatial relationships, and quantities and properties of building components [9], some specific logic relations among BIM components are excluded [6]. Considerable commercial software facilitates FM utilising 3D virtual environment and BIM, however with no further logic relationships embedded and because of the great number of entities in a large MEP project, FM functions are insufficient and the display efficiency is typically unacceptable.

By investigating the common requirements for large MEP projects utilising BIM, this research proposes a multi-scale solution for both CM and FM of large MEP projects. Particularly, a possible multi-scale BIM that consists of macro-, micro- and schematic-scale models for CM, as well as micro- and macro-scale models for FM is presented with the details of its architecture and its representation compliant to the industry foundation classes (IFC) [10]. Based on this multi-scale BIM, a CM system and an FM system for MEP engineering are developed. Finally, the paper examines and discusses the in-depth application to the MEP project of a large real-world airport terminal, the Kunming Changshui International Airport terminal.

2. Related research

A BIM contains a variety of relevant engineering data of a building [11]. Through the establishment of a single project data source, BIM technology aims to achieve the integration of distributed, heterogeneous engineering data and to support information sharing and collaboration among various participants and different phases within the building lifecycle.

BIM is extensively adopted during the design phase of MEP systems. For example, a prototype tool based on an MEP knowledge database and BIM has been developed for automatically detecting clash and facilitating MEP coordination [1,10]. Researchers have indicated that establishing detailed models with appropriate attributions and fineness is critically important for collaborative design [12].

BIM technologies for CM include quantity take-off, cost estimation [13], construction safety analysis [14], workspace conflict [15] and four-dimensional (4D) CM [14,16] with various functions, such as construction simulation, schedule management, resource and cost management and site management. Russell [17] and Staub-French [18] introduced linear scheduling into 4D CM because of its insufficiency in visualising relationships among tasks in large-scale linear projects. Kuo [19] comprehensively employed the Gantt chart, network diagram, tree structure view and 3D graphics platform in visualising temporal, relational, hierarchical and spatial information to support the CM of multiple systems. Some researchers successfully applied BIM to MEP construction, for instance, by proposing a method for drawing up the transporting and installing programme of MEP elements according to their size, weight and other information extracted from BIM [20], or by creating MEP 3D/4D models to aid in MEP collaborative design and construction [21,22]. These studies also summarized the guidelines for creating MEP 3D/4D models and suggested the importance of clarifying modelling requirements and the levels of detail.

For BIM applications in the operation and maintenance phase, data description standards, such as an FM data model FMC [23] an object-oriented product model utilising unified modelling language (UML) use cases [24], were presented to assist facility managers in managing lifecycle information more effectively. An extension of IFC, including FM information (i.e. performance requirements, conditions and inspection) and repair information of MEP assets [25] has been established. Researchers have developed a few FM systems, including a 3D visualisation of buildings for FM with a method of reusing BIM created in previous phases through Ifcxml files [26], an FM system according to some existing problems such as tedious and error-prone tasks in practice [27] and an integrated system for capturing information and knowledge of building maintenance operation to support preventive or corrective operations by understanding how a building is decorating [28]. On the other hand, a prototype of a BIM-based game system that integrates BIM and game environment has been developed for interactive visualisation [29]. IFC files were used as input for path planning to facilitate the sharing of both geometric information and rich semantic information on building components [30]. These studies have laid the foundation for indoor path planning during the operation and maintenance period. An investigation showed that facility managers agreed that the application of BIM in FM could save information query and management time, but the extra investment and work process changes would hinder the application to a certain degree [31].

To identify the processes that are undertaken within a project and the corresponding information required by each process, buildingSMART proposed the information delivery manual (IDM) [32] approach to support the IFC-specified information. Model-view-definition (MVD) [33] provides a formal process for specifying the mappings between the IFC schema and the information requirements in different domains to address the standardization of such model subsets [34]. Particularly for identifying the information requirements for the performance analysis of HVAC systems, Liu [35] introduced an improved IDM approach for mapping information requirements to multiple information sources that use various formats and schemas. Construction operation building information exchange (COBie) [36] was developed to provide a specification for final information delivery to the operation and maintenance phase. COBie also uses MVD to represent mappings between its information requirements and the IFC data model. Most of these approaches are utilised in service-oriented architectures to facilitate the remote access of model repositories through standardised network protocols [37–39]. These achievements enable data sharing between various participants within different phases of a project.

Even though BIM brings many benefits to the AEC industry, problems and barriers still exist to accept BIM without discomfort [40]. For example, IFC is a rich product-modelling schema,

[1] LOD (Level of Details) refers to the detail of a model, describing a BIM component from the lowest conceptual design level to the highest as-built modelling level. There are 5 levels: LOD 100, LOD 200, LOD 300, LOD 400 and LOD 500 refer to conceptual design model, developed design model, presentation and bidding model, construction model and as-built model, respectively.

however, highly redundant and offering different ways to define objects, relations and attributes [41]. MVDs are proposed to narrow down the complete IFC schema [42] and make it easier to use [43]. Nevertheless, current approaches to define MVDs depend on the experience and still have a lot of problems, for example, the translation from exchange requirements to model views is carried out manually and error prone [44,45], thus making MVDs expensive to build, test, and maintain [41]. Besides, the LOD in the provided and exchanged models for each information unit can vary based on the project stage, purpose of model exchange, model recipient, and local practices, but current MVD technology does not specify such an LOD requirement for each phase of the project [44] and every potential function.

Gaining from the practical experiences, the new ideas of multi-scale or multi-level models/methods have been proposed for the industry to give different levels of detail information and meet demands of different project stages and management requirements. For example, a multi-level 4D model that considers the activity, discrete operation and continuous operation levels has been suggested for different purposes in a bridge project [46] and a stadium [47]. A multi-scale geometry model in different levels of detail has been introduced [48] and adopted for synchronous collaborative modelling in railway projects [49,50]. A collaborative platform supporting the modelling, management, and visualization of 3D multi-scale models was developed to facilitate planning processes for subway track planning [51]. However, few of these ideas fucoses on the MEP projects within a large public building, which is quite different from other projects and crucial to people's lives.

3. Requirements identification for large MEP projects utilising BIM

3.1. Problems

A large MEP project, which is always an important component of a large public building such as an airport terminal, a medical building, a stadium or a railway station, etc., has significant differences with relatively small MEP projects. Through field investigation with construction and facility managers of an airport terminal and a stadium respectively, the following three common problems in current BIM-based MEP engineering practises are concluded.

3.1.1. The contents, details and workload of modelling efforts are out of control

In a residential building or even in a high-rise commercial building, the BIM consultant who is in charge of modelling task claims that the total number of all MEP elements is normally no more than 50 thousands with triangles (once converted to boundary representation for efficient 3D display) less than 10 millions in LOD 500. However, in a large MEP projects, these two numbers can be more than 200 thousands and 50 millions. All the participants agree that it is not necessary to model all the components in LOD 500, which is too much a pressure to not only the modellers but also the BIM software. Researchers have highlighted the importance of extracting partial model subsets or domain-specific views on large models [52]. For example, the BIM consultant can establish LOD 500 BIM for CM and FM of important spaces such as apparatus rooms, LOD 300 BIM for CM and FM for the power system in a single floor and LOD 100 for CM of the whole piping system within the building. This multi-scale idea balances the workload and the value of modelling efforts in a large MEP project. However, how many levels will be sufficient and what contents should be modelled in each level are remained to be instructed.

3.1.2. The construction is much more complicated than normal MEP projects

Covering a huge space with quite a lot of duplicated and individual tasks, the construction of a large MEP project lasts for 2 to 3 years and even more. There are too many participants and simultaneously tasks during everydays work. Without advanced techniques, it is difficult to arrange a perfect schedule for spaces with clustered MEP components, thus the general contractor always argues with sub-contractors on planning the tasks that should be finished in the coming few days. Even though, the plan may not be fully carried out because of many unforeseen conflicts. BIM and 4D technologies help in solving parts of these problems by providing a cooperated and visualised platform for discussing the plan. However, preparing all the details of models, schedules and resources within such a large project takes too much time and thus is not always valuable for those straightforward or duplicated spaces. On the other hand, different managerial personnel have different concerns in the CM. A team leader of a contractor faces every detail of the construction activity while the senior system manager pay close attention to the general installation schedule of a single MEP system, ignoring most of the rococo details.

3.1.3. Retrieving valuable information with strict requirements on FM is hard

In large public buildings, the running conditions of MEP systems should be monitored dynamically with much more strict requirements because even a failure of a valve or a leak of a water pipe may cause people panic. On the other hand, when a malfunction task is assigned to a maintenance worker, the worker should response as soon as possible and take the activities according to the manual book of the facility; when a pipe is leaking out, the worker should find out the upstream valve and shut it down in maybe 10 min as an emergency treatment. These works are not easy in large MEP projects because of the huge amount of facilities and assets, spreading in a broad space, and the workers have to find out solutions according a lot of documentations and guides in the repository. Moreover, currently most facility managers prefer 2D planar management tools to 3D platforms.

3.2. The multi-scale solution

By analysing the above three problems and learnt from practical experiences, a multi-scale BIM based CM and FM is proposed as a solution for large MEP projects.

