A BIM-based Decision Support System Framework for Predictive Maintenance Management of Building Facilities

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Abstract:

Facility management (FM) involves multidisciplinary efforts and requires the coordination of different people, properties and processes. Therefore, extensive information of multiple dimensions needs to be stored and managed for FM. Currently, some buildings and facilities are managed manually, while some use databases and automated devices like sensors to capture and manage FM records. However, the current approaches do not fully utilize the collected FM records and provide a user-friendly interface for facilitating the operation and maintenance (O&M) of building facilities. Several academic and commercial efforts attempted to leverage building information modeling (BIM) technology to link and visualize FM records, but these efforts are still weak in proactively predicting asset failure, suggesting maintenance schedules and allocating budget for FM.

This paper presents a decision support system framework based on BIM for O&M of buildings. The framework consists of three modules: Condition Assessment Module, Failure Prediction Module, and Maintenance Planning and Budget Allocation Module. The Condition Assessment Module manages the facility condition data that are automatically captured by sensor devices as well as collected via inspection and condition survey. Incorporated with failure records and lifetime estimation models, the Failure Prediction Module integrates with the Condition Assessment Module and forecasts component failures. The results provide a basis for predictive maintenance of building facilities. BIM is also leveraged to manage and visualize not only the FM data but also the predictive maintenance results. Since each O&M action has its cost implications, the Maintenance Planning and Budget Allocation Module is included in this proposed framework to help facility managers evaluate cost implications and dynamically adjust maintenance plan.

Keywords: Facility Management, Decision Support System, Building Information Modeling, Predictive Maintenance

1. INTRODUCTION

Facility management (FM) is a strategic approach to the optimal capital and operational spending on assets to ensure control of cost and risk, asset life, reliable performance, and stakeholder satisfaction (Teicholz, 2013). Asset and property managers face many difficult decisions regarding when and how to inspect, maintain, repair and renew their existing facilities in a cost-effective manner (Vanier, 2000). To facilitate making these challenging decisions at different operational, tactical and strategic levels, asset managers need to collect and run analytics on key data systematically to create business intelligence (Teicholz, 2013).

Recently, building information modeling (BIM), as a rapidly developing technology, has demonstrated potential for tackling problems in all phases including O&M period. BIM is extensively used in the architecture, engineering, construction (AEC) industry. BIM creates a digital database of all building assets and can serve as virtual 3D coordination of the construction and operational activities (Liao et al., 2012). The benefits of BIM implementation in the AEC industry has been recognized by many researchers. For example, Arayici et al. (2009) listed five benefits of BIM, which are (1) efficient collaboration amongst construction stakeholders, (2) availability of accurate documentation of the building development, (3) common understanding of project costs, schedule, and project progress, (4) ability to assess design alternatives and lifecycle impact, and (5) reduced error, rework, and waste for improved sustainability in design and construction.

BIM mainly provides a structured framework for integrating information of different disciplines and exchange of information about facilities and therefore provides the underlying foundation to support effective FM (Liao et al., 2012). A federal project in New Jersey was studied to use COBie (Construction-Operations Building information exchange) for transfer of data from BIM to the CMMS (Computerized Maintenance Management System) or

CAFM (Computer-Aided Facility Management) system. Onuma System was used for validating COBie deliverables. It also indicated the implementation of COBie has not been fully realized yet (Teicholz, 2012). However, the potential of BIM in the O&M phases have not been fully utilized due to various limitations. For example, poor access to accurate data/information/knowledge in a timely manner; lack of interoperability between software systems; limited integrated view of multiple domains for decision support; and inability to assess uncertainties, risks, and the impact of failures (Akanmu et al.,2014).

Among different facility management tasks, facility maintenance is particularly important and it directly effects the service level and customer satisfaction of built facilities. Effective facility maintenance management (FMM) can help facility managers to identify problems early and maintain the facility in a time, cost and resource effective manner. For facility managers, other than only maintenance, identifying the optimum maintenance and management strategies and repairing facilities before faults occur have become increasingly important. Commonly, the maintenance strategies for buildings are reactive maintenance and preventive maintenance. However, they are often conducted during breakdown repair and cannot really prevent failure of equipment and machines. In order to improve FMM, this paper will use another kind of maintenance strategy, predictive maintenance (PdM). PdM is the condition-based or condition monitoring approach to maintenance. This approach helps by measuring the condition of the equipment using tools such as vibration analysis, infrared thermographs, ultrasonic detection (Hisham, 2003) and involves inspections at equipment running conditions and during stoppage periods. Zhou et al. (2005) presented an intelligent prediction and monitoring system for equipment failure prediction to support equipment maintenance. Until now, it is mainly used for the machine maintenance in manufacture industry, but not for building facilities maintenance. In this paper, this paper attempts to apply PdM into building facility maintenance.

The above mentioned studies did not combine PdM and BIM-based FM to improve the maintenance process of building facilities. This paper presents a framework of BIM-based decision support system, which is based on BIM models, online monitoring systems, and facility management software with three modules to provide a better way of decision making in predictive maintenance. The system aims to dynamically adjust maintenance plan according to real-time data acquisition. In following sections, the DSS framework is illustrated, including information layer and application layer. Moreover, the application methods of three main modules are introduced in detail. The paper also provides useful recommendations for facility managers to conduct better predictive maintenance.

2. THE PROPOSED BIM-BASED DECISION SUPPORT SYSTEM FRAMEWORK FOR PREDICTIVE MAINTENANCE MANAGEMENT OF BUILDING FACILITIES

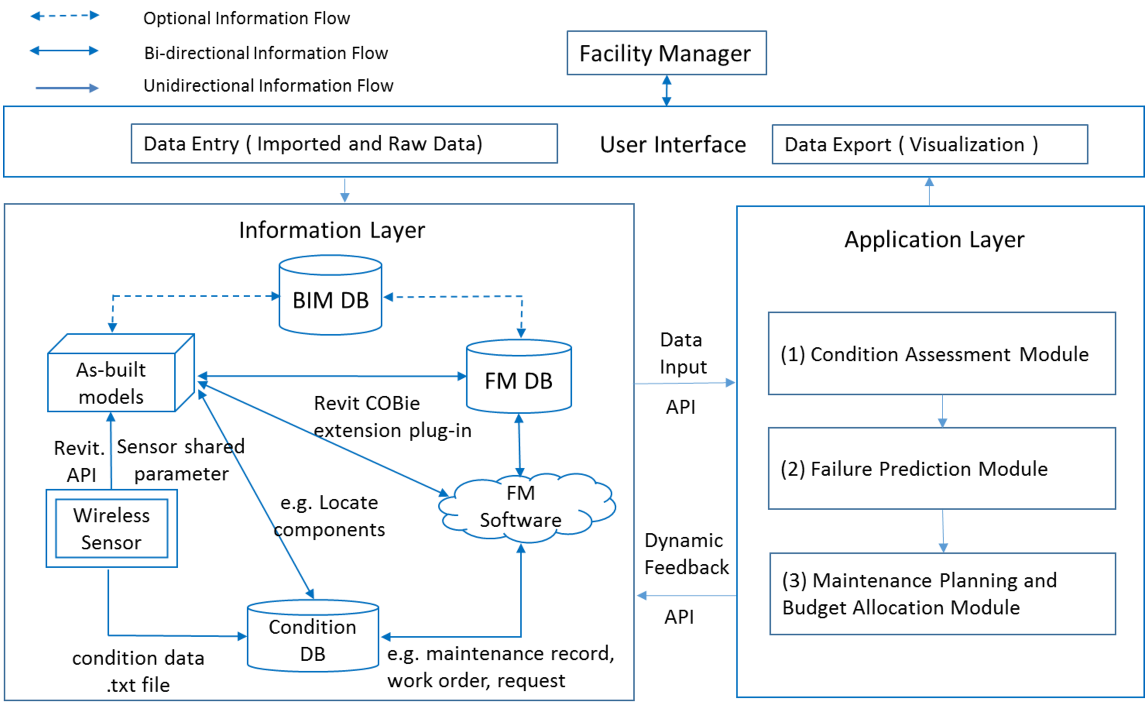

Figure. 1 The proposed BIM-based decision support system framework for predictive maintenance management

The paper proposes a decision support system (Figure 1) that integrates as-built BIM models, and historical and real-time maintenance information from facility management system (e.g. historical maintenance record, work order and maintenance request), as well as real-time data and analysis results from condition monitoring system. In addition, in order to improve facility maintenance process, three modules are recommended to facility managers for decision making. Based on real-time data from online condition monitoring system and condition survey, condition assessment module provides the current condition of each building component or system for next failure prediction. Not like the common preventive maintenance strategy, this paper introduces predictive maintenance by using failure deterioration algorithm to forecast the future condition and remaining life time of system and component. Based on the result from the failure prediction module and data from information layer, the system also enables FM manager to dynamically adjust the maintenance plan and budget allocation in the last module.

2.1 Information Layer

2.1.1 BIM-FM Model Creation

(1) BIM Model

BIM model can be considered as a big database by itself. The LOD (Level of Development) framework addresses these issues by providing an industry-developed standard to describe the development situation of various systems, assemblies, and components within a BIM model. LOD is essentially how much detail is included in the model element. The definitions for LOD 100, 200, 300, 400, and 500 are included in different literatures such as the LOD Specification developed by BIM Forum (2015).

When the as-built model is delivered to the owner, including information of attributes, layout, material, properties, geometry and placements, etc., the model element must meet the facility information requirement (LOD500) for maintenance and operation. The model element of LOD 500 is a field verified representation in terms of size, shape, location, quantity, and orientation. Importantly, non-graphic information may also be attached to the LOD 500 model elements, which enables managers to add more attributes and description information into BIM model for satisfying the extended information requirement in FMM.

(2) Facility Management Software

Traditionally, FM data and information are organized and maintained in dispersed information systems such as CMMS, CAFM, