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# BIM-Enabled Streamlined Fault Localization with System Topology, RFID Technology and Real-Time Data Acquisition Interfaces

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*Abstract*— **With the view to streamlining fault localization process for building operation and maintenance (O&M), a novel architecture for managing decentralized building facilities information is proposed, by exploiting the information interoperability and reusability among Building Information Modelling (BIM), system topology, Radio Frequency Identification (RFID) technology, and real-time data acquisition interfaces including Building Automation System (BAS), wireless sensors, Closed Circuit Television (CCTV) system, and Real Time Location System (RTLS). Cross-platform mobile and desktop systems have been developed based on the proposed architecture. It is shown that significant time-saving of more than two hours can be achieved on fault localization in a typical air-conditioning fault situation.**

## I. INTRODUCTION

Fault localization of building facilities such as Mechanical, Electrical and Plumbing (MEP) systems has been the most labor-intensive and time-consuming process in corrective maintenance management. It involves the activities of iterative inspection, testing and diagnosis in order to identify the root cause and the exact location of faulty equipment. For years, fault localization heavily relies on BAS provided by centralized control manufacturers, e.g., Honeywell, Siemens, Schneider Electric, etc., together with as-built 2D computer-aided design (CAD) drawings, e.g., floorplan layout, service drawings and system schematics. To effectively manage and optimize building facilities, some organizations may even develop their own facility management (FM) / asset management (AM) systems or adopt commercially available software solution such as Computerized Maintenance Management System (CMMS) and Computer-Aided Facility Management (CAFM). These systems generally provide desktop platforms for managing preventive and corrective maintenance tasks with complete maintenance workflow, for examples, resource and task allocation, asset register, stock system, and maintenance records. Some may also equip with space management and energy management modules. However, the effectiveness of merely using FM/AM system in facilitating fault localization process is limited due to de-linked and scattered building facilities information among different decentralized data sources, e.g., BAS, CCTV systems, FM/AM systems and 2D CAD drawings. Since fault localization always requires cross-referencing of building facilities information among these standalone information systems, interfacing/integration is deemed necessary for streamlining fault localization process by enhanced information interoperability and reusability. Building facilities related information could be very beneficial to the maintenance engineers, facility mangers and facility owners who confront a large amount of corrective maintenance works every day. For instance, the Electrical and Mechanical Services Department (EMSD) of The Government of the Hong Kong Special Administrative Region is the largest MEP government maintenance agency responsible for operating and maintaining over 2,000 government buildings in Hong Kong.

Inspection, testing and diagnosis in fault localization process in practice does not only relate to cross-referencing of multiple data sources for building facilities information, it also relates to tracing of system routing and identification of equipment location using 2D CAD drawings. Tracing and identification using 2D CAD drawings could be very complicated where there is overlapping layered services. It is particularly difficult for inexperienced maintenance engineers to understand. Inconvenience of cross-referencing among different 2D CAD drawings also hinders a clear visualization of concerned service like duct and pipe works of Heating, Ventilation, and Air Conditioning system. A better visualization of service drawings is therefore always preferable from O&M perspective. In this regards, Building Information Modelling (BIM), one of the recent development in architecture, engineering and construction (AEC) industry, can provide 3D visualization of service models with numerous additional benefits such as design collaboration, clash analysis, quantity takeoff and programme scheduling during design and construction stages [1]. BIM is conceived as an object-oriented (OO) parametric modelling system that supports the digital representation of building elements in terms of their 3D geometric and functional attributes as well as their inter-object relations. Conventional application of BIM mainly focuses on reducing construction and design efforts/resources for building design and MEP engineering works. By facilitating early coordination among different disciplines, BIM can significantly reduce variation orders for rework, hence shrinking construction schedules and project costs. However, application and approach of adopting BIM in the O&M stage of the long remaining building lifecycle is yet to be investigated.

This paper aims at contributing to the field of BIM application in fault localization by presenting a BIM-based novel architecture for streamlined fault localization of building facilities, leveraging the conceptual framework of BIM in facilitating effective storing, exchanging, sharing and managing O&M information in an interoperable and reusable

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way. The proposed architecture exploiting BIM in integrating AM, in particular the system topology, with a variety of O&M systems/tools, including RFID technology and several real-time data acquisition interfaces, has been successfully implemented and piloted in EMSD Headquarters. The pilot results have broken new ground in the application of BIM and could potentially fill a void in the market.

The rest of the paper is organized as follows. In Section II, some previous works related to the integration/interfacing among real-time acquisition interfaces, BIM and FM/AM system are discussed. Section III focuses on our proposed system architecture for managing decentralized building facilities information. In Section IV, the demonstration result of a typical fault situation are shown and the benefits of the proposed architecture is also summarized. Section V gives the further discussion followed by the conclusion in Section VI.

## II. Background

In recent years, integrating real-time data acquisition interfaces, e.g., BAS and wireless sensor network, with FM/AM systems has attracted considerable attention. A mobile FM application for real-time monitoring of building facilities was developed [2]. Some studies also included the maintenance process integration from fault reporting, handing to clearance [3, 4]. In other studies, integrating maintenance management and AM with sensor networks based on mobile and web technologies were investigated [5, 6, 7]. Albeit that there are many research literatures studying the benefits of integrating real-time data acquisition interfaces with FM/AM systems, fault localization were not emphasized. In addition, visual integration between building facilities and spatial information, e.g., 2D/3D drawings and BIM model, was not included in these studies.

The use of BIM should not be limited to building design and construction processes, but also be extended to FM/AM and O&M stages by seamlessly conveying the necessary asset information from an as-built BIM model. Undoubtedly, there is enormous potential in BIM's value. By virtue of the utmost importance of information accessibility for efficient fault localization in O&M, the asset related information that can be obtained by maintenance engineers should not be limited to static asset attributes of each building element residing in the BIM model. While there are many research studies and real-world applications of BIM in FM, most of them tend to focus on information transfer from BIM to FM systems [8, 9, 10, 11]. In these studies and applications, they focused on the mere data population of facilities information from an as-built BIM model to a FM/AM system by Revit Add-ins, open standard in IFC format [12], or a spreadsheet or an XML file for Construction Operations Building Information Exchange (COBie) [11, 13, 14]. Moreover, there are real-world projects involving information exchange between BIM and FM/AM system with BAS integrated in the same system [11, 15] as well as the studies on integrating RFID technology with BIM for fixed assets [16, 17] and interfacing RTLS with BIM for movable assets [18, 19]. However, these real-world applications are, in essence, generally not considered as true and full integration as to the integration diversity and extent whereas the system architecture that we proposed and implemented is a full integration of BIM, AM in particular the system topology, RFID technology as well as a variety of real-time data acquisition interfaces including BAS, wireless sensors, CCTV system, and RTLS in one single system.

## III. System Architecture

A novel architecture for an integrated maintenance management system called BIM-AM System is proposed as depicted in Figure 1, offering real-time O&M information sharing/retrieving and exchange capabilities, thus making fault localization much more efficient and effective. The dotted line in Figure 1 indicates the integration that may have been implemented in some other FM/AM software applications whereas the solid line indicates the full integration that was first proposed and implemented by EMSD.

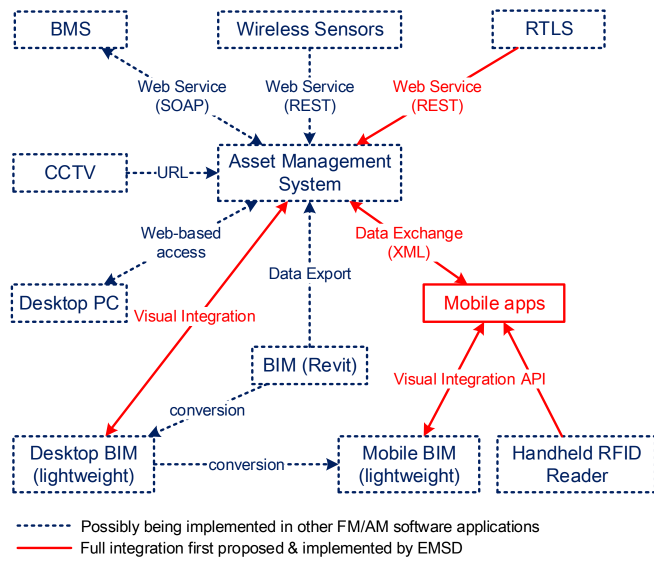



Figure 1: The novel architecture for BIM-AM System

Under this architecture, AM software is considered as an O&M software application for asset management, preventive maintenance and corrective maintenance management including workflow for fault reporting, handling and monitoring. It is worth noting that the BIM-AM System is at the forefront of BIM integration in terms of the integration diversity and extent as compared with other researches and relevant real-world applications. One of the most distinguishing differences is that the AM software in the proposed architecture serves as a middleware to integrate/interface with other systems/tools whereas other research works take BIM as a middleware for information exchange with other systems/tools, thus increasing the integration complexity. This is because direct integrations between BIM and other systems/tools would result in high complexities in the Application Programming Interface (API) developments on BIM software and the systems/tools. Moreover, BIM cannot replace the role of AM software in storing and upkeeping AM-related information as well as performing other comprehensive AM features. Another distinguishing difference between our works and other researches is that the visual integration between BIM and AM system is in a seamless and intuitive manner, in the sense that the BIM-AM System allows locating and visualizing any particular asset with its real-time asset information by maneuvering freely throughout the BIM model in one single integrated system, instead of mere data exchange between BIM and AM systems.

In addition, we have established our own BIM-AM asset hierarchy of MEP installations for Heating, Ventilation, and Air Conditioning, Fire Services Installation, Low Voltage Switchboard, and Lift and Escalator, etc. To facilitate MEP contractors to input asset information and particularly asset relationships in efficiently populating the data to the BIM-AM System, spreadsheet templates of BIM-AM MEP asset register as shown in Figure 2 were also specially designed.

| Equipment No. | Equipment type | Parent Equipment 1 | RFID No. | Switchgear No. | Type of Circuit | Rating (A) | Make | | |
|---|---|---|---|---|---|---|---|---|---|
| 123456 | Switchgear (ACB) | 111122 | ABCD0001 | 6N1 | Incomer | 3200 | Ellison | | ...... |
| 123457 | Switchgear (MCCB) | 111121 | ABCD0002 | 6N2 | Sub-main (Normal) | 400 | Merlin Gerin | | ...... |
| 123458 | Switchgear (MCCB) | 111121 | ABCD0003 | 6N3 | Sub-main (Normal) | 800 | Merlin Gerin | | ...... |
| 123459 | Switchgear (MCCB) | 111121 | ABCD0004 | 6N4 | Sub-main (Normal) | 400 | AEG | | ...... |
| 123460 | Switchgear (MCCB) | 111121 | ABCD0005 | 6N5 | Sub-main (Normal) | 800 | Federal | | ...... |
| | | | | | | | | | ...... |

Figure 2: Sample spreadsheet templates of BIM-AM MEP asset register for switchgears

## A. System Topology and Other Static Asset Information

Cross-platform mobile and desktop solutions were developed for the BIM-AM System in this pilot. Static asset information such as asset attributes, maintenance records, manuals, as-built system drawings, asset relationships and system topologies can be accessed anytime and anywhere. It should be noted that the feature of displaying system topology was purposely developed to visualize the asset relationships of any selected asset within a particular system for efficient fault localization. The system topology clearly indicates the dependence among assets, thereby facilitating the maintenance engineers in fault diagnosis as well as fault localization. Even if an inexperienced maintenance engineer does not know the root cause of a fault and has not yet identified the location of faulty equipment, he/she can try to inspect and locate the concerned equipment along the relationship of equipment. The mobile screenshot of asset relationships as shown in Figure 3 indicates the parent assets, dependent assets and related assets of a VAV box whereas the system topology as shown in Figure 4 provides a graphical view of the asset relationships of the VAV box within the overall system.


Figure 3: Asset relationships displaying the parent assets, dependent assets and related assets of a VAV box

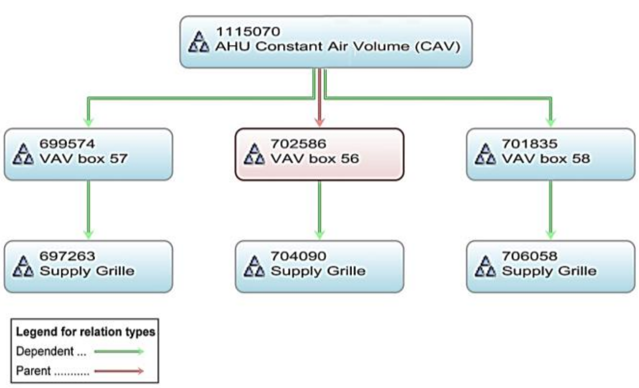



Figure 4: System topology visualizing the asset relationships of a VAV box within the overall system

## B. Real-Time Data Acquisition via Integration with BAS, Wireless Sensors and CCTV System

It was found that real-time asset related information is crucial for effective and efficient fault diagnosis and fault localization in MEP systems. When such real-time information could be made available together with the live site images from remote-eye CCTV cameras before fault attendance on-site, it would enable maintenance engineers to carry out pre-diagnosis so that they may bring all necessary spare parts/tools to the site in one go. The BIM-AM System has been integrated with BAS and CCTV system to make such real-time information available at the mobile terminal for maintenance engineers, so that he/she could remotely access not only the system status by the BAS sensors and live view of the site, but also may attempt to locate and clear the fault by remotely controlling/configuring some of the major MEP equipment, if appropriate, simply via the keyboard at his/her fingertips. Figure 5 is the screen-shot of the mobile terminal showing the captured real-time BAS monitoring sensor values of an Air Handling Unit (AHU).

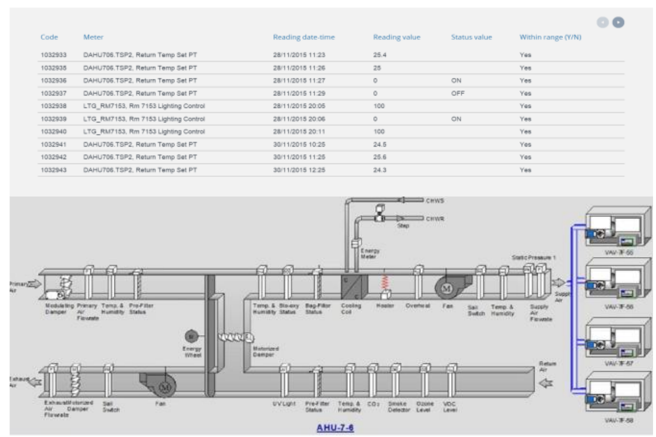



Figure 5: BAS monitoring interface of an AHU in the BIM-AM System

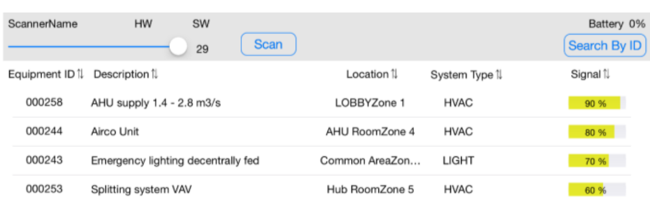
In some instances where suspected system components causing potential system breakdown are required to be closely monitored, wireless ad-hoc sensors were developed for prompt installation and monitoring of any abnormal change of equipment/ambient temperature, sound pressure or power consumption. The hyperlink of sensors data could easily be appended to the particular asset in the BIM-AM System as part of its ad-hoc attributes. The data collected from the wireless sensors and the existing BAS can be further analyzed for on-going condition monitoring, generation of pre-fault alerts, thus facilitating fault localization process. Similarly, a wireless ad-hoc mobile pan-tilt-zoom CCTV camera was developed for incident handling. It can easily be installed at any strategic location not covered by the existing CCTV system and the live feed hyperlink can also be appended to any particular asset in the BIM-AM System as part of its ad-hoc attributes, such that supervisor and maintenance engineers can visualize the real-time incident situation and closely monitor the contractor's work progress when necessary. Figure 6 shows the live feed of a wireless camera available at the mobile terminal for monitoring the subject plant room area. It should be noted that the integration with CCTV system via an URL link to a Network Video Recorder / IP camera would not be difficult if the existing CCTV system is built based on IP network.

However, when it comes to the integration with BAS and wireless sensors, data exchange via web services may be required. In our case, web services using Simple Object Access Protocol (SOAP) and Representational State Transfer (REST) are required for pushing the collected data of BAS and wireless sensors to the AM server, respectively.


Figure 6: CCTV live feed in the BIM-AM System at the mobile terminal

## C. *Integration with RFID Technology and RTLS*

For years, RFID has been considered as a practical methodology in FM/AM application such as managing and tracking inventory and assets. Having attached passive RFID tags to critical building assets and integrated its Application Programming Interface with the BIM-AM System, the System as shown in Figure 7 would facilitate maintenance engineers to efficiently and effectively locate critical equipment for further enquiry of asset information such as maintenance record, static and animated O&M manuals, the afore-mentioned real-time sensors data and site image, etc., even if the equipment is hidden above a false ceiling or underneath a raised floor. By quickly maneuvering and cross-referencing the related area in the BIM model, details of the connected pipe work and upstream/downstream equipment locations can be easily traced, making all that is invisible visible.

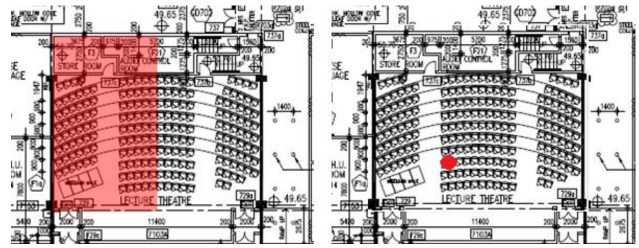


ScannerName HW SW 29 Scan Battery 0% Search By ID

| Equipment ID | Description | Location | System Type | Signal |
|---|---|---|---|---|
| 000258 | AHU supply 1.4 - 2.8 m3/s | LOBBYZone 1 | HVAC | 90 % |
| 000244 | Airco Unit | AHU RoomZone 4 | HVAC | 80 % |
| 000243 | Emergency lighting decentrally fed | Common AreaZon... | LIGHT | 70 % |
| 000253 | Splitting system VAV | Hub RoomZone 5 | HVAC | 60 % |

Figure 7: RFID scanned results listing nearby assets

To extend the locating feature from fixed assets to movable assets, such as a master key or a mobile special tool that is required for fault localization, or even certain mission-critical mobile medical devices deployed inside a hospital which may be difficult to be located for timely fault localization and repair, two advanced RTLS over WiFi as well as Ultra-Wide-Band (UWB) technologies were piloted in EMSD Headquarters. This aims to help locate a concerned equipment more efficiently for fault inspection, diagnosis and localization based on its real-time position. As shown in Figure 8(a), RTLS over WiFi was integrated with the BIM-AM System for locating movable assets in zone level of approximately 3-meter radius. UWB-based RTLS as shown in Figure 8(b) has been successfully examined as a viable solution for applications demanding higher positioning accuracy in the order of centimeters, such as patient tagging.



(a) (b)

Figure 8: (a) RTLS over WiFi; (b) RTLS over UWB

Though these electronics systems are standalone O&M systems/tools in themselves, their capabilities would be much enlarged via interfacing with BIM for O&M application such as fault localization.

## D. *BIM Visualization for Asset Georeference*

RFID technology has its limitations in accurately locating a particular tagged asset due to its fundamental constraints of electromagnetic radiation and orientation of the tag being attached. RFID tag detection is hardly feasible when the tag is attached behind a metal surface. Under such circumstance, cross-reference to the related BIM model could be an effective alternative. The BIM model provides abundant visual information of any MEP installations down to detailed piping and ducting works. Such visualization is particularly useful when the site is not easily accessible or the concerned asset is installed in a concealed area. If the faulty equipment is in a public area, visualization in BIM can eliminate the need for on-site visits, thus significantly reducing interruption and inconvenience caused to the public during fault localization.

BIM is also superior to 2D/3D CAD drawings for fault localization, as its visualization corresponds more closely to the depth and quality of building information. 3D views formulated by 2D CAD drawings of facilities such as elevations, plans and sections are difficult to be visualized. Even 3D CAD images are only composed of graphical entities supplemented with separate document files. Hence, when editing 3D CAD views, checking and updating all related drawings and document files are still required and such operations are error-prone and inefficient. Where spatial information is available in 2D CAD drawings, 3D CAD drawings and BIM model, the information in BIM is deemed more reliable and accurate for fault localization. On the contrary, BIM is a centralized database model with all documents interdependent and carries coordinated information in an effective and efficient way. It allows full BIM integration in the BIM-AM System, which was achieved by associating individual assets with its Global Unique Identifier (GUID) in the BIM model such that each individual asset could be tied to its 3D geometric location. This is far superior to the mere non-geometric information exchange between BIM model and BIM-AM System in other FM/AM software applications. As shown in Figure 9, a VAV box can be visualized and quickly located in its approximate real-world physical location. This enables easy cross-referencing to a BIM model when carrying out on-site fault localization. The BIM-AM System also supports association between an asset and its location in 2D

CAD layout drawing. Figure 10 shows the georeference of a VAV box in a CAD drawing generated by the BIM-AM System. In relation to the value and practicality of georeferencing assets and assets information for O&M applications, a mobile application showing floor plans in JPEG format has been developed and used by EMSD for streamlining fault attendance and site performance measurement activities [20]. In future, it is envisaged that Geographic Information System can also be integrated with the BIM-AM System to enrich the features in managing multiple buildings in a holistic view based on geographical locations.

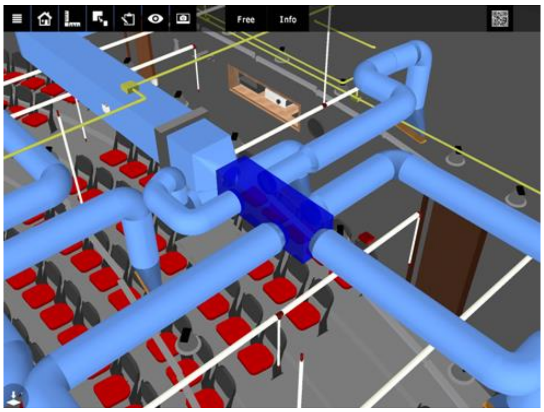



Figure 9: Georeference of a VAV box in a BIM model

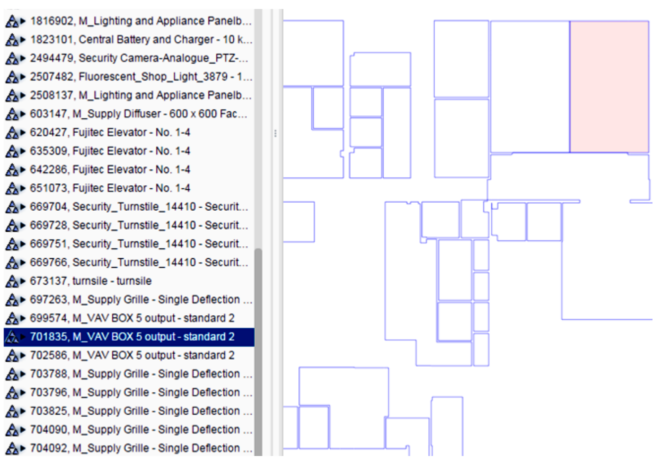



Figure 10: Georeference of a VAV box in a 2D CAD layout drawing

*E. Maintenance Management for Fault Localization*

The BIM-AM System provides a comprehensive and coordinated maintenance management platform for fault handling, especially fault localization. The entire maintenance workflow from service request creation to service order management can easily be achieved. To facilitate fault localization, maintenance engineers must be able to retrieve the service order details before attending the site. In real-life building O&M service situations, the interaction among different parties in the client, contractor organizations and EMSD is dynamic and versatile. The BIM-AM System is able to cater to these highly dynamic interactions by assigning different roles to different parties on its platform to facilitate efficient and effective O&M service, supervision and communication at all times.

In the BIM-AM System, we have identified four key generic user models, namely Client, Helpdesk, Supervisor and Maintenance Engineer. Respective user interface design with system features have been specifically developed for each user model to carry out their role activities effectively at either a desktop or mobile terminal. To make the BIM-AM System design truly generic and versatile, we have worked to ensure that the system can cater for different user operational modes and requirements at different venues. As shown in Figure 11, the user interface for the Maintenance Engineer provides readily accessible asset information, such as asset attributes, maintenance record, equipment relationship, system topology, manual, and system drawing as well as creating service request and cross-reference in BIM.

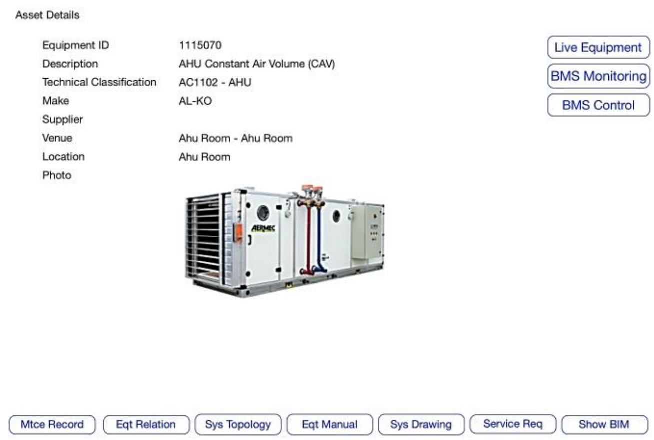



Figure 11: User interface for the Maintenance Engineer

## IV. DEMONSTRATION

To evaluate the effectiveness of the integrated BIM-AM System based on the proposed architecture, maintenance works scenarios using an AHU model in the BIM-AM System was recorded in a video for demonstration purpose [21]. The result shows that significant time-saving of more than two hours can be achieved on fault localization in a typical air-conditioning fault situation as compared with the current practices. The benefits of the BIM-AM System in streamlining fault localization process are summarized in Table 1.

| Fault Localization Process | Current Practices | BIM-AM System |
|---|---|---|
| **Pre-diagnosis via CCTV, BAS & wireless sensors** | Available only on-site | Yes |
| **Off-site identification of fault location & faulty equipment** | Difficult by 2D CAD drawings | Easier by BIM visualization, system topology and RTLS |
| **On-site fault localization and verification** | Difficult if hidden | Easier with the aid of RFID scanner & BIM visualization |

Table 1. Summary of the BIM-AM System based on the novel architecture for streamlining fault localization as compared with the current practices

In fiscal year 2015/2016, the total number of service orders created for maintenance works was about 639,000 in over 2,000 government buildings maintained by the EMSD. Since the maintenance works involved were of different natures and difficulties, projecting the potential time-savings of applying the BIM-AM System to all buildings maintained merely based on these figures without real trials would lead to inaccurate and inconclusive findings. Nonetheless, the benefits of the full rollout of the BIM-AM System are foreseeable. It improves productivity in numerous aspects, such as faster fault response, better workflow management, easy retrieval and appending of maintenance record, prompt access of asset details, relationships and manuals, clear visualization of MEP system routings in 3D and so on. The benefits differ according to venues and applications. One of the key benefits worth mentioning is that the integrated system can enable maintenance engineers to respond faster to incidents and emergencies for fault localization and repair, especially at mission critical venues such as hospitals and airports.

## V. Discussion

Though the successes arising from the proposed pilot BIM-AM architecture and system are only on a limited scale, we hopes the integrated BIM-AM System would not only benefit our services in operating and maintaining over 2,000 government buildings, but also encourage and facilitate the construction industry in Hong Kong to better deploy this new technology for next-generation building O&M services, ultimately benefitting the public. In this regard, we have been collaborating with the Construction Industry Council (CIC) of Hong Kong in designing and building a pilot BIM-AM System for its Zero Carbon Building, with the view to promulgating awareness of BIM-AM to the industry and assisting CIC to formulate the Hong Kong BIM MEP data and drawing standards. Furthermore, the BIM-AM System for the Zero Carbon Building will be used by CIC to promote BIM know-how to the industry. We are delighted to have the opportunity to support the construction industry via our BIM work and will contribute further via more knowledge sharing.

## VI. Conclusion

To streamline and enhance fault localization process during corrective maintenance, we has proposed a novel architecture for exploiting BIM in asset management and realized the concept in an integrated BIM-AM System featuring multiple O&M systems/tools including RFID technology and real-time data acquisition interfaces in one single platform. Results of our pilot project demonstrate that BIM-AM is a highly visual, real-time O&M and asset management tool that can enhance the maintainability and availability of MEP facilities in buildings, especially in streamlining fault localization process. The tool has great potential to bring major benefits including long-term cost savings in the O&M building lifecycle.

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