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Research paper

BIM-based integrated delivery technologies for intelligent MEP management in the operation and maintenance phase

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ABSTRACT

Incomplete building information in delivery and the lack of compatible tools for Operation and Maintenance (O&M) have hindered the development of the intelligent management of Mechanical, Electrical and Plumbing (MEP) systems. In fact, the information related to the O&M management of the MEP system conventionally comes from the completion documents in the forms of hard copies or unstructured digital files, making it hard to search for useful information in the “sea” of documents and drawings. Therefore, digitalization of information is an urgent task to facilitate the intelligent management of the MEP system. As a project deliverable, the as-built information model shall not only contain geometrical information and necessary construction-related data, but also built-in information useful for the intelligent O&M management. In the present study, based on the Building Information Modeling/Model (BIM) technology, a set of solutions including the automatic establishment of the logic chain for MEP systems, an equipment grouping and labeling scheme and an algorithm to transform BIM information to GIS map model, is proposed to digitalize and integrate the MEP-related information into the as-built model. Subsequently, a cross-platform O&M management system is developed using the MEP-related information in the as-built model to run routine O&M tasks and to effectively response to MEP-related emergencies. The developed system is applied to aid the O&M management of MEP engineering in a real project, showing that the developed system facilitates the intelligent O&M management and guarantees the security of the MEP system and its subsystems.

1. Introduction

In buildings, the Mechanical, Electrical and Plumbing (MEP) system provides services to people’s daily needs, and hence plays a critical role in creating a comfortable and safe environment for building occupants. MEP engineering is a general term referring to the management of non-structural functions of a building. It consists of management of plumbing, Heating, Ventilation and Air-Conditioning (HVAC), electricity, energy conservation and elevator maintenance, etc. In fact, MEP engineering concerns the lifecycle of any MEP subsystem, including the design, construction, operation and maintenance (O&M) of the MEP system and its subsystems.

The O&M phase takes most of the time, resulting in the highest cost among various phases within the lifecycle of a building. In fact, previous studies [1] indicated that, the cost associated with the O&M could take up to 60% of the total project cost. In addition, it is shown in a National Institute of Standards and Technology (NIST) report [2] that American building industry wastes around 15.8 billion USD every year, and approximately 10.6 billion USD of the waste occurs in the O&M phase. As a main target of the O&M management, improving the efficiency of the MEP system is critical for the success of a construction project. In fact, the cost associated with the MEP engineering can be up to 50% of the total investment in some large-sized public projects [3]. The popular O&M management software, however, usually comprises only modules pertaining to financial management, data management, customer service, warehouse management, engineering equipment, office management, and procurement management, lacking a dedicated component focusing on the MEP system. Such a deficiency pronounces when an emergency occurred in the MEP system, the useful information about a specific equipment can only be found manually from the bulk of the project completion documents (in the form of either electronic files or hardcopy documents). The low

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efficiency of manual search may lead tremendous losses of properties and even life causalities in the worst case.

One of the reasons lying behind the low level of intelligence in managing the MEP system in the O&M phase is that the MEP management does not fully utilize new techniques emerged along with the development of information technology, such as the Building Information Modeling/Model (BIM) technology. For example, incomplete building information in delivery and the lack of tools dedicated to the O&M management of MEP engineering are the two reasons explaining the delay in the development of the intelligent O&M management of MEP engineering. Consequently, the digitalization of the MEP-related information and the development of an intelligent system to manage the MEP system in the O&M phase are not only the direction to improve the O&M management but also an important task in the lifecycle management of a building.

Significant progresses have been made regarding the BIM technology in the past decade. As a trend, BIM has gain common acceptance in the community. The reason why BIM has grown so quickly is that it benefits participants in the lifecycle of a building, i.e. in the processes of planning [4], design [5,6], construction [7,8] and O&M [9–11]. The BIM technology, when applying to integrate MEP-related information in the delivery and to aid the management, is a viable way to improve the intelligence level of the O&M management. However, the delivered as-built model always tends to be difficult for O&M personnel to directly utilize because it lacks some key MEP-related information, such as the logical relationships among MEP components. To provide better support in the creation and delivery of the as-built model with these key information, the paper proposes a set of solutions including an approach to automatically build the logic chain, a mechanism of identifying and grouping equipment, and an algorithm to generate the GIS map based on the building information available during delivery.

The rest of the paper is organized as follows. A literature review concerning both the BIM technology and the O&M management of the MEP system is presented in Section 2. Afterwards, three key techniques for applying the BIM technology to integrate the MEP-related information into the as-built model for delivery are discussed thoroughly in Section 3. Then, a set of solutions to implement an intelligent O&M management system, which is based on the web-service technique to achieve platform-independency, is suggested in Section 4. In Section 5, a description of the developed BIM-based intelligent facility management system (BIM-FIM) and its application to the real project is presented. Conclusion remarks are presented in Section 6.

2. Literature review

Recently, the BIM technology keeps its pace going forwards in the aspects of standards, tools and applications. The studies concerning the application of the BIM technology in the O&M management, on the other hand, are still relatively rare [12]. The related literatures are reviewed from two aspects: BIM applications in the O&M management and particularly in the management of the MEP system.

2.1. Applications of BIM in O&M management

A surveying of 125 facility managers shows that the majority of them considered that the application of the BIM technology would reduce the information search time, and three-dimensional (3D) visualizations are useful in the property management [13]. Unclear adaption procedures and large investments, on the other hand, are the concerns preventing the widespread of the BIM technology in the O&M management. For instance, although transmitting MEP-related information created in the design and construction phase into the O&M phase would ultimately improve the management efficiency, it certainly changes the conventional procedures to apply the BIM technology in building management due to the additional MEP-related information. To this end, scholars have shown their concerns in the integration of additional information in the as-built model for the use in the O&M phase. For example, Yu et al. [14] created a set of facilities management classes, which was essentially an embryonic formation of information description standards for the O&M management. Hassanain et al. [15] extended the Industry Foundation Classes (IFC) to enable relevant information, such as requirements for specific equipment to properly function, running status of an MEP subsystem and inspection routines of air ventilation tunnels, be integrated into the IFC. El-Ammari [16] studied the IFC-based property management model, which was built through sharing the design and construction information generated based on the IFC standard via the eXtensible Markup Language (XML) within the O&M management. Wang et al. [17] created the IFC-based building property management information model via combining equipment monitoring information with property management system using middleware technology. In addition, the National Institute of Building Science (NIBS) of United States instituted Construction Operation Building Information Exchange (COBie) [18], which standardizes the final information that created in design and construction phase to be transmit to the O&M phase.

Besides inheriting the information created in the design and construction phase, the information pertaining exclusively to the O&M phase, such as the repair, maintenance and running status information of particular equipment, should also be integrated in the BIM for the O&M management. In this field, Liu et al. [19] proposed an approach using SensorML standards to describe characteristics of sensors. In addition, IFC standards were employed to describe physical information of sensors. The standardized information can then be used to support decision-making for facility managers. Supplementing to the IFC standards, Lucas et al. [20] explored an object-oriented O&M management model and looked into the data structure needed in the O&M management process. In addition, Motawa et al. [21] developed a Revit-based BIM knowledge system, acquiring the operation information at the decoration and fit-out phases to facilitate the O&M management. Orr et al. [22] developed an intelligent property management system. Lin et al. [23] devised an indoor path planning method, which used the IFC data as inputs to provide geometrical and non-geometrical expanded semantic information, supporting the indoor path planning. Kang and Choi [24] developed a database based on the BIM metadata to connect external facility management (FM) with the BIM data by analyzing the practice of FM. Kang et al. [25] proposed a software architecture for the effective integration of BIM into a geographic information system (GIS) -based FM system.

Open BIM standards and data specifications such as IFC and COBie have been accepted as data sources and information exchange formats by several countries and organizations in the project delivery and the O&M phases [26,27]. According to the roadmap proposed by the BIM Task Group [28] for the implementation of BIM in the UK [29], fully collaborative BIM Level 2 (with all project information, documentation, and data in an electronic format) has been basically achieved for all public projects [30]. Particularly, COBie was adopted as information exchange schema by the UK Government for BIM Level 2 [31–33]. In the USA, COBie was also selected to be an important element in the National BIM Standard (NBIMS) [34,35]. ISO, on the other hand, proposed the standard ISO 15686-4 for service life planning information using the IFC4 standard and the COBie data specification [30,36]. Some researches and case studies were conducted to assess these standards and data specifications. Patacas et al. [30] performed the use cases for testing IFC and COBie in asset creation and service life planning applications and proposed workflows for embedding and extracting client maintenance requirements into and from BIM. Gu et al. [37] by detailed case studies of two old academic buildings, proposed the approach to generate the accurate and semantically-rich as-is BIM from existing information sources, which were compared to IFC and COBie. Lavy et al. [38] investigated the use of BIM and COBie for FM on three projects where the implementation concepts were tested. The results were qualitatively analyzed to demonstrate the application of these concepts and to identify the problems encountered.

2.2. Applications of BIM for MEP engineering

Applying the BIM technology in the management of the MEP system engineering is essentially an optimization process concerning the design, manufacturing, construction and O&M of the MEP system and its subsystems. The application procedures are normally as follows, (1) establishing an information model targeting the integration of the MEP-related information, which includes both geometrical information and component attributes (material, cross-section area, location, etc.) [6], (2) using the established model or other Computer Aided Engineering (CAE) software to analyze the specific condition of the MEP system and its subsystem and (3) employing the analysis results and the data contained in the model to support decision-making for the property managers.

In the design phase, the BIM technology can be used to facilitate the co-design practice [3,5] and to optimize the blueprint by automatic fine-tuning [6]. Korman et al. [5] employed a knowledge-based MEP information model to develop a collaborative design platform, which runs automatic analyses to improve the collaborative design. Leite et al. [39] adopted Navisworks for automatic collision detection in the design of MEP systems. Riley et al. [40] investigated main impact factors on the cost associated with the co-design practice of the MEP system to assist project managers in analyzing the cost-effectiveness ratio. Tabesh et al. [41] instituted a collision test for co-design of the MEP system by categorizing knowledge in three groups: knowledge field, knowledge content, and collaboration demand. Khanzode et al. [3] applied BIM/VDC (Virtual Design and Construction) to install MEP components in a collaborative way. Xie et al. [6] carried out analysis on energy consumption of the MEP system in a medical building for design optimization of the MEP system.

In the construction phase, the BIM technology is mainly applied to run collision tests [3], to monitor component prefabrication and manufacturing [42], to facilitate collaborations in the detail design [43], to supervise pipe prefabrications [42], and to manage site transportations [41] etc. It is found that, a detailed and accurate MEP-related information model established in design and construction preparation phases could be directly applied to pipe prefabrication, manufacturing and procurement, and to facilitate modularized construction [42]. On the other hand, by integrating scan-to-BIM and scan-vs-BIM, Bosché et al. [44] presented an approach to automatically recognize and identify objects with circular cross-sections in 3D terrestrial laser scanning. Kalasapudi et al. [45] presented a relational-graph-based framework for automated spatial change analysis of MEP components and validated it in real building construction sites.

In most of these studies, establishing an MEP-related information model was the first step, so as to share the BIM created in the design and/or construction phases with the personnel participated in the O&M phase [16,46]. Then the model could be applied to the practical O&M management, such as performing routine maintenance of the MEP system and its subsystems by sorting out the priority of maintenance tasks [47], employing the 2D barcode to identify and locate specific equipment, and utilizing wireless sensor network to monitor thermal conditions [48].

2.3. Summary

There is already a considerable amount of studies concerning the use of information technology in the field of broadly defined MEP engineering, among which the BIM-based design system is in the mature state with many commercialized design software, such as Revit, MagiCAD, Navisworks and so on. In the construction phase, attempts have been made to apply the BIM technology to facilitate the construction work, but they are limited in the structural construction. In the O&M phase, focuses are mainly placed on the formulation of standards, and discussions are continued concerning the development direction. Thus, the application of the BIM technology in the O&M management is considered still in the premature state, meaning that there are still shortages in feasible software systems and management tools to assist the facility managers to run O&M tasks. Meanwhile, the premature state also implies that information contained in the building model is incomplete when delivering and further efforts are required to improve the as-built BIM delivered to the owners when the project is finished.

3. As-built information creation and delivery

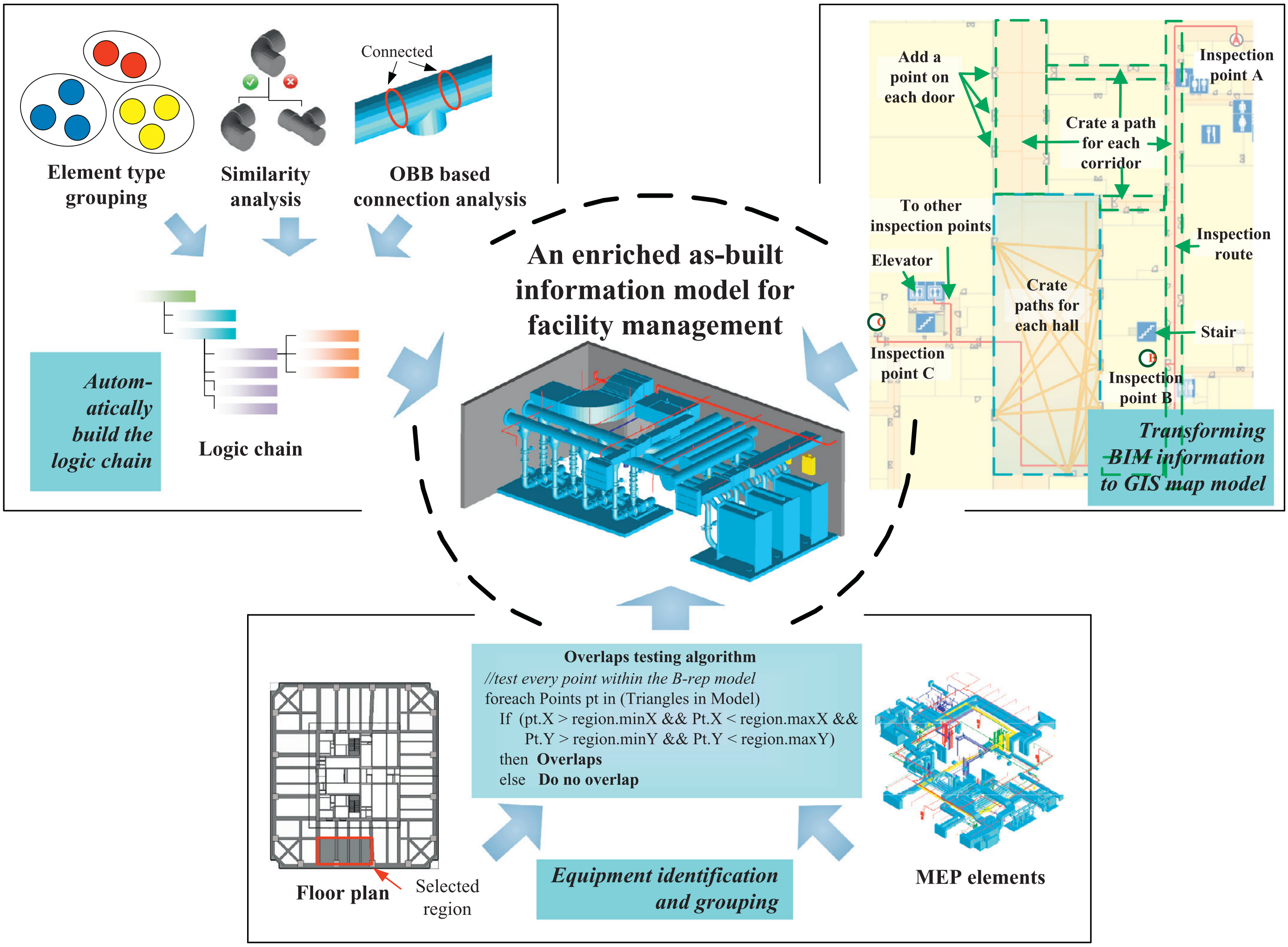
Besides accurate geometrical information and necessary construction information, it is crucial to institute FM-oriented information architecture before delivering the as-built model. Taking the pipeline work as an example, there are thousands of components logically linked with each other in a complex way. When a pipe is leaking out, the upstream valve should be shut down as soon as possible. Therefore, a clear picture showing logic chains linking proper building components should be generated and embedded in the as-built model, making it an information-enriched FM model for the O&M personnel to run routine maintenance and to quickly response to emergencies. Such logical relationships are, however, absent from the conventional BIM created in the construction phase. Meanwhile, the BIM should be able to transform into other forms when necessary. For example, the BIM is often required to be transformed into a GIS map of buildings to facilitate the O&M management [49].

In the light of providing better support in the creation and delivery of the as-built model with the additional MEP-related information, this Section (1) presents an approach to automatically establish the logic chain for a given MEP subsystem, (2) describes a component grouping scheme based on specific zones, such as in rooms, to form groups, and (3) presents an algorithm to automatically generate the GIS map based on the building information available during delivery. A sketch of the creation and delivery of the as-built model is shown in Fig. 1.

3.1. An approach to automatically build the logic chain

An MEP system consists of multiple independent sub-systems including HVAC, fire protection, electric and security, etc. In any system, countless components/pipelines form a logic web with intertwined relationships. For example, an HVAC system, as shown in Fig. 2, consists of a number of equipment with different functions. The logic chain corresponding to Fig. 2 is reported in Table 1.

As the base of the intelligent FM and the well-prepared emergency-response, the systematic logic chain of the MEP system should be built. The manual set-up of the logic chain is, however, a fallible task requiring tremendous workload. Based on the information on the component type, this study proposes an algorithm to



```
Overlaps testing algorithm
//test every point within the B-rep model
foreach Points pt in (Triangles in Model)
    If  (pt.X > region.minX && Pt.X < region.maxX &&
         Pt.Y > region.minY && Pt.Y < region.maxY)
    then  Overlaps
    else   Do no overlap
```

Fig. 1. Sketch of the as-built BIM generation and delivery method.

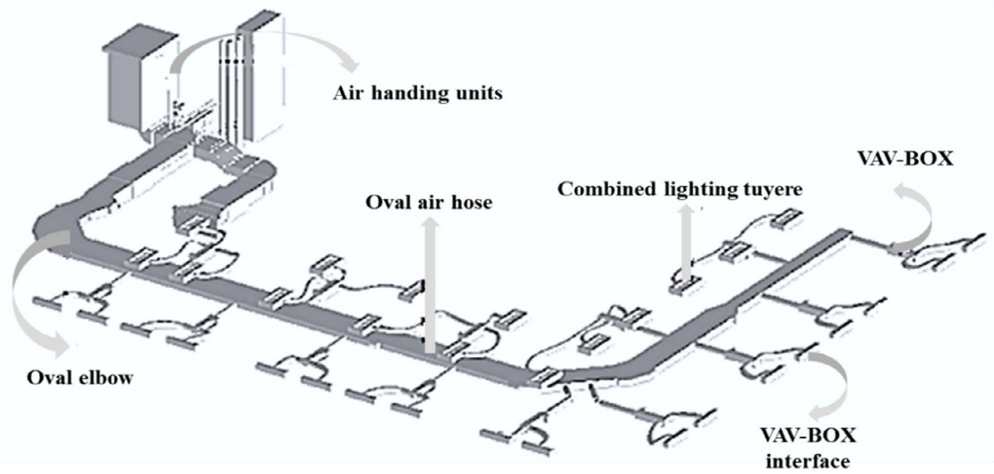
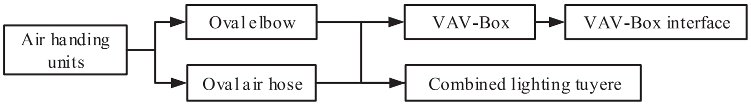
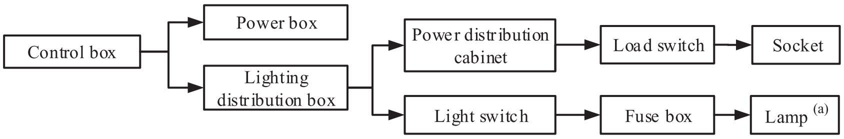
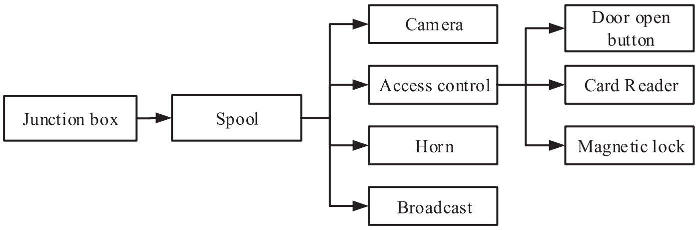
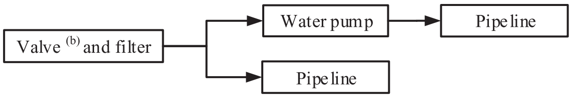
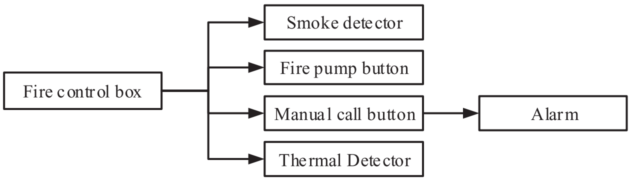
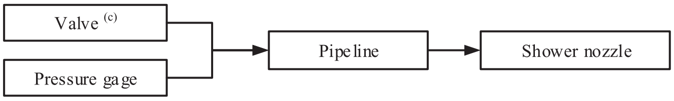


Fig. 2. A schematic diagram of the HVAC subsystem.

automatically setup the systematic logic chain via similarity analysis and continuity analysis. The algorithm reduces the workload for setting-up the logic chain. The general idea of the algorithm is that the two adjacent components will either be in the same logic layer, or the upstream or the downstream of each other, and this relationship can be further determined by a type logic tree structure of typical MEP systems. For example, when two pipelines are connected to each other, they can always be considered as in the same logic layer; while if a pipeline is adjacent to a valve, the valve can always be the upstream component and the pipeline the downstream one. The details of the proposed algorithm are itemized as follows,

Table 1
Type logic structures of element types within several typical MEP systems.

MEP system	Tree-structure of element type logic relationship
HVAC	
Electric	
Electronic	
Plumbing	
Anti-power	
Anti-water	

Note: (a) The lighting fixture include single-tube fluorescent lamp, double-tube fluorescentlamp, pilot lamp (left), pilot lamp (right), two-way pilot lamp, ring-type energy-efficient lamp,and aviation obstruction lamp; (b) valves including gate value, globe valve and check valve; (c) valves including butterfly valve, gate valve and globe valve.

(1) Within a single MEP subsystem, the type information of various components is extracted to form a type tree-structure indicating the logic relationships among components. The tree-structures of element types corresponding to several common MEP subsystems as shown in Table 1 are extracted from the knowledge accumulated along with field engineering practices, literatures and manuals of each MEP subsystem.

(2) For components of the same type, a geometrical similarity analysis is conducted to find components with similar geometries. The geometrically similar components are then assigned to the same logic layer for further subdivision.

(3) The Oriented Bounding Box (OBB[1]) algorithm, with the help of end-section analysis, is adopted to identify spatial connections of various components. For groups containing connected components, different parts of the connected component are either assigned to the same logic layer or automatically formulate the logic chain based on the component type or the subdivision of the component group.

Chan and Tan [50] proposed a method to generate a minimum OBB by projecting the 3D objects to its three principle planes. This method is suitable for discerning spatial connections in a MEP subsystem containing a large number of long pipes (either square-sectioned or round-sectioned). In order to picture spatial connections of components, the created OBB is used to run collision detection for any pair of components. If collision is not detected for a particular pair, there is no chance these two components are spatially connected. If a collision is detected, on the other hand, an end-section analysis is conducted to verify if these two components are spatially connected. In detail, the end-section analysis is conducted in two steps by extracting the end sections of components to detect if a face of one component is collocated with any face of the other component. (1) Because a B-rep 3D model externally profiling the component contains all edge-sharing triangles (any two triangles share one edge), the angles between the normal vectors of any two triangles can be checked to find the edge of the end section. Specifically, when the angle is larger than a critical value (60° for example), one of the two triangles is determined to be parallel to the end section, and put into the candidate database. After the examination of the angles between normal vectors, all the triangles in the candidate database parallel to the same plane are selected to form the possible end-section. (2) All triangles constituting a possible end-section should go through a continuity check. Specifically, if all points share a same plane, the

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[1] In geometry, the minimum or smallest Bounding Box (BB) for a point set (S) in N dimensions is the box with the smallest measure (area, volume, or hypervolume in higher dimensions) within which all the points lie. In the case where an object has its own local coordinate system, it can be useful to store a bounding box relative to these axes, which requires no transformation as the object's own transformation changes and this is named as Oriented Bounding Box (OBB).

possible end-section is determined to be continuous and the two components are recognized as spatially connected.

3.2. Mechanism of the equipment identification and grouping

After creating the logic chain of the MEP subsystems, the logic chain, together with the basic information, of equipment can be recorded in the RFID[2] tags or 2D barcode (i.e., QR code[3]), which enables the quick assess of useful information in the O&M phase.

It is noticed that different MEP subsystems are intricately located in a building layer. Some of the MEP subsystems (such as ventilation tubes) are even hided above the ceiling. Therefore, it is impossible, and also unnecessary, to label every single piece of equipment. For the sake of convenience, the equipment is grouped according to the location, and the label is attached to identify a specific group. For example, pieces of equipment stored within a single room are grouped together. Then, the most important information is of all components (i.e., global IDs of every components) in the group is coded into a QR code or a RFID tag. The grouping scheme can be detailed as follows.

(1) The boundaries of different zones, such as rooms, hallways, stair channels etc., in a single building layer are automatically calculated. It should be noted that the mechanical room is usually a space where a large number of the MEP subsystems are stored. If all the MEP subsystems in a mechanical room are labeled in one group, the label may contain too much information, which makes it difficult for users to search for useful data. Consequently, the important equipment (i.e., cabinets and distribution boxes, etc.) stored in a mechanical room is labeled individually while other less important MEP components (i.e., pipelines and elbows, etc.) are labeled on group basis.
(2) The building floor information contained in the BIM is then extracted. All pieces of equipment belonging to the same floor are projected onto a 2D plane, and a 2D overlapping test (as shown in the bottom of Fig. 1) is conducted to examine the relationship between the 2D projection of particular equipment and the zone boundaries found in step (1). If the overlapping is detected, the particular equipment is put into the corresponding group.
(3) Through code generation algorithm, the information is coded into a QR code or a RFID tag.

3.3. Transforming BIM information to GIS map model

Unlike the BIM, the GIS technology relies primarily on the spatial or geographic data, as well as the topologies of points, lines and areas to express spatial relationship between different parts. Usually, a GIS system presents information without 3D rendering, and hence is suitable for Personal Digital Aids (PDAs), smart phones, tablets and devices without powerful graphic hardware to show the room, indoor path and logic connections among MEP subsystems. In this study, a BIM-based algorithm reads the information on the room, path, hallways, doors and elevators stored in the BIM database via web-service (a technique to exchange information stored in platforms with different structure via internet/intranet to support interoperable machine-to-machine interaction over a network) to generate the GIS-based topographic map as well as the indoor patrol path. Such a map provides the data for patrol path planning. This algorithm consists of two main parts: (a) the automatic generation of nodes and paths and (b) the calculation of weight values assigned to different paths.

The nodes and paths are generated as follows,

(1) Extracting the spatial information on rooms, halls and hallways, the geometric information on doors, stairs and other building components, and the access-authority information on doors from the BIM.
(2) Drawing a polygon-shaped path along the hall boundary, denoting every door on the path as nodes and connecting nodes to form paths.
(3) Generating two nodes at the ends of the hallway and connecting the nodes to formulate the hallway path.
(4) Connecting the hallway end node to the nearest node in the hall if the hallway is connected to the hall.
(5) Generating nodes at every room doors and connecting the door node to the node belonging to either the hall or the hallway.
(6) Generating nodes at every stair entry/exist or the elevator to formulate connections between two layers.

The values of indoor path weights are assigned to simulate the actual pedestrian circumstance, which takes both the path length and marching speed into consideration. In fact, the weight value is calculated as,

$$\omega = \begin{cases} \dfrac{\text{legnth}}{k_1}, & \text{Horizontal path} \\ \dfrac{\text{legnth}}{k_2}, & \text{Horizontal path} \\ \dfrac{\text{legnth}}{k_3} + c, & \text{Elevator path} \end{cases} \tag{1}$$

where, k_1, k_2 and k_3 represent for the marching speed in a single floor, by stair path, and by elevator, respectively. And c is a constant for the elevator acceleration, deceleration and waiting time.

4. Operation management based on web-service and heterogeneous platform

The O&M management of the MEP system includes asset management, maintenance management, running status monitoring, patrol inspection and emergency-response management, etc. To facilitate rapid field enquiry, mobile devices are frequently employed to identify a specific MEP component. It is apparent that the use of mobile devices helps quickly access the relevant information regarding a specific MEP component, which includes its position in the logic chain, detailed component information, blueprint of the equipment, maintenance-related information etc. Mobile devices include portable terminals (PDAs, smart phones and tablets) and laptops. On one hand, the portable terminal is lightweight, small-sized and easy to move, but the small screen and less efficient performance limit 3D rendering. On the other hand, the laptop is large-sized and relatively difficult to perform in narrow and high spaces, but its high performance allows efficient 3D viewing and interaction with the BIM. In the present study, the web-service technique is employed to “expose” all the data and functions to the two heterogeneous platforms to make the data integration and task cooperation feasible. Under such conditions, both platforms are employed to run the cross-platform intelligent O&M management of the MEP system. For example, the cross-platform system provides data support to facilitate repair tasks, to optimize the routine patrol path, and to aid the emergency response.

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[2] Radio-frequency identification (RFID) uses electromagnetic fields to automatically identify and track tags attached to objects. The tags contain electronically stored information. Unlike a barcode, the tag need not be within the line of sight of the reader, so it may be embedded in the tracked object.

[3] QR code (abbreviated from Quick Response Code) is the trademark for a type of 2D barcode. It uses four standardized encoding modes (numeric, alphanumeric, byte/binary, and kanji) to efficiently store data.

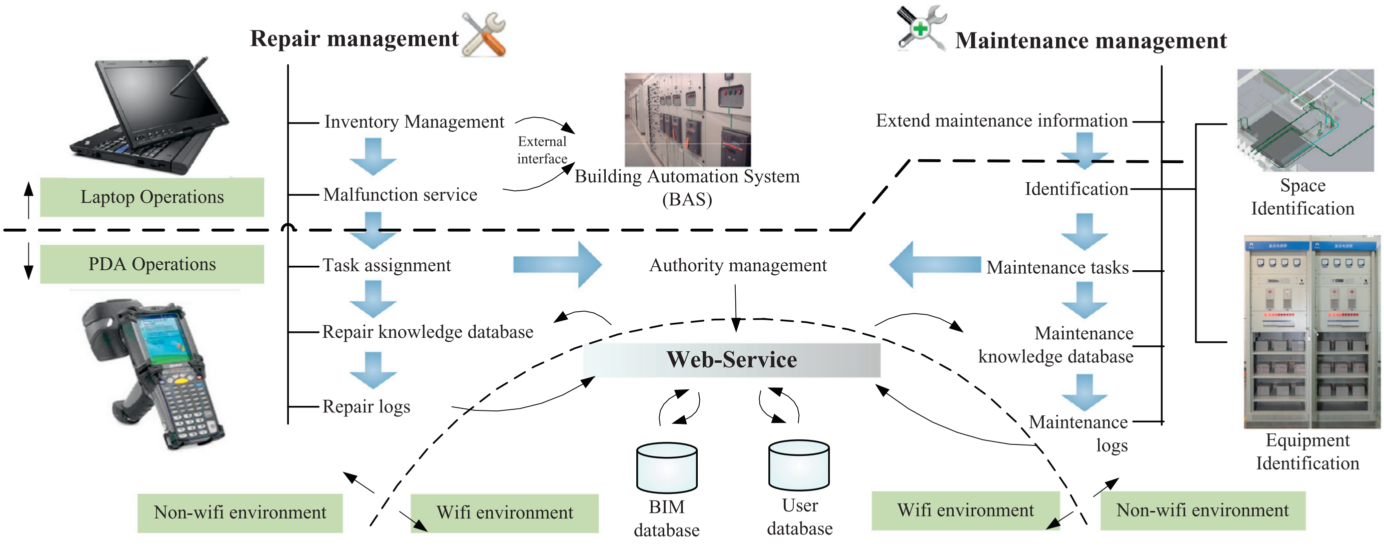


Fig. 3. Architecture of equipment maintenance and repair management based on web-service and heterogeneous platforms.

4.1. Maintenance and repair processes in the cross-platform system

The procedures for the maintenance of the MEP system as shown in Fig. 3 can be listed as follows. (1) Equipment suppliers, constructors or facility managers input the maintenance plan into the BIM via laptops. (2) O&M personnel identify (find the Global ID) the equipment group, or directly the specific piece of equipment, via scanning the QR code or the RFID tag. (3) Based on web-service technique, the authority of the user who made the enquiry is checked. If the access is guaranteed, the enquired maintenance-related information will be extracted from the BIM database. It should be noted that the information, pertaining to different equipment, should be input before the delivery. (4) Based on the extracted information, O&M personnel carry out the maintenance task. (5) A maintenance record is then generated and inserted into the BIM database via the web-service. The record contains the name of maintenance personnel, time, object and content of the work.

The repair management consists of five tasks: management of back-ups, report of malfunctions, assignment of repair work, updating the knowledge library and logging the repair. Just the same as in the maintenance management, portable terminals and laptops are responsible for different tasks (see Fig. 3). For one thing, laptops are suitable to tackle with management of back-ups and report of malfunctions.

(1) Management of back-ups: keeping records of inventory, details of back-ups and purchase-related information for equipment of different types; sharing the information interface with common property management tools such as Building Automation System (BAS).

(2) Report of failures: including the manual report and automatic report. The manual report requires the equipment keeper to manually input the relevant information, such as the name, code and condition of the equipment. The automatic report requires continuously monitoring of particular equipment.

For another thing, the portable terminal, within a wifi-enabled environment, is suitable for assigning the repair work, updating the knowledge library and logging the repair work. In detail, the facility manager could be informed about the equipment failure via portable terminals, and assign a proper worker to deal with the failure. In the process, the manager needs the authorized information, such as the worker-related information, in the user database via web-service. When the worker arrives, he/she could extract the relevant information from the BIM database via web-service according to the QR code or the RFID tag at the site. The relevant information (including the details of the equipment and knowledge pertaining to the repair procedure of common failures) provides supports for the repair task. After the repair work is done, repair log can be updated right on site through web-service.

The architecture of maintenance and repair management is shown in Fig. 3.

4.2. Patrol path planning in the cross-platform system

The GIS map, in which the indoor paths and their corresponding weight values are available, provides virtualization and data support for the routine patrol path planning. Since the authorities of doors and space are important, especially for the large-sized public building, it is necessary to combine the authority information stored in user database and path information stored in BIM database when planning the routine patrol path. In such a case, the accessibility of space can be virtually presented for path planning.

Through reading the RFID tags by portable terminals, the walking patrol personnel can be prompted about the optimal patrol path in real-time with the following aids: (1) the specific equipment can be identified in the BIM database via scanning the RFID tag, (2) the data extracted from the BIM database via web-service contains the location (3D coordinates) of the particular equipment and (3) the distance between patrol personnel located by signal intensities [51], signal performances [52] or model matching [53], etc., and the particular equipment can be calculated. Then, the patrol path can be prompted to the walking patrol personnel in real-time by performing the path search algorithm.

4.3. Integration of monitoring information

The monitoring information contains data on MEP running status (temperature, humidity, pressure, etc.) obtained via sensors. The information gathered can then be used to aid the decision-making in terms of making or altering the maintenance plan or determining if a repair task needs to be assigned. Monitoring the MEP system in buildings produces two kinds of data: the metadata corresponding to the monitoring sensor and the monitoring

Table 2
Monitor information of mainframe equipment.

Equipment type	System group/Main system	Equipment code	Equipment/Point description	Equipment location
PRA1	BAS	K1	RIO Frame State	Environmental Control Room

Table 3
Monitor sensor information of mainframe equipment.

Equipment/ Sensor description	Point type (DI/DO/AI/DDI/ VDDI/VTDI)	Value	Value description	Alarm value	Alarm types (1/2/3/4)	Length (Bit, Byte)	Information object address
Communication Normal	DI	0–1	0=FAULT/ 1=NORMAL	0	2	1 Bit	7419.15

records. The metadata pertaining to the monitoring record includes the description of the monitoring point, type of data, range of reasonable data value, critical value for issuing alerts, data length, object address etc. while the matadata related to the monitoring sensor itself includes the location, hierarchy, type and coding . Tables 2 and 3 show the information on monitoring MEP "PRA1" extracted from a BAS system. Usually, the monitoring metadata has a fixed format. Hence, developing an interface transferring the monitoring record into the readable table information can facilitate the formulation of a data chain such as "building-system-subsystem-zone-equipment-monitoring".

Monitoring record contains the current and historical running status of particular equipment, and can be divided into discrete and continuous quantities. The monitoring data is usually stored in the database developed by specific monitoring equipment supplier, whose format and structure are different for different suppliers. Consequently, the monitoring record can be read either from the monitoring equipment directly or from the database exclusively corresponding to certain monitoring equipment. The first method is better in terms of processing efficiency while reading from the specialized database, on the other hand, has two options: synchronizing the specialized database with user-built database, or enquiring the specialized database following the procedures set-up by the equipment supplier.

There are normally two basic types of enquiries made concerning the monitoring information. The first type acquires the monitoring sensor information given the type and zone information of a piece of known equipment. The second type enquires the equipment and its information given the known monitoring record. More complicated enquiry can be formulated based on the combination of these two basic types of enquiry. For example, given the flow data of a specific pipeline, the upstream on/off switch status of a butterfly valve can be checked as follows, (1) locating the monitoring sensor which reports the known flow data; (2) identifying the association of the located monitoring sensor; (3) looking up the logic chain which contains the pipeline; (4) finding the relevant information on the valve extracted from the logic chain.

4.4. Technology of emergency response

The logic chain and the grouping label are useful for the decision-making in the emergency-response case. For example, in the case of pipeline cracking, scanning the broken pipeline and locating the up-stream component with the help of the embedded logic chain in the as-built model can guide the facility manager to shut down the up-stream valve to limit the influence and make the failure under control.

The maintenance personnel can use laptops and scanning guns to identify the malfunction equipment in the BIM, and then locate the equipment and its up-stream corresponds in the 3D virtual space; or read QR code and RFID through the portable terminal, which extracts key information (component name, upstream component description, etc.) and enquiry documents such as blueprint and maintenance manual for necessary information within the wifi-enabled environment. They can also search for the optimal path to the upstream component and the locations of nearby repair workers and tools.

5. Implementation and a case study

Based on the techniques described above, the BIM-FIM, a cross-platform system was designed and implemented to intellectively mange the MEP system during the O&M phase. It consists of six main function modules and five auxiliary modules. Fig. 4 shows the functions of the BIM-FIM system.

Fig. 5 shows the programming architecture of the BIM-FIM. Eight layers are designed to run the O&M management of the MEP system. The data source layer includes all the original engineering data, such as IFC files containing initial as-built project information, monitoring data recording the running status of equipment, construction drawings, etc. The data interface layer provides methods to read and parse the original data, which will be handled by the proposed algorithms embedded in the algorithm layer, then transformed into permanent data in structured, computer-sensible formats and stored in the BIM database of the data layer. These data form the as-built BIM. Monitoring information and user information are stored in separate databases due to the particularity of the data. Web services are remotely called to retrieve the required information from the databases. In the model layer, data is extracted, converted and integrated into different BIMs to aid the intelligent MEP management. The platform layer forms the environment for visualizing the BIM, the FM-related information and management activities in portable terminals. The application layer consists of the aforementioned specific function modules, and the user interface (UI) layer provides different interfaces for different devices including portable terminals (PDAs, smart phones and tablets) and laptops.

The system was applied to several real projects including the Shenzhen Kerry Plaza II project to make the MEP-related information digitalized in delivery and to increase the intelligent level of the MEP management in the O&M phase. Located in the Central Business District (CBD) of Shenzhen, China, the Kerry Plaza II is a high-grade office building, occupying over 7900 m^2 of land and total floor area in excess of 100,000 m^2. The building consists of 3 underground floors and 41 floors above the ground, and the total height of the building is 200 m. The initial as-built model of the project was created by the general constructor using Revit. The BIM-FIM was developed to run on a laptop configured with 2.6 GHz 2-core processor, 8GB memory, and the display card with 1GB memory. A QR code scanning gun is connected to the laptop. The portable terminals suitable for installing the BIM-FIM include all smart phones running either iOS or Android. In addition, a Motorola MC9090-G tablet (mainly used for reading RFID tags) was

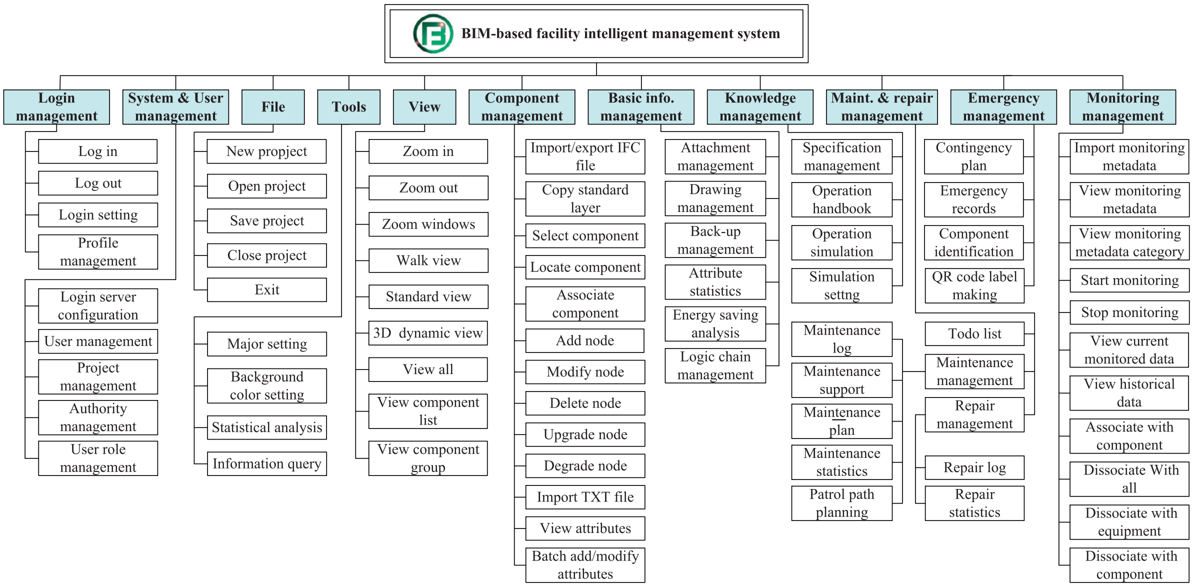


Fig. 4. Functions of the BIM-FIM.

included to support the intelligent O&M management of the MEP system.

5.1. Establishment of the as-built information model

The establishment process of as-built information model is based on the standard schemas including IFC and COBie, even though COBie was not directly adopted in the case study due to the tight schedule of this project. The typical process [38] of using IFC and COBie as a tool for the as-built information model at the end of construction is: (1) Collect BIM created during design and construction phase and turn them into IFC format; (2) Extract the information required by the O&M personal from IFC files into a COBie-based Microsoft spreadsheet; (3) Import the spreadsheet into a maintenance management system to aid FM. However in this project, the BIM consultant hadn't been involved in this project before construction and there was no design BIM. Thus three young engineers with less-than-one-year-experience on Revit were appointed by the general contractor to build up the whole Revit model during construction, and they completed the task in 2 months. Every major as-built model contained one sub-model of the standard building floor and over 15 sub-models for other floors. The Revit models were exported into IFC formatted files. On the other hand, COBie based Microsoft spreadsheet was not generated because the IFC formatted BIM files, which contain the geometrical information and the engineering attributes inputted in the Revit model, were directly imported into a BIM database through the IFC input/output interface embedded in the BIM-FIM. Then it took the general contractor about 6 weeks to integrate all the major models and extend other engineering information (e.g., the logic chain) in the BIM-FIM with the help of a BIM consultant team. During this process, COBie data provisions were employed to confirm and add in some missing information and documents, such as vendor specific information, installation information and warranty information. These extended data and related documents were inputted by batch methods embedded in the BIM-FIM and the logic chain information was generated using the strategies articulated above. Information related to O&M management activities was inputted through user-friendly interfaces provide by the BIM-FIM. It should be noted that the database was a permanent asset of the building and provided supports for the FM in the O&M phase. A sketch showing the process is presented in Fig. 6 (Part I).

Since there are many types of MEP components provided by different suppliers, the structured data, such as the names, parameters and codes, and non-structured information, such as manuals, specifications and operation diagrams, of a specific piece of equipment are tremendous in amount. According to the general contractor, totally 125 kinds of equipment, 20 sizes of pipes were involved in the integrated model. Each MEP component was associated with at least one operation manual, one specification and 10 extended attribute records about the location information, vendor specific information and installation information. These associated information and extended attributes were inputted in the BIM-FIM was given comprehensive consideration of COBie and the collected advice by experienced O&M personals. Consequently, the data input is a heavy-burdened and fallible task. The BIM-FIM provided as many ways to input data as possible. For example, the data contained in Excel files was input into the BIM-FIM database automatically. Fig. 6 (Part III) shows two Excel tables containing the attributes of a specific piece of equipment inputted into the BIM-FIM database.

Using the data stored in the BIM-FIM database and following the logic chain creation technique described in Section 3.1, the logic chains linking all MEP components (plumbing, HVAC, figure-fighting, electrical and security equipment) were built up. Besides the automatic creation, the created logic chains were checked manually to ensure the logic relationships were correctly set up. A statistic shows that the accuracy of the proposed approach to automatically build the logic chain is about 85% in the HVAC and plumbing systems, and 70% to 80% in other MEP systems due to the inaccuracy of modeling and complex logical relationships among specific components. However, it still saves about 25 man-days in this project. The logic chains, together with the BIM-FIM database, were delivered to the owners as a part of the as-built model. Take the HVAC system as an example, Fig. 7 shows when the user selected an upstream fan system, the equipment logically downstream the fan system were highlighted.

5.2. The application of the as-built BIM

The constructor delivered the as-built BIM together with the BIM-FIM to the owner to facilitate the O&M management of the MEP system because the combination of the BIM database and the

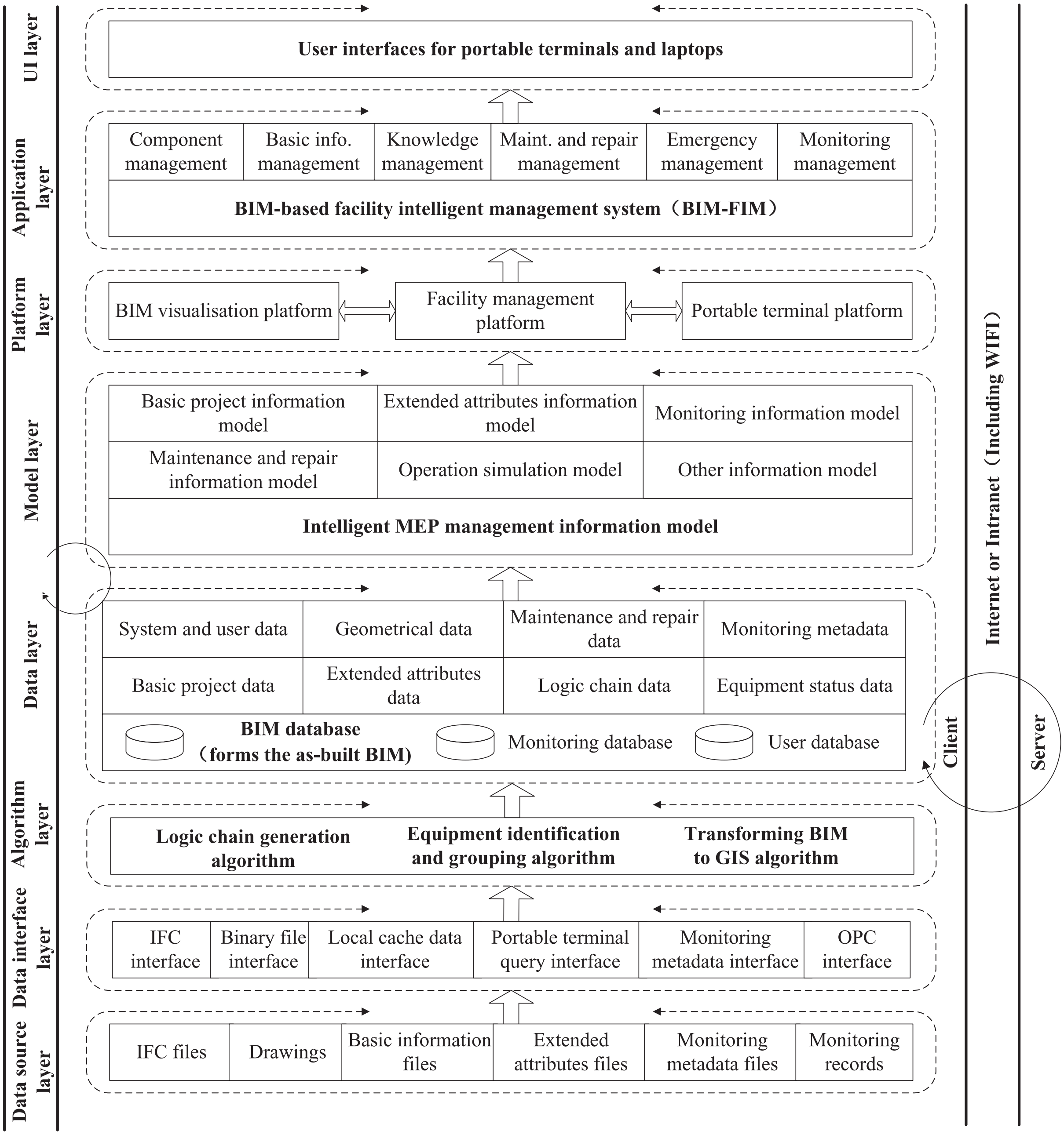


Fig. 5. Programming architecture of the BIM-FIM.

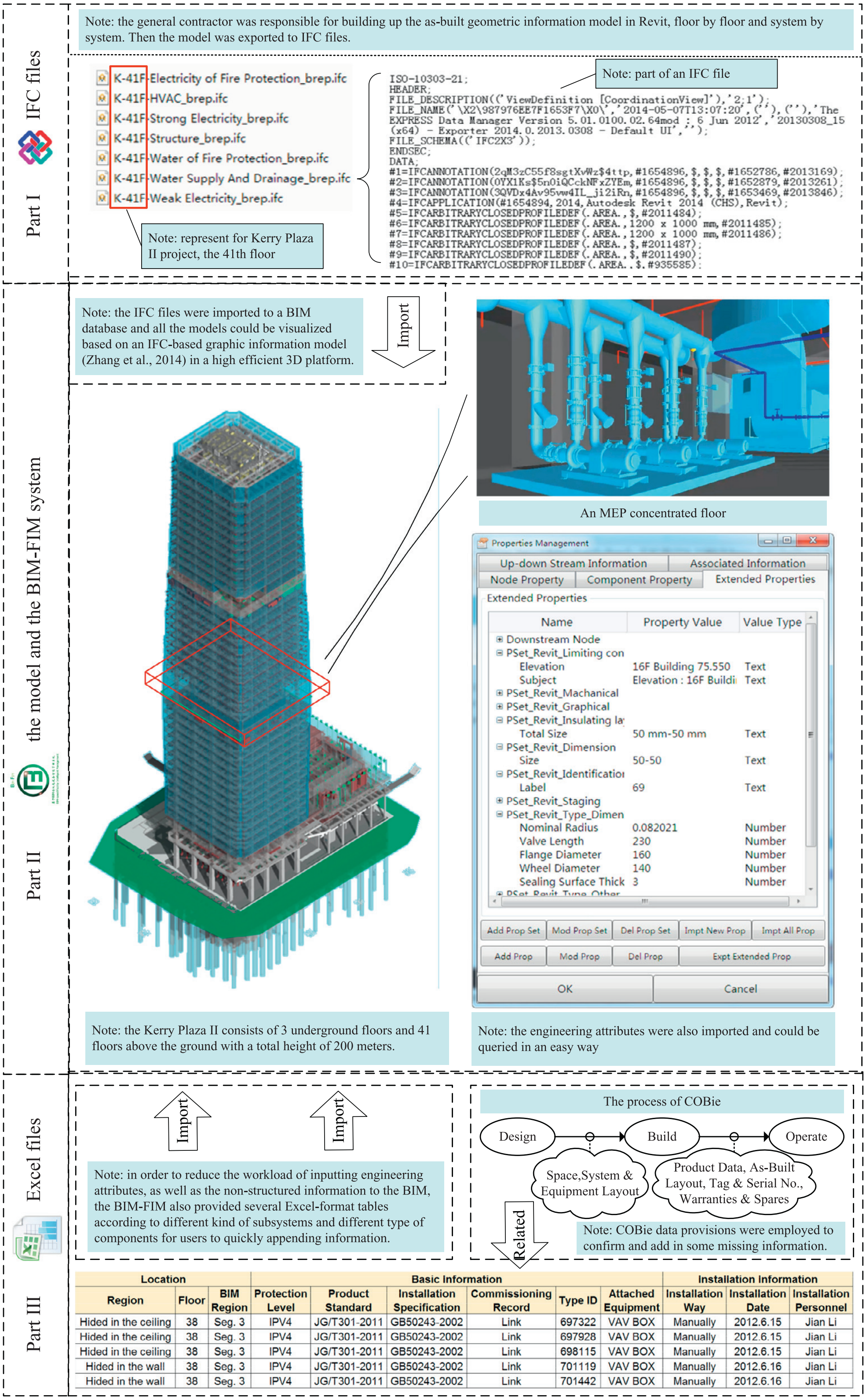
BIM-FIM made it convenient to enquiry, to analyze and to calculate statistics pertaining to the MEP system status.

For instance, engineering information pertaining to specific equipment could be sourced through the attribute dialog box of specific equipment in the Client/Server (C/S) application program, or alternatively read through the attribute interface via portable terminal when the equipment was identified. The information included the blueprint, attached files, maintenance plan, operation and maintenance manual, as indicated in the left sheet of Fig. 8.

The statistics allowed O&M personnel to rapidly acquire knowledge on the engineering attributes and running status of all MEP subsystems, and hence to quickly check and response to changes in the MEP running status. For example, right sheet of Fig. 8 shows the statistical results of loss coefficient for all the HVAC system in the first floor, which provide data for centrally adjusting the HVAC system.

5.3. FM applications

In this project, through attaching labels with QR codes and RFID tags, almost all the important large MEP components had been organized. In fact, QR codes in the labels had different background colors for equipment of different subsystems, and scanning the QR code enabled O&M personal to access the relevant information. For example, acquiring the equipment parameters helped the repair worker to locate and replace the malfunction part, which ultimately increased the efficiency of the repair work. Meanwhile, accessing the relevant information stored remotely in real-time could help avoiding the unnecessary accidents.



Note: the general contractor was responsible for building up the as-built geometric information model in Revit, floor by floor and system by system. Then the model was exported to IFC files.

Note: represent for Kerry Plaza II project, the 41th floor

Note: part of an IFC file

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('ViewDefinition [CoordinationView]'),'2;1');
FILE_NAME('\X2\987976EE7F1653F7\X0\','2014-05-07T13:07:20',(''),(''),'The
EXPRESS Data Manager Version 5.01.0100.02.64mod : 6 Jun 2012','20130308_15
(x64) - Exporter 2014.0.2013.0308 - Default UI','');
FILE_SCHEMA(('IFC2X3'));
ENDSEC;
DATA;
#1=IFCANNOTATION(2qM3zC55f8sgtXvWz$4ttp,#1654896,$,$,$,#1652786,#2013169);
#2=IFCANNOTATION(0YX1Ks$5n0iQCckNFxZYEm,#1654896,$,$,$,#1652879,#2013261);
#3=IFCANNOTATION(3QVDx4Av95vw4IL_ji2iRn,#1654896,$,$,$,#1653469,#2013846);
#4=IFCAPPLICATION(#1654894,2014,Autodesk Revit 2014 (CHS),Revit);
#5=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,$,#2011484);
#6=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,1200 x 1000 mm,#2011485);
#7=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,1200 x 1000 mm,#2011486);
#8=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,$,#2011487);
#9=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,$,#2011490);
#10=IFCARBITRARYCLOSEDPROFILEDEF(.AREA..$.#935585);
```

Note: the IFC files were imported to a BIM database and all the models could be visualized based on an IFC-based graphic information model (Zhang et al., 2014) in a high efficient 3D platform.

An MEP concentrated floor

Name	Property Value	Value Type
⊞ Downstream Node		
⊟ PSet_Revit_Limiting con		
Elevation	16F Building 75.550	Text
Subject	Elevation : 16F Buildi	Text
⊞ PSet_Revit_Machanical		
⊞ PSet_Revit_Graphical		
⊟ PSet_Revit_Insulating la		
Total Size	50 mm-50 mm	Text
⊟ PSet_Revit_Dimension		
Size	50-50	Text
⊟ PSet_Revit_Identificatio		
Label	69	Text
⊞ PSet_Revit_Staging		
⊟ PSet_Revit_Type_Dimen		
Nominal Radius	0.082021	Number
Valve Length	230	Number
Flange Diameter	160	Number
Wheel Diameter	140	Number
Sealing Surface Thick	3	Number

Note: the Kerry Plaza II consists of 3 underground floors and 41 floors above the ground with a total height of 200 meters.

Note: the engineering attributes were also imported and could be queried in an easy way

Note: in order to reduce the workload of inputting engineering attributes, as well as the non-structured information to the BIM, the BIM-FIM also provided several Excel-format tables according to different kind of subsystems and different type of components for users to quickly appending information.

Note: COBie data provisions were employed to confirm and add in some missing information.

Location			Basic Information						Installation Information		
Region	Floor	BIM Region	Protection Level	Product Standard	Installation Specification	Commissioning Record	Type ID	Attached Equipment	Installation Way	Installation Date	Installation Personnel
Hided in the ceiling	38	Seg. 3	IPV4	JG/T301-2011	GB50243-2002	Link	697322	VAV BOX	Manually	2012.6.15	Jian Li
Hided in the ceiling	38	Seg. 3	IPV4	JG/T301-2011	GB50243-2002	Link	697928	VAV BOX	Manually	2012.6.15	Jian Li
Hided in the ceiling	38	Seg. 3	IPV4	JG/T301-2011	GB50243-2002	Link	698115	VAV BOX	Manually	2012.6.15	Jian Li
Hided in the wall	38	Seg. 3	IPV4	JG/T301-2011	GB50243-2002	Link	701119	VAV BOX	Manually	2012.6.16	Jian Li
Hided in the wall	38	Seg. 3	IPV4	JG/T301-2011	GB50243-2002	Link	701442	VAV BOX	Manually	2012.6.16	Jian Li

Fig. 6. Sketch map of importing IFC and Excel files to generate the as-built BIM.

Using the specially designed interface to convert the monitoring records into readable tables, the monitoring records were inserted into the BIM database. In detail, when the monitoring record was available, it could be viewed in the virtual 3D space in real time. Not only the actual monitoring records could be enquired, but also the metadata pertaining to the monitoring sensor was available through the interface of the BIM-FIM. For example, the real-time monitoring information gathered from all the sensors monitoring the water supply system could be integrated and displayed graphically. Fig. 9 shows the monitored flow data in a water supply sys-

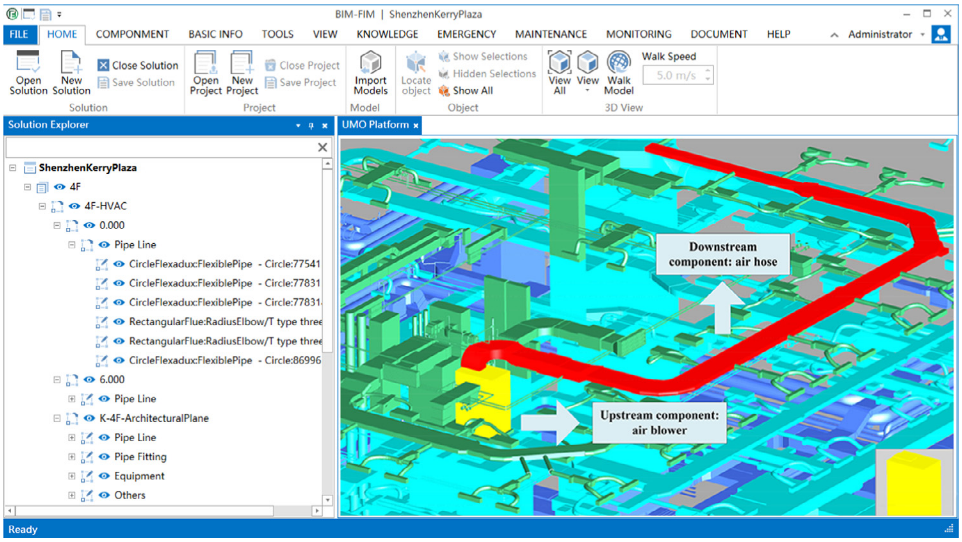
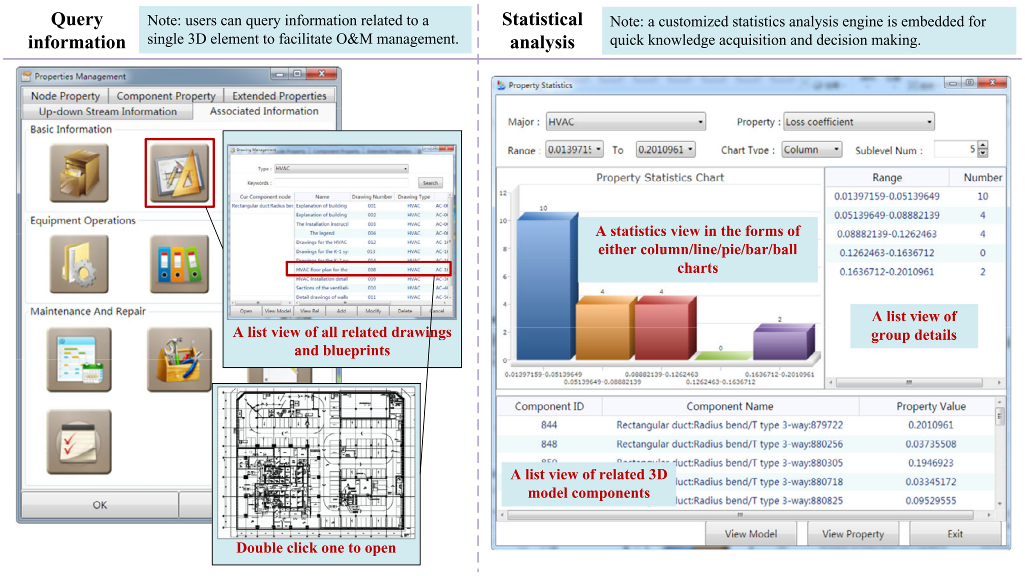


Fig. 7. A sketch showing the logic relationships among parts in a HVAC system.



Range	Number
0.01397159-0.05139649	10
0.05139649-0.08882139	4
0.08882139-0.1262463	4
0.1262463-0.1636712	0
0.1636712-0.2010961	2

Component ID	Component Name	Property Value
844	Rectangular duct:Radius bend/T type 3-way:879722	0.2010961
848	Rectangular duct:Radius bend/T type 3-way:880256	0.03735508
850	Rectangular duct:Radius bend/T type 3-way:880305	0.1946923
[illegible]	uct:Radius bend/T type 3-way:880718	0.03345172
[illegible]	uct:Radius bend/T type 3-way:880825	0.09529555

Fig. 8. A sketch showing the enquiry results in terms of statistics.

tem, where different flow speeds calculated by the real-time monitoring data were colored differently.

The laptop running the C/S application of the BIM-FIM system also provided means to check maintenance plans and logs, to calculate maintenance-related statistics and to enquiry information on back-ups. For one thing, the system reminded O&M personnel about the location and procedure to run routine maintenance according to the prescribed maintenance plan. For another thing, the system aided the repair workers by providing the knowledge support. Meanwhile, the portable terminal was useful for maintenance personnel to access the necessary maintenance knowledge and procedure and to quickly update the record after the work was done. As regarding the patrol path planning, the portable terminal could not only plan the patrol path beforehand, but also prompted the patrol personnel in real-time in the process of patrolling. Fig. 10 shows the sketch representing the maintenance and repair work.

When there is an emergency, facility managers would rush into the site with laptops or the portable terminals. Through scanning the QR code or RFID tag, the relevant information on the malfunction equipment and its logic chain will be extracted from the BIM-FIM. Such information is valuable for the emergency-response team to come up with a feasible solution. In addition, the BIM-FIM could help find the influential circle of particular emergency, which was the key to determine response procedures. For instance, the information could help the emergency-response team to determine if a specific upstream valve should be shut down and who should be alerted. There were mainly two ways to search for relevant upstream equipment: through interactions in a virtual 3D space presented in a laptop or through 2D diagrams in a portable terminal. Fig. 11 shows the process of emergency-response.

5.4. Discussion

The case study was carried out to verify the effectiveness of BIM-based integrated delivery technologies proposed for enhancing the intelligent level in managing the MEP system in the O&M phase. During the application, the general contractor created the as-built information model with the help of the BIM-FIM. Then the as-built information model, together with the BIM-FIM, was deliv-

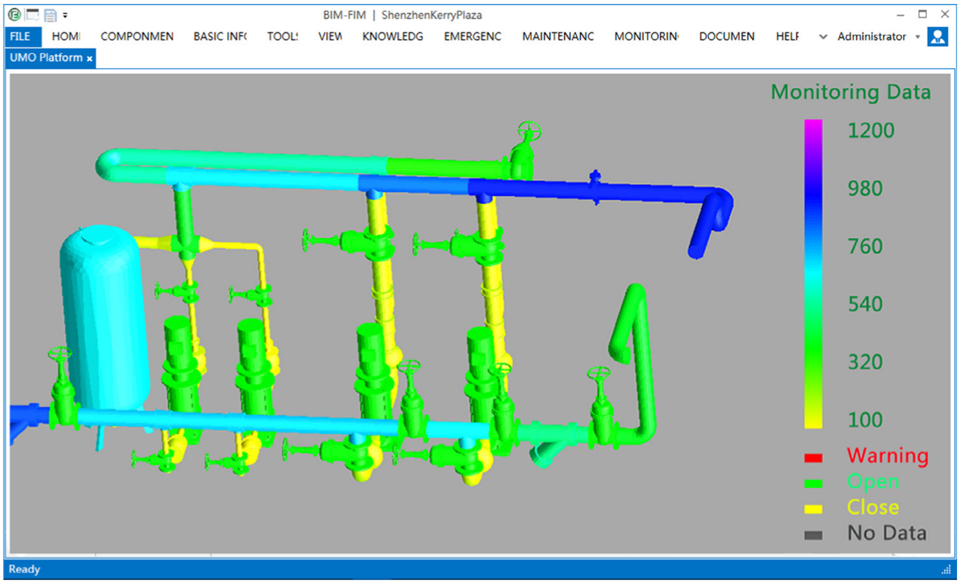


Fig. 9. Monitored flow data in a water supply system.

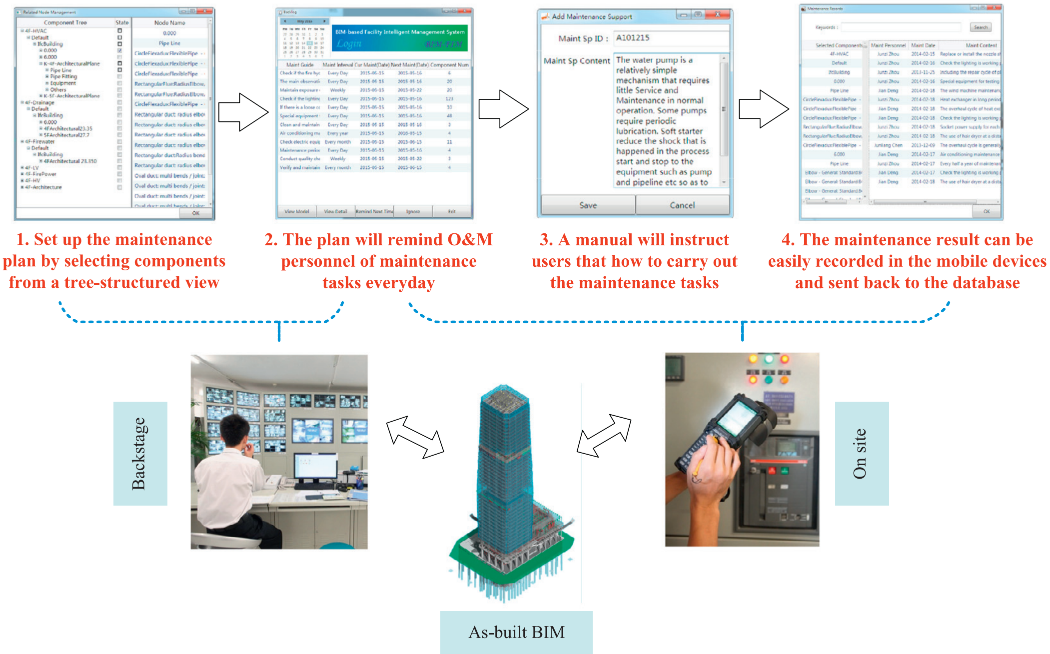
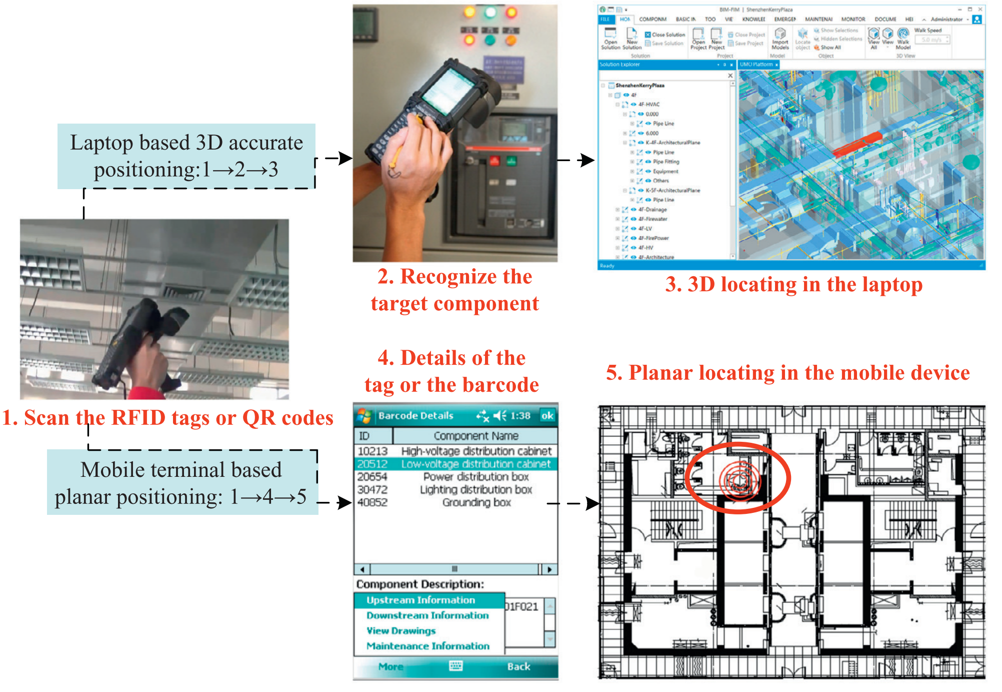


Fig. 10. A sketch of maintenance and repair tasks.

ered to the owner to facilitate the O&M management of the MEP system. Based on the as-built BIM, the system helped not only in enquiring, analyzing and calculating statistics, but also in managing the MEP system on site and emergency-response.

The owners were satisfied with the as-built information model because it facilitated the delivery of project completion documents. They declared that it reduced the time and cost by about 20%. It is understandable since the original delivery of the completion documents makes it cumbersome to rearrange and organize the tons of hardcopies and digital disks. The organizing process was especially time-consuming for the MEP system because the relevant information of a specific piece of equipment was usually spread out in different documents. In this case study, the delivery process was easy because completion documents were transferred to the owners not only in the form of either electronic files and hardcopy documents, but in the form of a BIM database together with the BIM-FIM to aid FM as well.

The maintenance personnel were enthusiastic about the BIM-FIM as well for four reasons. Firstly, the system provided an easy way to search for relevant information and upstream/downstream components when running daily O&M tasks. By scanning the QR code attached to the MEP component through the portable terminal, they could get the basics right away and access all the needed information stored in the remote server when wifi was enabled. Secondly, visualization function of the BIM-FIM facilitate the FM. In fact, the BIM and GIS views of the system provided visualized and convenient management tools. For example, the MEP system and its subsystems could be monitored in the virtual 3D space in real time. Monitoring records could then be enquiry and analyzed to devise energy-saving measures. Moreover, the GIS map provided



ID	Component Name
10213	High-voltage distribution cabinet
20512	Low-voltage distribution cabinet
20654	Power distribution box
30472	Lighting distribution box
40852	Grounding box

Note: In case of emergency, users can obtain the information of tagged components, and their upstream and downstream components by receiving RFID signal or scanning 2D QR code with mobile devices or scanning gun. Related components can then be located in 3D view in Laptops or 2D view in mobile devices.

Fig. 11. Flow of emergency treatment in both laptop and mobile environments.

virtualization aids and data supports for the routine patrol path planning, which shortened the time by about one hour every day. Thirdly, they could respond much faster to emergencies with the help of the system, because sufficient information was important for facility personnel to make decision when facing an emergency. Finally, the BIM-FIM promoted collaboration among facility personnel. All the FM data was stored in a single BIM database, so when one updated the database, it could be synchronized among all working terminals of the O&M management system.

However, there were also some obstacles when the BIM-FIM was deployed. In detail,

(1) The general contractor had not adopted BIM technology during the construction until being directed by the owners as the BIM-based integrated delivery was included in the updated contract in order to facilitate the FM in the O&M phase. The contractors hence had to pay extras to establish the as-built information model. Such an obstacle was an evidence that the application of BIM technology in the O&M period was not yet common in China at that time. Since the number of owners realizing the potential value of the BIM technology increases, other participants were encouraged to adopt the BIM technology during the design and construction phase. Therefore, the delivery of the as-built BIM would become a common practice, which would not result in extra cost for contractors in the near future.

(2) In the preparation of the as-built BIM, the general contractor had to manually input all the as-built engineering data due to the lack of batch input methods and it took 3 staffs about 20 days to finish all the data inputting task for the water supply and drainage subsystem. In order to address the time-consuming issue for inputting data, the BIM-FIM was upgraded by providing as many batch data input methods as possible to make the input task less time-consuming. These methods greatly reduced the data input time to about 3–5 days for one subsystem.

(3) The O&M personnel of this project had experiences as facilities managers but were not familiar with the BIM technology. Consequently, they needed to be tutored exclusively for use the BIM-FIM. Originally, the O&M personnel filled in the paper sheets concerning the running status of specific equipment. With the help of the BIM-FIM, they should maintain the running status paperless on portable terminals. Such a change requires tutorials. In fact, six workshops on the usage of the BIM-FIM were held on site to help the O&M personnel get familiar with the system. After three weeks, they were fluent with the new tool and found it valuable and more efficient in the management of the MEP system.

6. Conclusions and future works

Considering that the O&M management of the MEP system lacks advanced tools, this study proposed to apply the BIM technology to build up a comprehensive as-built building model containing MEP-related information for delivery. Specifically, an approach to automatically establish the logic chain, a component grouping and labeling scheme, and an algorithm of generating the GIS map based on the BIM information were proposed for better support in the creation and delivery of the as-built model with the additional MEP-related information. In addition, the present study investigates the cross-platform O&M intelligent management software, which is valuable in increasing the O&M management efficiency and enhancing the emergency-response performance. Then a BIM-FIM system was developed and applied to a real large-sized building, demonstrating the feasibility and effectiveness of techniques discussed. The conclusions can be listed as follows,

(1) MEP system is characterized by the large size and complex logic structure. Consequently, the as-built model for delivery

should contain not only the geometrical and construction information, but also necessary engineering information to facilitate the O&M of the MEP system. In detail, the MEP O&M management requires logic chains of various MEP components, grouping information and maintenance-related data.

(2) Based on web-service techniques, the MEP-related information is available on different platforms, such as PCs and portable terminals, to facilitate cross-platform cooperation. The cross-platform cooperation is useful in maintenance/repair, routine patrol, monitoring equipment, emergency-response etc. By adopting an intelligent O&M management system featuring cross-platform cooperation, the management of the MEP system is improved in terms of efficiency and performance, and the safety of MEP components is guaranteed.

(3) The proposed techniques are embodied in a real intelligent O&M management system named BIM-FIM. The BIM-FIM exemplifies the digitalization of MEP-related information in delivery. The successful application of BIM-FIM provides the technical base for further propagation of the techniques discussed in the present study.

In order to further improve the intelligence level of the O&M management of the MEP system, the following works are planned. At first, except for the logic chain, more augmented information should be integrated into the as-built model for delivery. Secondly, further investigation should be conducted to dig out more from the monitoring information. Finally, efforts should be made to widen the application of the proposed system. In other words, the increase in the need for the BIM-based O&M management of the MEP system would stimulate the improvement of the system designed in the present study.

Acknowledgments

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Glossary

BAS: building automation system
BIM-FIM: an existing BIM-based intelligent facility management system developed by the authors
BIM: building information modelling/model
CAE: computer aided engineering
COBie: construction operation building information exchange
C/S: client/server
FM: facility management
GIS: geographic information system
HVAC: heating, ventilation and air-conditioning
IFC: industrial foundation classes proposed by BuildingSMART
MEP: mechanical, electrical and plumbing
NIBS: the national institute of building science
OBB: oriented bounding box
O&M: operation and maintenance
PDAs: personal digital aids
QR code: quick response code
RFID: radio-frequency identification
VDC: virtual design and construction
XML: eXtensible markup language