As the basement of this solution, the multi-scale BIM refers to the information requirements, definitions and organisations. Firstly, it consists of several different scaled information models, such as micro-scale model, macro-scale model and schematic-scale model. Though there is no explicit distinction between these models, it can be normally divided by LOD. For instance, models of LOD 400 or 500 can be regarded as micro-scale BIMs, LOD 200 or 300 as macro-scale BIMs and LOD 100 as schematic-scale BIMs. The contents that should be modelled in each single model rely on the purpose of this model and the potential functionalities in aiding CM and FM. Secondly, all these models are closely linked to each other. In most spaces in a large MEP project, a macro-scale BIM may be sufficient for CM and FM. However, in those equipment clustered rooms, micro-scale BIMs with much more details should be built up together with the macro-scale BIM. In this case, these two scaled BIMs (or even more scaled BIMs built up for potential applications) should have close linkages, describing the same space object with different functional abilities. Finally, the combination of these models are free to the requirements of CM and FM. According to the management requirements, a number of macro- and micro-scale BIMs can be built up and combined in a project. For example in Section 4, a possible and practical multi-scale BIM is proposed by combining several scaled BIMs. The multi-scale BIM is crucial to overcome several management problems that exist in current CM and FM systems. It employs simplified information models of the overall MEP project, together with only a small number of detailed models, thus significantly reducing the workload of 3D modelling and hardware requirements of BIM systems. Importantly, all of the models share a unique BIM repository with consistent information.

Another key point of this solution is developing corresponding multi-scale management functions in BIM systems to facilitate CM and FM based on the multi-scale BIM. According to the CM and FM problems, BIM-based management systems are important to provide means and tools for cooperated and intelligent CM and FM among all participants. These functions reply on different scaled models. For example, Collaborative CM, including 4D simulation, schedule management, resource management and cost estimation, among all MEP engineering participants can be carried out because the multi-scale BIM provides appropriate models and views for different managerial roles. In this regard, the macro-scale CM model may be appropriate and valuable for senior managers to understand the overall construction process of the MEP project; the schematic-scale CM model may be effective in displaying the logic structures of MEP systems; and the micro-scale CM model of only critical areas provides virtual scenes in detail to avoid most of the construction conflicts and streamline parallel construction. During operation and maintenance period, highly organised information and innovative tools are helpful for facility managers to improve management efficiency through the transformation of the as-built CM BIMs to FM BIMs. For example, the micro-scale FM models facilitate the querying of information and the macro-scale FM models improve the understanding of the layouts and structures of MEP systems. Consequently, operation and maintenance management is served, including the query and visualisation of MEP systems, inspection path planning, intelligent control of MEP systems, regular maintenance works and emergency management. Some typical management functions based on the multi-scale BIM will be further discussed in a case study of an airport terminal in Section 6.

4. A multi-scale BIM for both CM and FM

In order to instantiate the multi-scale solution, this section discusses the overall architecture of a practical multi-scale BIM that assists CM and FM, as well as the types of information required for this multi-scale BIM and how these types of information are defined.

4.1. Architecture of the proposed multi-scale BIM

Various scaled models are necessary for different requirements. As illustrated in Fig. 1, the architecture of the proposed multi-scale BIM consists of macro-, micro- and schematic-scale models for CM, as well as micro- and macro-scale models for FM. Each model in any scale is a subset of the total MEP information model and extracted according to different user requirement. In the process, different managers are supported in the establishment of an appropriate view according to their own requirements, and cooperative CM and flexible FM on their own individual view are achieved.

4.1.1. Macro-scale CM models

When construction managers require brief information to grasp the overall construction status, a simplified subset MEP model of the overall project describing elements without details, is sufficient to aid CM in a large-span space. According to actual requirements, the geometric model of elbows, valves and other small fittings may be excluded from this model. The model adopts simple geometric models to represent equipment and axes to represent pipes, thus improving the rendering efficiency of 3D platform while considerably reducing 3D modelling efforts. Furthermore, axial line representation method can be adopted instead of a real 3D representation to improve the visualisation effect of small-scale pipes in a macroscopic view. Based on these macro-scale models, BIM systems provide senior and middle managers with functionalities, such as macro-scale CM construction simulation, overall construction progress analysis and management and dynamic requirement analysis of principle materials.

4.1.2. Schematic-scale CM models

A schematic-scale CM model, which consists of the schematic of a single MEP system, is proposed to describe the status of the construction of a single sub-system among different floors and varied regions. Together with macro-scale simulation and management, this model can be rendered to provide managers with a rapid understanding of the logic structure and brief construction progress of a single MEP system. This model also synchronously provides the position of MEP elements being installed in a schematic diagram. These views and functions aid the managers in analysing the construction schedule from the perspective of a single system by covering the 3D view's deficiency in visualising the complex logic structures of MEP systems in a large construction area.

4.1.3. Micro-scale CM models

A detailed model must be established when detailed construction simulations are required to support decision making on every construction task among various participants. A micro-scale CM model consists of detailed MEP information (including all of the components with a detailed schedule and related constructors etc.) on one area where MEP elements are clustered. For instance, check-in zones, equipment rooms and corridor ceiling in an airport terminal are the areas clustered with more than 10 MEP systems and structural systems, and parallel construction often occurs in these areas. This model may use different colours to distinguish the elements being constructed by different constructors during the simulation. The intuitive visualisation of construction scenes can also be provided for communication and interoperation among these constructors. The visualisation of the model aids field engineers, managers and other participants in identifying construction conflicts and other problems existing in the current schedule and avoiding them in actual activities. The model also supports managers in annotating each day's potential problems found through simulation and each problem's feasible solutions made by multiple participants. It facilitates the actual progress of parallel construction in these areas.

4.1.4. Micro-scale FM models

During operation and maintenance, tasks such as equipment repair, regular maintenance and emergency handling require not only a BIM with a high level of detail, but also other related information, such as manuals, historic records and even the logic chains between the objective equipment and other elements. Each subsystem in MEP engineering consists of thousands of elements and pipes with complex logic relationships among them. Consider as an example the air supply, whose supply fan controls the air outlets. Therefore, the supply fan is regarded as the upstream element, and the air outlets the downstream elements. These logic chains must be established in the as-built model, making it an information-enriched micro-scale FM model. Given that manually building up the relationships is unacceptable because of the huge workload and non-assurance of accuracy, some automatic relation-generation methods can be implemented to accelerate the process and improve the accuracy. In detail, within a single MEP system, the component type can be extracted to form a tree-structure that indicates the logic chains among components, thus the potential

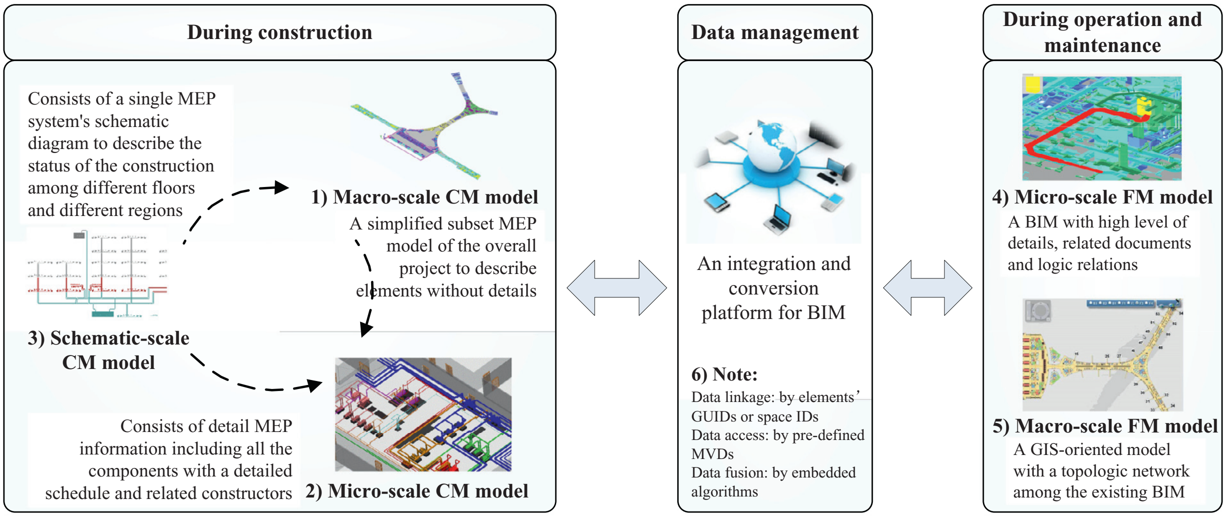

Fig. 1. Framework of multi-scale 4D model.

relationships among elements can be roughly determined by classifying the elements into different types. Then, for components of the same type, similar components are assigned to the same logic layer by analysing the geometry for further subdivision (similar components with the same type are often in the same logic layer). Finally, end-section analysis helps in identifying spatial connections of various components. Different parts of the connected component are either assigned to the same logic layer or formulate the logic chain based on the type tree-structure. Experiments in real projects show that this method provides about 70% to 80% accuracy in relation generation and overall a 60% reduction in workload.

4.1.5. Macro-scale FM models

For the convenience of FM, Geographic Information System (GIS)-oriented information with topology relationships among rooms, corridors and accesses, or even among electric or water supply systems, is necessary to meet the requirements of routine check tasks and emergency management. GIS is a system to capture, store, manipulate, analyze, manage, and present all types of geographical data [53]. The advantages of integrating BIM and GIS have been studied by numerous researchers and proved in real projects. For example, when designing a building in a crowded urban environment, the designer need data from GIS on neighbourhood buildings and surrounding infrastructure to get a better understanding about the noise sources and take necessary measures in the design process in BIM [54]. Some researches have been taken to achieve a seamless data integration between BIM and GIS by using IFC and City Geography Markup Language (CityGML) [54], semantic web technology [55], the data model [56] and so on. The integration of BIM and GIS could also bring benefits such as providing better supports to the visualisation of the supply chain process [57], to facility management [58] and to emergency response [59], etc. It is believed that BIM is used in a relatively micro level of the real world while GIS on the other hand is used in a macro level [60]. Besides being taken as a single building (micro level), a large public building is also big enough to be managed in macro level. For instance, indoor path generation can support managers in planning an optimal inspection path to pass through the required inspection points. However, room or path information is typically lacking in normal as-built BIMs established by modelling platforms, such as Revit and ArchiCAD. Therefore, it requires to transform normal BIM to a GIS-oriented model. This model, which is referred to in this paper as macro-scale FM model, recognizes the spaces, roads, routes or wires connections, and generates a topologic network among these existing solid components in current BIMs. This topologic 2D/3D model constantly meets the requirement of routine check tasks and emergency management to efficiently and clearly represent a large area management. By contrast, a micro-scale FM model provides 3D objects with accurate position and geometry.

4.1.6. Data management among the multi-scale models

To take advantage of the aforementioned multi-scale models, related information must not be managed or manipulated separately. Firstly, the models are linked to each other to facilitate their recall and transformation to other models for various management requirements. The global unique ID (GUID) attached to every element is used as a linkage among all of the aforementioned models. On the other hand, space information (e.g. the bounding box or the area formed by floor and axes) is used to link macro- and micro-scale models. Secondly, different models require particular information stored in the unique BIM. When acquiring such information, pre-defined MVDs assume the responsibility of accessing the appropriate data by extracting information from the integrated BIM platform. Finally, these models are related to each other but they focus on different information. For example, the micro-scale FM model contains detailed information for each asset within a room, whereas the macro-scale FM model focuses on the room itself and the access between the rooms, or between the room and the corridor. Thus, the BIM management platform must have some data conversion or fusion algorithms to automatically create such information and join all of these useful data.

4.2. Information requirements and definition of the multi-scale BIM

The information in the multi-scale BIM for both CM and FM is required to describe MEP components and their engineering information. As shown in Fig. 2, the information consists of four parts, namely, MEP object definition, design information, construction information and operation and maintenance information. IFC is the practical data standard for BIM; hence, the IFC 2 × 4 is adopted to describe the representation of the multi-scale BIM. The representation is important for exchanging such information in different BIM applications using IFC files or other IFC compliant data interfaces.

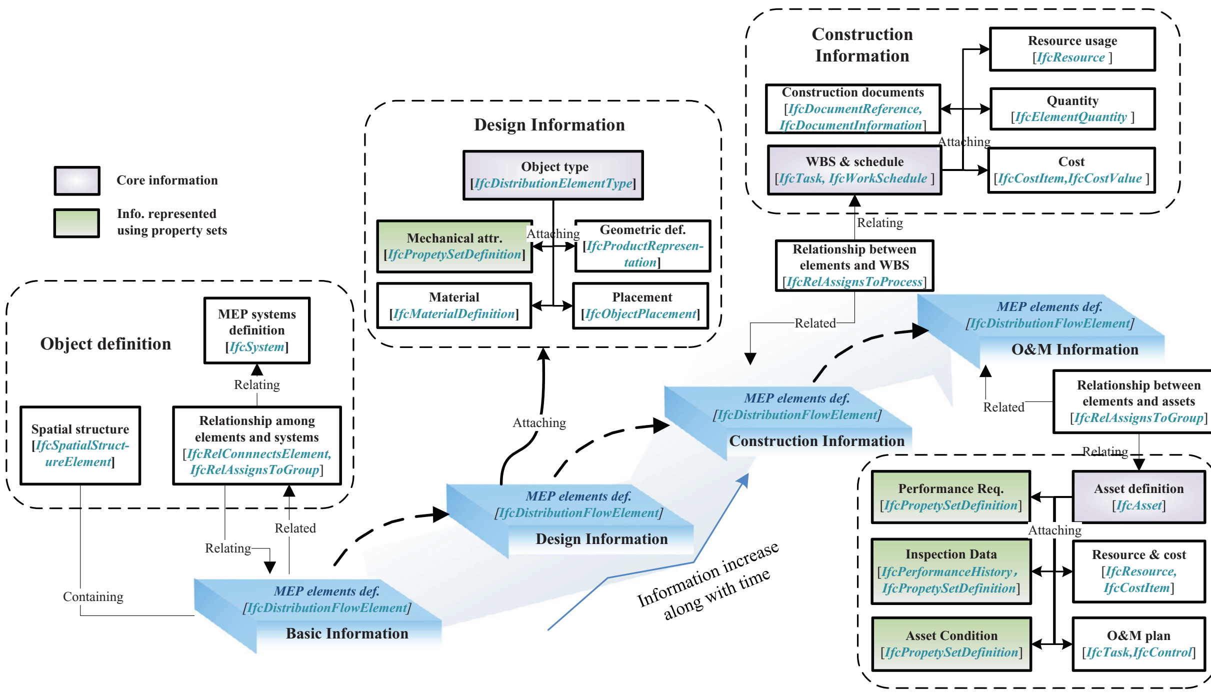

Fig. 2. Architecture of the MEP information model.

4.2.1. Object definition

Object definition defines the MEP components and their relationships. The definition of MEP elements specifies the category, global ID and other basic attributes of an MEP component. Spatial structure is a model structure defined according to floors, zones and other spatial information of a building. The IFC standard applies `IfcDistributionFlowElement` and its subtypes to represent MEP element definition and `IfcSystem` to represent MEP systems definition. The 'IFC Model Implementation Guide' [39] contains more details about IFC representation.

4.2.2. Design information

Design information includes spatial location, geometry representation, material and performance attributes. The MEP components of the same specification exhibit several common properties. An MEP type is typically defined as a representative of all similar components. Fig. 2 lists some of the IFC classes generally used in representing design information.

4.2.3. Construction information

MEP construction information includes quantity information, schedule and progress, organisation, resource usage, cost and construction documents, among others. MEP construction information is dynamically created in the construction process and added to the established design information model to form an integrated information model for CM. For example, construction schedule is added into the design information model to form a 4D model. Several researchers, such as Tanyer [61], Ma [13] and Zhang [16], have analysed the IFC model framework for construction information. Fig. 2 lists the predefined types of IFC generally used to represent construction information.

4.2.4. Operation and maintenance information

Operation and maintenance information for MEP engineering mainly includes the definition of assets, inspection data, equipment condition and maintenance schedule [23,25]. An asset is a combination of MEP elements and is defined according to management requirements. After defining an asset, the manager needs to define its performance parameters and their normal range. Inspection data reflect the dynamic inspection results of performance parameters. Equipment condition can be specified according to the performance requirement and inspection result of an equipment. FM schedule arranges operation and maintenance tasks, including daily and emergency tasks. The MEP FM information model based on the IFC 2×4 is presented in Fig. 3. Generally, `IfcAsset` is used to represent assets, performance requirements are represented by property sets, inspection data are represented by `IfcPerformanceHistory` and property sets, and equipment condition is represented by the predefined property set `Pset_Condition`.

In summary, the IFC 2×4 can represent the information required for the proposed multi-scale BIM. Property sets are used to represent important information, including performance attributes and requirements, inspection data and equipment conditions. However, considering that information represented by property sets is complex to interpret, low efficiency may ensue, particularly when vast amounts of property sets exist in a single IFC file.

5. Design and implementation of the systems

This section focuses on the design proposal of two systems, namely, 4D-BIM_MEP and BIM-FIM_MEP. The 4D-BIM_MEP is a BIM-based construction management system developed on the basis of the existing 4D-GCPSU [14]. By contrast, the BIM-FIM_MEP is a BIM-based facility management developed on the basis of the existing BIM-FIM [62]. These two systems are developed based on the proposed multi-scale BIM to facilitate the CM and FM functions.

5.1. Functions of the systems

The 4D-BIM_MEP system is particularly designed and implemented for MEP construction management. It consists of three main function modules, namely, information modelling and management, 4D construction simulation and construction management. The BIM-FIM_MEP is designed and implemented for facil-

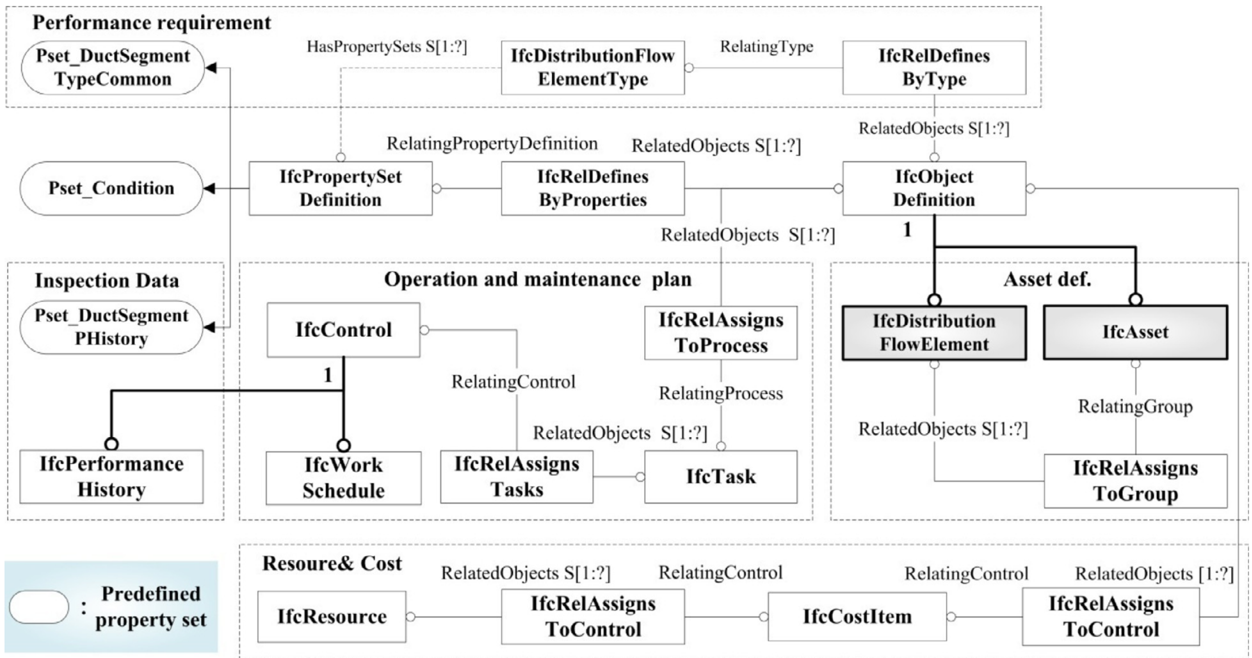

Fig. 3. FM information model of MEP engineering in IFC 2 × 4.

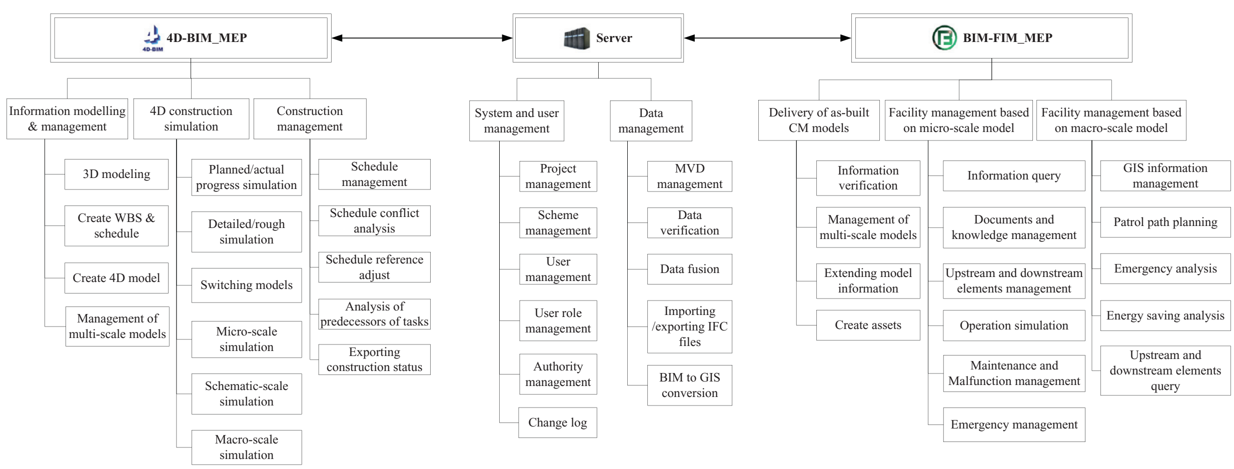

Fig. 4. Functions of the 4D-BIM_MEP and the BIM-FIM_MEP.

ity management of MEP engineering. It also consists of three main function modules, namely, delivery of as-built CM models and FM based on micro- and macro-scale models. Accompanying these two systems is a server client that is also implemented with the function modules of system and user management and data management. Fig. 4 shows all of the function modules with detailed functions.

5.2. Programming architecture of the systems

Fig. 5 depicts the programming architecture of the 4D-BIM_MEP and the BIM-FIM_MEP. There are six layers, namely, server layer, model layer, system layer, platform layer, application layer and surface layer. The server layer provides a BIM data repository, as well as some data interfaces and algorithms for data extraction, conversion, fusion and integration. It also manages all of the users and authorities. The model layer extracts the proposed multi-scale CM and FM models from the server layer for the system layer, which consists of the two proposed systems. The platform layer forms the environment for BIM/GIS visualisation, as well as for CM and FM. The application layer refers to the aforementioned specific function modules, and the surface layer provides a user-friendly human-machine interaction interface for all the application functions.

6. Application to a real-world airport terminal project

The proposed multi-scale BIM and the two systems were applied to a real-world large-scale MEP project, the terminal of Kunming Changshui International Airport. The terminal with a total building area of 435, 400m^2 is one of the largest single buildings in China. It consists of four floors above the ground and three floors underground. The MEP project started in January 2008 and was completed in May 2012, and put into operation in June 2012. The general contractor of the MEP project was Beijing Urban Construction Group. More than 20 different sub-contractors worked for weak electricity engineering, fire protection system and baggage system, among others. The owner, the Office of Kunming Changshui Airport Construction, adopted BIM to aid CM and collected a well-organized engineering data model for BIM-based terminal FM. A BIM consultant group aided all of the participants in developing

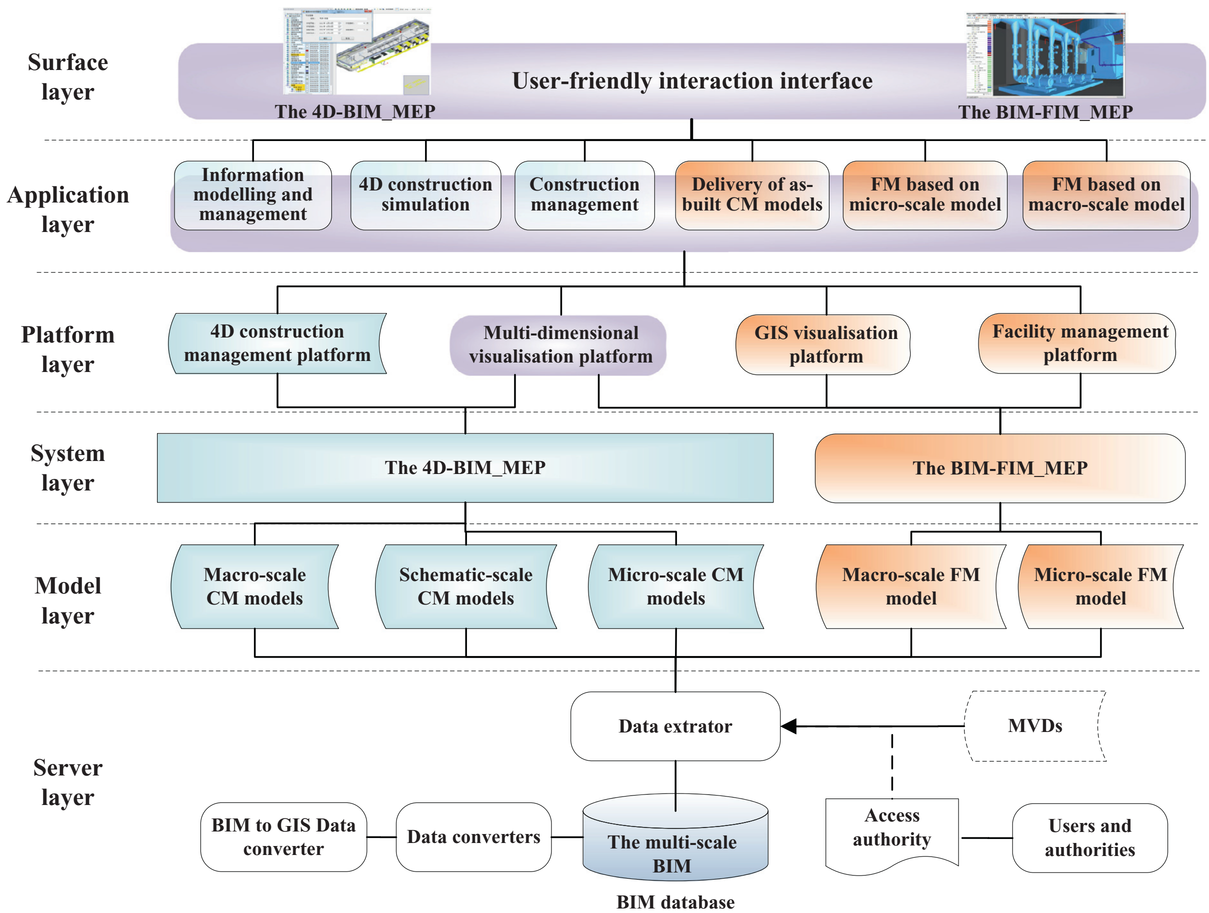

Fig. 5. Programming architecture of the two proposed systems.

the multi-scale BIM and the two systems, as well as some of the modelling and application tasks. The group also provided training on applying the two systems. Overall, roughly fifteen construction or IT experts from eight participants, including the general contractor, six sub-contractors and the BIM consultant group, joined in the CM. Additionally, four facility personnel were involved in the BIM-based FM. Approximately 20 personal computers equipped with two dual-core processors (2.3 GHz) and 8 GB memory, a mid-range computer in terms of comprehensive performance in 2011, and a server computer equipped with two dual-core processors (2.3 GHz), 16 GB memory and 1 TB HD, were used to implement the application.

6.1. Establishing the multi-scale BIM

As shown in Fig. 6, the total MEP information model consisted of 3 macro-scale CM models, 2 schematic-scale CM models, 6 micro-scale CM models, 3 macro-scale FM models and 5 micro-scale FM models. The modelling process and the information flow are shown in Fig. 6 and described as follows in detail.

(1) According to the blueprints, the general contractor used the Revit series to create the architectural model with all the beams, columns, walls, slabs, doors and windows.
(2) During the preliminary design period, the BIM consultant group created 2 macro-scale and 2 schematic-scale CM models, that is, the water supply and drainage model and the electrics model, and the general contractor created 6 micro-scale CM models as listed in the middle of Fig. 6, on the base of the architectural model. At the same time, the BIM consultant group also established the logic chains between the elements and the spaces through an embedded space mapping algorithm. These models were directly delivered to the construction phase.
(3) During construction, the general contractor, together with most of the sub-contractors, created the corresponding multi-scale construction plans in Microsoft Project and then imported those plans to the 4D-BIM_MEP to form several work breakdown structures (WBS) with tasks and relationships between the tasks.
(4) Other information, including quantity and budget, as well as the actual construction progress and cost, was also extended in the 4D-BIM_MEP to build the multi-scale CM models.
(5) The BIM consultant group performed the data conversion or fusion algorithms embedded in the server to deliver the construction information to the next phase, as a delivery-oriented simplified MEP information model. For example, the rooms and the corridors were defined and the paths were generated.
(6) During the operation and maintenance, the owner and concurrently the facility manager used the BIM-FIM_MEP to extend FM information, including assets definition and their performance requirements, indoor path, operation and maintenance plans, logic relations between MEP elements, inspection data and running condition of MEP assets, Operation and maintenance records, etc.
(7) All of the BIM information was stored, shared and managed in a central unified BIM repository (i.e. SQL server with a server management tool).

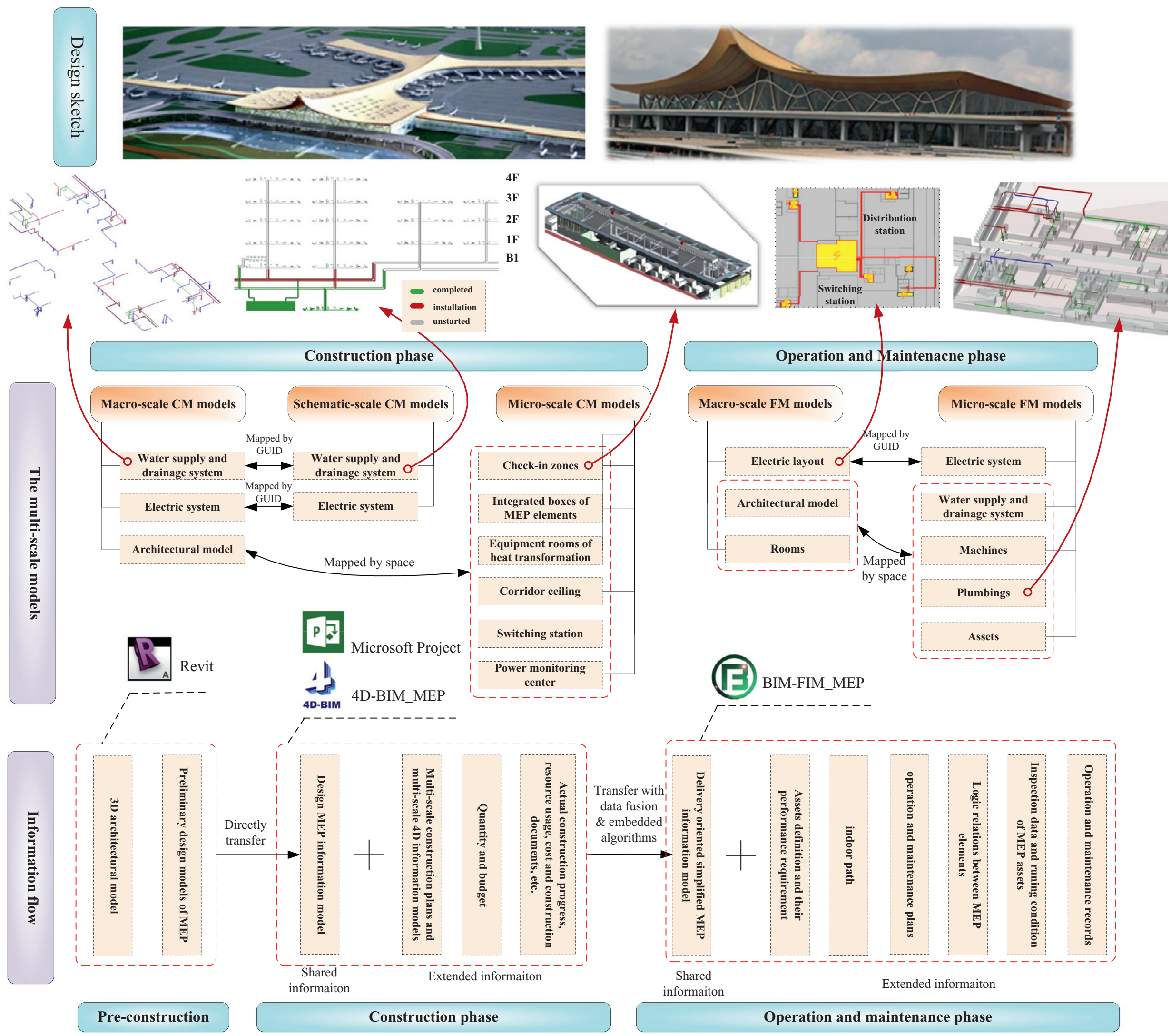

Fig. 6. Contents and the modelling process of the multi-scale BIM for the Kunming Changshui International Airport terminal.

6.2. CM for the MEP project utilising the multi-scale BIM

The 4D-BIM_MEP was applied by six constructors to the macro-scale CM of plumbing, electric power systems and micro-scale CM of many critical areas, such as check-in zones, integrated boxes of MEP elements and equipment rooms of heat transformation. This paper focused on the application of macro- and schematic-scale 4D CM to the drainage system and micro-scale 4D CM to the check-in zones.

6.2.1. Application of the macro- and schematic-scale CM models to the drainage system

Taking advantage of the multi-scale BIM, construction simulation can be presented in a traditional manner to reflect the components and schedule in a single view; at the same time, such simulation can also be rendered schematically for a single MEP system. During simulation, the schematic-scale 4D simulation runs synchronously with the macro-scale 4D simulation. The former shows the logic segmentation of the MEP system in a vertical view, whereas the latter presents a broad view of the large construction area. Fig. 7 illustrates the construction process of installing the drainage system in zone A on storeys B3 and B2. In the 3D scene, the architectural model only functioned as spatial reference. Moreover, it was dynamically rendered in translucency to avoid covering the plumbing components being installed. Synchronously rendering these two scale models allowed senior and junior managers to grasp the overall construction progress in both the planar scene and the vertical scene of the construction status of the drainage system.

6.2.2. Application of the micro-scale CM model in the check-in zones

6.2.2.1. Construction simulation. The construction simulation was presented in a micro-management-oriented manner for highly detailed construction activities. When a user clicked the abstract component of the construction site (i.e. the space for the equipment room or the simplified model of the check-in zone), the interlinked relationship established among the models could load the corresponding micro-scale CM model for demonstrating the MEP clustered area with a detailed construction schedule for all of the components inside. The check-in zone provided a good example. The MEP project of a check-in zone included more than 10 disciplines, including electric power, ventilation, fire protection, telecommunication and baggage system, etc. It was one of the most complex areas in the terminal involving six sub-contractors related to this area, namely, structural constructor, decoration constructor, general contractor of MEP engineering, fire protection constructor, weak electricity constructor and baggage system constructor. Several challenges existed in the actual construction pro-

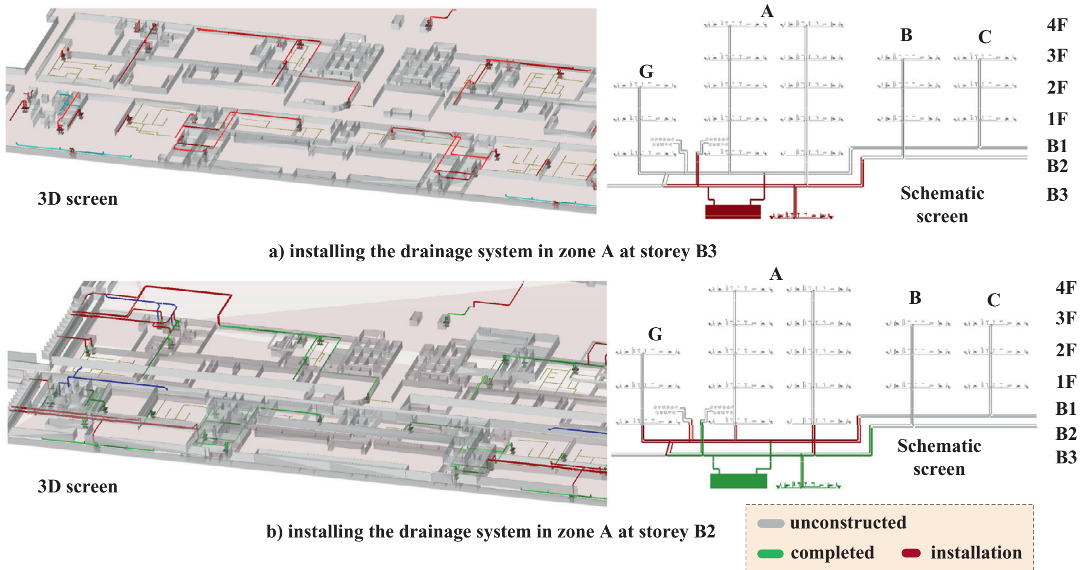

Fig. 7. Macro-scale and schematic-scale 4D construction simulation of the drainage system.

cess of the area, such as cross and parallel constructions with many disciplines, limited construction space and protection of the finished elements. Thus, the generation of a construction plan that fit the needs of all of the participants using traditional methods posed a difficulty. To address this issue, the 4D-BIM_MEP was applied to draw up the construction plan and assist the dynamic CM.

Firstly, managers from all contractors applied 4D simulations, predecessor task analysis and other functions of the 4D-BIM_MEP to identify the problems in the current plan. Subsequently, all of the participants communicated with 4D virtual scenes and optimised the preliminary plan. Finally, a reasonable construction schedule, including a list of 67 tasks, of the check-in zone was reviewed and accomplished through the circulation of 4D simulation and analysis, problem identification and schedule optimisation.

6.2.2.2. Schedule analysis. However, parallel construction processes in such a 'reasonable' construction schedule continue to transpire because large MEP projects usually involve many workers working in the same area. Conflicts usually ensue when task orders are improperly scheduled. Therefore, the visualised simulation of task orders was carried out for checking construction conflicts to ensure the involvement of sub-contractors in the discussion of scheduling works in the succeeding few days, even after some tasks were delayed for any reason. Beyond the visualised simulation, analysis and reports for predecessors of tasks were exported every day for daily meetings among the participants given that the MEP information model contained the pre-task requirements, as well as the planned and actual schedules. The constructors subsequently identified the potential challenges in the actual construction and attached notes and preparative solutions to each challenge in the corresponding elements. This approach helped the manager in avoiding labour-hour loss caused by insufficient communication and the lack of assurance of pre-task completion among different works performed by various sub-contractors. In actual practice, the constructors attempted to address these challenges. A final 4D simulation was drawn up after conducting substantial works on analysing the processes of the check-in zone among the constructors. As shown in Fig. 8, six different colours were used to distinguish the components being installed by various constructors to allow managers to easily grasp the parallel constructions. The notes for potential challenges also emerged in time to remind the managers.

6.2.2.3. Schedule reference for repetitive objects. Some repetitive clustered areas constantly require construction. Once all of the participants have certified the successful collaborative schedule of one clustered area by examining it in practice, such schedule can be duplicated to other unfinished areas or areas that have yet to be started after re-scheduling the start time with logic relationships, thus providing the least possible construction conflicts. Considering the similarity of the eight check-in zones in the terminal, the micro-scale 4D information model with the optimized final schedule was used for the CM of all of the zones. Construction progress analysis, resource requirement analysis and other functions were also applied to assist the actual CM, aside from construction simulation. With these functions, the practise showed that the construction duration of a check-in zone was reduced from about 40–50 days to normally 30 days and the construction duration of integrated boxes of MEP elements was reduced by 6 days each.

6.3. FM for the MEP project utilising the multi-scale BIM

When the MEP project was completed, the general contractor delivered not only the real MEP components but also the as-built MEP information model to the owner of the airport. The BIM consultant group firstly simplified the as-built BIM and converted it to an FM-oriented multi-scale BIM. Specifically, the BIM to GIS data conversion algorithm [63] was applied to generate the macro-scale FM BIM including basic map, room layout and MEP elements by importing the required information, followed by generating the indoor path. At the same time, in order to enhance the micro-scale FM BIM, the BIM consultant established the logic chains among the elements in most sub MEP systems and the FM managers identified the assets and their performance requirements. Then, the relationship between the macro- and the micro-scale FM models was established. During the FM process, the inspection information of MEP equipment and assets was appended to the corresponding objects. The multi-scale FM models have significantly reduced the modelling efforts of MEP elements. The BIM-FIM_MEP has been running on personal computers until now. The applications of the main functions are described as follows.

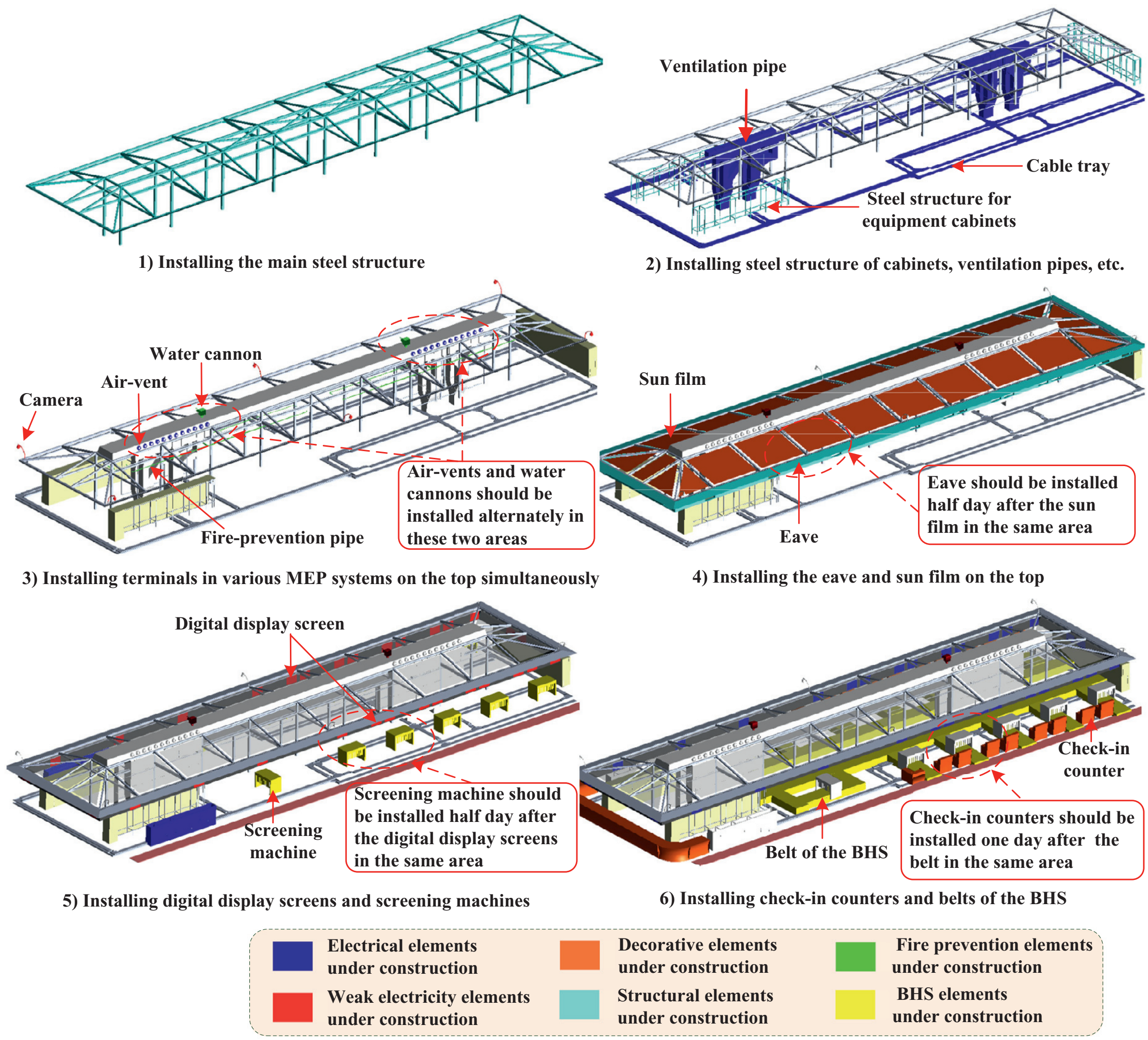

Fig. 8. Micro-scale 4D construction simulation of a check-in zone.

6.3.1. Application of the macro-scale FM model

6.3.1.1. Query and visualisation of the layout and structures of MEP systems. When a manager selected an MEP element in GIS view, the BIM-FIM_MEP would query its upstream and downstream equipment and routes of wires or pipes and favourably visualise them according to the embedded logic chains. Fig. 9a) shows the layout and structure of switching station `KB1` of the power system, and Fig. 9b) demonstrates the layout of the lighting system in room `F1C0380`. These certain layouts and structures have helped maintainers formulate repair programmes. At one point, when a maintainer was replacing a lamp in room `F1C0380`, he could determine that the `TC2F J2-AAL-10X` switch must be turned off beforehand according to the logic structure queried through the BIM-FIM_MEP. The feedback from the facility personnel shows that this function is valuable in large MEP projects to ensure the safety and reduce the operation time.

6.3.1.2. Inspection path planning. Based on the generated indoor path, the macro-scale FM model was utilised to query and visualise the layout and logic structures of MEP systems and to plan inspection paths. The principles for the indoor path generation method are described as follows. (1) The algorithm only handled paths connecting rooms and did not take interior paths in general rooms, except for halls. (2) Rooms were connected through corridors, stairs, elevators and halls. (3) Rooms were divided into main rooms and sub-rooms; the main room connected with halls or corridors, whereas the sub-rooms only connected with another room. Considering that indoor paths in the terminal were complicated with strict access limits, the maintenance staff applied the BIM-FIM_MEP to identify the most practical and the shortest paths to execute their daily equipment inspection. Fig. 9c) illustrates an inspection path in B3 floor, represented by red lines, which passed through three inspection points and proceeded to other floors via an elevator.

6.3.1.3. Intelligent control of MEP systems for energy conservation. The generated paths were related to corresponding space objects; hence, MEP equipment was intelligently managed based on dynamic pedestrian flow in indoor paths by combining the relationships among paths, space objects and MEP equipment. For example, when a few pedestrians traversed a path for a long period, the lighting and other equipment along the path were turned down to save energy and turned up automatically as pedestrian density increased. As illustrated in Fig. 10, only the red-mark path was em-

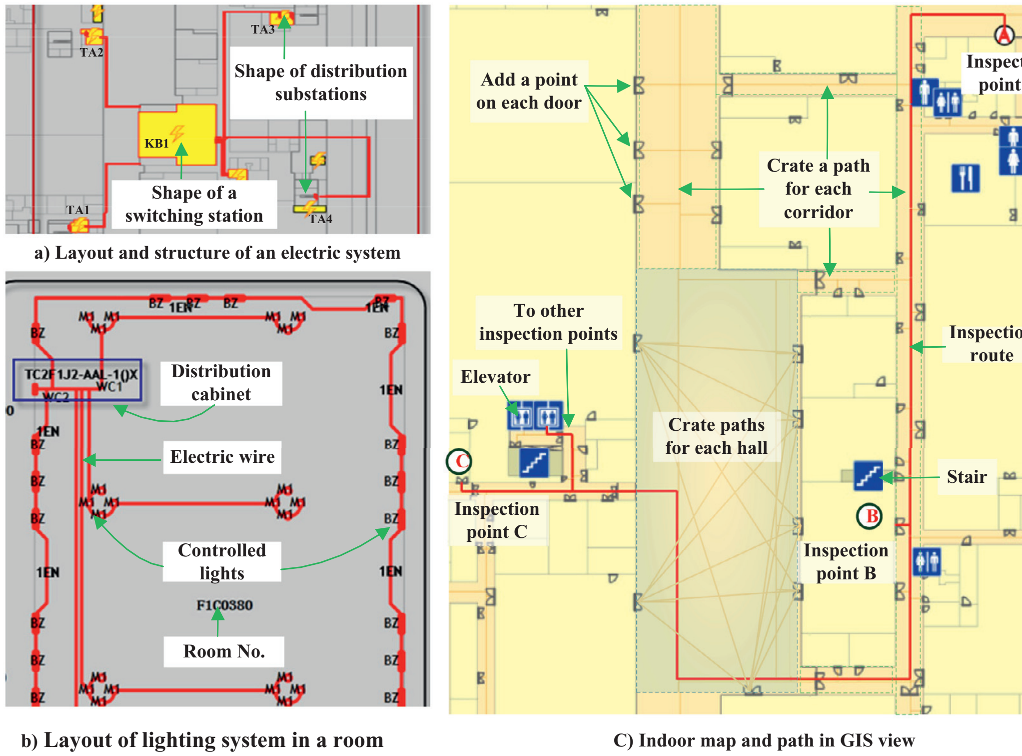

Fig. 9. Visualisation of room, indoor path, MEP system layout and structure in GIS.

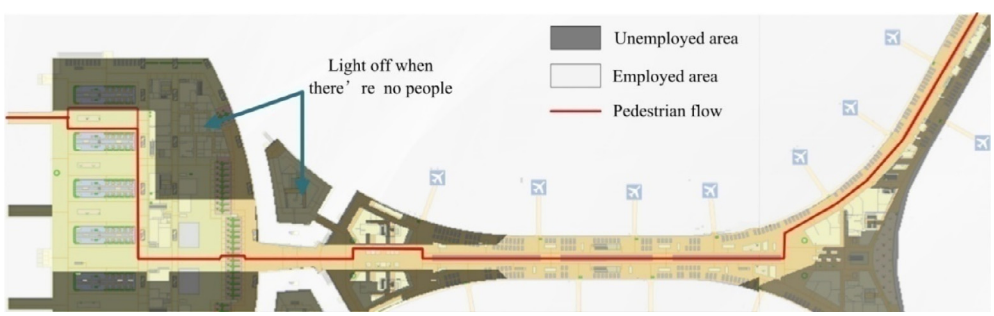

Fig. 10. Intelligent control of MEP system with pedestrian flow of indoor path.

ployed between 1:00 a.m. and 1:50 a.m. according to the flight information. Therefore, MEP equipment, such as lights, air conditioning and hot water supply in other unemployed corridors and halls, was rejected. In this manner, considerable energy and cost were saved by intelligently controlling the MEP elements during the FM of the terminal with the aid of the BIM-FIM_MEP.

6.3.2. Application of the micro-scale FM model

6.3.2.1. Regular maintenance works for MEP elements. The micro-scale FM model with everyday maintenance plans and logs assisted facility personnel in enhancing maintenance efficiency and interoperability among facility managers, workers and warehouse managers by providing maintenance-related statistics and information on back-ups, etc. Therefore, the BIM-FIM_MEP reminded facility personnel about the location and procedure to run routine maintenance according to the prescribed maintenance plan assigned by the facility manager. It simultaneously aided the repair workers by providing knowledge support. The use of a portable terminal or a mobile phone allowed the facility personnel to access and read the necessary maintenance knowledge and procedure before working on the assets and to quickly update the maintenance record after the work was concluded. The need for updated inventory information emerged after the workers' completion of a repair work, thereby prompting the warehouse manager to place an order.

6.3.2.2. Running condition analysis and emergency management. With the help of the micro-scale FM model, the BIM-FIM_MEP dynamically analysed the running condition of assets by comparing the inspection and required values of performance parameters. The inspection and repair data were also added to the MEP information model, and these data would be useful for analysing the performance of assets and helping managers in emergency. In case of a broken and leaking pipe, for example, the manager could identify the upstream element of the pipe (e.g. a valve) and locate it in 3D view or 2D planar view (see Fig. 11) so he/she could turn it off as soon as possible for emergency. This particular innovation also substantially aided in determining the potential problems of MEP assets.

6.4. Discussion

This study aimed to propose an approach to facilitate the CM and FM of large MEP projects with BIM technology. Therefore, in this application validation, the multi-scale BIM was gradually es-

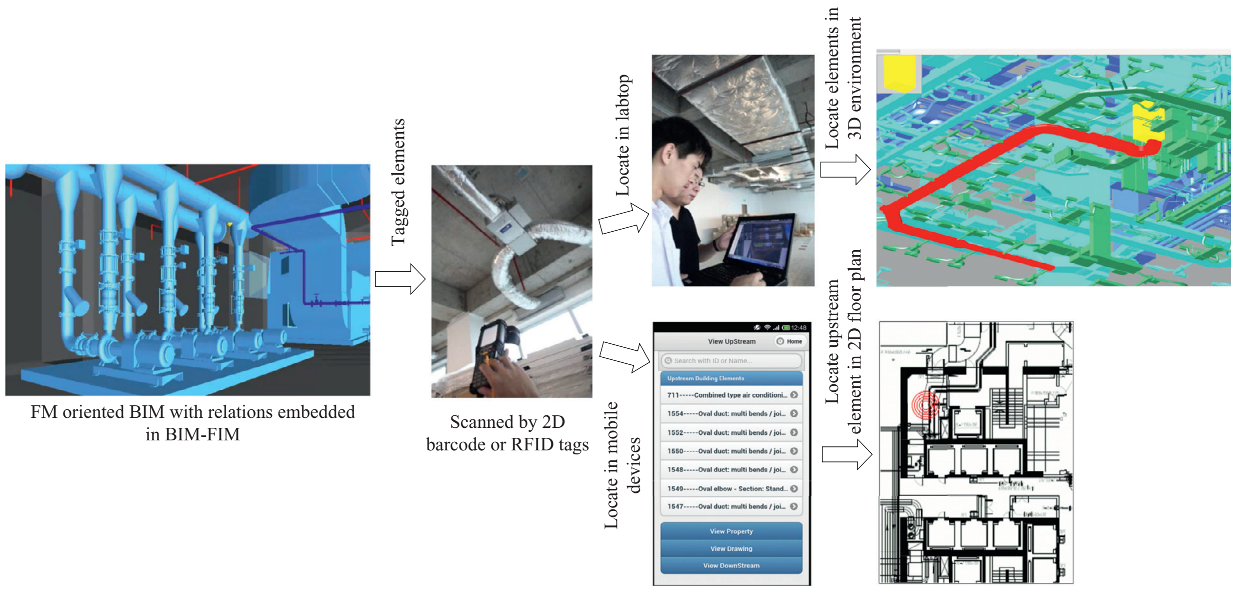

Fig. 11. Positioning of upstream elements during emergency circumstances.

tablished during the construction, and operation and maintenance periods. Based on this BIM, the general contractor implemented the multi-scale CM and then delivered the multi-scale FM models to the operation office of Kunming Changshui International Airport. The latter participant took advantage of the information shared by the construction period to improve FM activities. Both participants appraised the idea of the multi-scale BIM and the corresponding management systems.

In particular, the general contractor managers were enthusiastic about two improvements. Firstly, the idea of multi-scale BIM facilitated the smooth performance of 4D simulations because the number of surfaces in any CM model was reduced to no more than 2 million, less than 5% of which were in the entire design model. Secondly, these models improved the schedule management. At the beginning of the project, due to the tight schedule and a vast number of schedule conflicts among over 10 sub-contractors, daily meetings from 9:00 p.m. to no earlier than 11:00 p.m. were obligatory tasks, with no rest days even on weekends. Schedule conflicts were irreversible because no one could investigate the potential problems in the pre-arranged schedule. Combined with multi-scale CM models, the 4D-BIM_MEP supported collaborative 4D schedule and resource management. For example, the 4D-BIM_MEP supported a manager in querying all of the predecessors of a task, which he/she would carry out shortly, and in analysing whether or not the task could start on time according to the status of all of its predecessors. If some predecessors could not be completed on time, alerts ensued and the manager would communicate with the predecessors' owners and formulate a new plan together to minimize the negative effects. In this manner, the communication process was significantly reduced to roughly one hour every two days, and approximately 85% of conflicts were avoided. The situation for the other similar construction parts was also improved, such as check-in zones and integrated boxes. Moreover, the macro- and schematic-scale models helped the contractors in grasping the general schedule information to determine the most urgent tasks in the subsequent few days. The general contractor claimed that the multi-scale solution and corresponding CM system saved about 2 millions in cost.

Information integration, visualisation and interoperability were three of the most valuable points that BIM brought to the operation office of the airport. The owners were satisfied with the rich information delivered by the general contractor, including the construction details, specifications, operation handbook, vendors, and particularly the logic chains of facilities and assets. Another key point was that both the BIM and GIS views provided visualised and convenient management tools for the facility personnel. Particularly, the GIS map was automatically generated according to the as-built multi-scale CM models, with paths and logic relationships, establishing a close linkage between BIM and GIS technologies. All of the elements within the GIS environment were connected to the BIM repository. Therefore, during the daily operation and maintenance activities, the facility personnel could easily search related information or files and upstream or downstream elements, and interoperate with other participants by selecting an asset in either GIS or BIM platforms or by scanning the 2D barcode attached to the asset. The system also provided quantitative energy-saving measures for managers, reducing approximately 3600 kW-h of electricity, which is equivalent to 2826 kg of CO_2 every year. The owner claims that the efficiency of maintenance and repair works is improved by about 30% roughly than before.

However, a few concerns also emerged when using these new methods and tools. Firstly, the usage of the novel methods required substantial efforts for the general contractor to establish the multi-scale BIM with the majority of the information during construction. In this project, aside from the complete architectural and structural models, 6 micro-scale models of all disciplines and 3 macro- and 2 schematic-scale models of particular MEP systems (i.e., drainage system and electric system) were established by five modellers in four months' time. The contractors also spent another month to link all of the related information and files to the building elements. Moreover, during the entire construction period, the BIM engineers were tracking the project information to maintain the models. Nevertheless, such a difficulty in large information entry can still be improved in the future. For instance, the modelling efforts are expected to be reduced by sharing models created by the designers during the design phase. In this event, the general contractor is only required to extend the construction information and some other necessary information for FM. Meanwhile, the automatic generation of logic chains through an analysis of the geometric and type information of MEP elements is time efficient and improves the quality of information.

The subsequent discussion focuses on refining the communication and management process. Most constructors made decisions based on their personal experience. When a task contained a huge number of activities and participants, only a few managers could solve the potential conflicts among them. In the adoption of the proposed models and systems, all of the participants were involved, communicating via a 3D visualised and analytical platform and making decisions together. However, some managers still intended to make arrangements by themselves, neither solely believing the data and the model nor adapting them to rely on computers. Moreover, instead of applying delicacy management, some sub-contractors insisted on extensive management, which imposed fewer restrictions on them. Nevertheless, as the project was progressing, significantly more conflicts were observed. However, the proposed approach and tools successfully solved some problems and were gradually accepted by all of the participants. The participants believed that the new approach helped in improving the construction process. During operation and maintenance period, facility personnel were familiar with 2D planar platforms (e.g., GIS) and at first declined to adopt BIM tools. Therefore, in this project, the macro-scale FM BIM was presented in GIS map forms to facilitate some ordinary management tasks. Instead, the micro-scale FM BIM focused on refinement of information. These multi-scale FM models provided a strong functional complementarity. Similar to other novel tools, the popularity of BIM technology is a gradual process.

The third discussion is on the applying of the BIM data. Though the multi-scale solution reduced the volume of the BIM data, scaling was still a big-data challenge for massive data sets in the database. First of all, in this research, the GUID and space information were used to link different scaled models while and pre-defined MVDs were responsible for extracting the appropriate model from the multi-scale BIM. On the other hand, the users of these two systems focused on the functions while the programmers of the systems should understand all the data, as well as the relations within the data. Besides a possible architecture proposed in Section 5, some data mining algorithms encapsulated in the dynamic link library (DLL) were the essential parts of the solution; otherwise, it was impossible for programmers to handle the multi-scale BIM. Beyond the data structure, relation finding and constraint transforming for data retrieval [64], some data analysis algorithms including cluster analysis, outlier detection and frequent pattern mining were embedded in the DLL.

Finally, the functionality of the newly introduced systems was insufficient for both CM and FM, particularly for the latter. The two systems were developed based on our previous platforms that were successfully applied to more than 10 projects. However, due to the tight schedule, the research and development duration was reduced to only six months. Completing such a task was impossible without a significant amount of accumulated experiences and skills. Hence, schedule management during construction must be facilitated, and the information delivered to operation and maintenance period must be validated. Collision detection, cost estimation, site layout management and other traditional BIM functions were ignored in this application. Some normal FM requirements, such as monitoring and automatic control, were implemented by existing commercial systems. The users responded, ‘Genuinely solving a problem is more meaningful than trying to solve all the problems’. Accordingly, this research achieved its objective. The operation office of Kunming Changshui International Airport has commenced on a new project to further explore and develop the BIM-FIM_MEP.

7. Conclusions and future works

A multi-scale BIM was proposed to address the insufficiencies of the current BIM-based CM and FM of large-scale MEP projects. Verified by actual application to a large and real-world terminal project, the following conclusions were drawn:

(1) The multi-scale BIM consists of several different scaled information models. The contents that should be modelled in each single model rely on the purpose of this model and the potential functionalities in aiding CM and FM. All these models are closely linked to each other and the combination of these models are free to the requirements of CM and FM. Particularly, a practical multi-scale BIM consisting of several macro-, micro- and schematic-scale information models is described in detail with the required information of the MEP components according to the schema of industrial foundation classes.

(2) The multi-scale BIM and the 4D-BIM_MEP provide different-scale views for different managerial roles to achieve the objective of cooperative CM with various constructors. Specifically, the micro- and schematic-scale 4D views assist senior managers in managing the overall construction progress. The micro-scale 4D views aid engineers and managers of different disciplines in cooperatively communicating, planning and managing the actual on-site construction. Furthermore, the multi-scale CM reduces the requirement of the geometric model. Accordingly, the modelling effort is reduced, and the efficiency of 3D visualisation is improved.

(3) By converting BIM to GIS data and by employing BIM repository as an attribute database, the multi-scale BIM shares rich information during the design, construction, and operation and maintenance phases, and the layout of MEP systems in GIS is visualised to serve FM. In this manner, both the low efficiency of 3D in rendering numerous elements and the ineffective visualisation of complex structures of MEP systems are addressed. Moreover, the multi-scale BIM and the BIM-FIM_MEP support the rapid query of MEP information, inspection path planning, intelligent control of MEP equipment, emergency management and energy-saving strategy.

In the near future, the newly released versions of IFC must be considered to validate the proposed multi-scale BIM in more practical projects. Refining the storage of BIM information by adopting cloud computing and virtual integration method is the next focal point of this research. Such an undertaking also demonstrates a significant potential for integrating the monitoring and automatic control systems into a single operation and maintenance platform. Some ways should be found to automatically and intelligently create different scaled models for particular participants rather than pre-defined scales. Based on the experiences gained from this application, more functions can be developed for both CM and FM.

Acknowledgements

This research was supported by the National High-tech Research and Development Program of China (No.2013AA041307), the National Natural Science Foundation of China (No.51478249 and No.51278274), the Science and Technology Project of Beijing (No. Z151100002115054), and the Tsinghua University-Glodon Joint Research Centre for Building Information Model (RCBIM).

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Glossary

4*D*: four dimensional
4*D-GCPSU*: an existing BIM-based construction management system developed by the authors
4*D-BIM_MEP*: a BIM-based construction management system developed for the Kunming Changshui International Airport project with the proposed model and methods based on 4D-GCPSU
BIM : building information modelling/model
BIM-FIM : an existing BIM-based intelligent facility management system developed by the authors
BIM-FIM_MEP : a BIM-based facility management system developed for the Kunming Changshui International Airport project with the proposed model and methods based on BIM-FIM
IDM : Information delivery manual proposed by BuildingSMART
IFC : industrial foundation classes proposed by BuildingSMART
IFC 2*x*4: the latest released schema for IFC
GIS : geographic information system
MVD : model view definition proposed by BuildingSMART
CM : construction management
FM : facility management
MEP : mechanical, electrical and plumbing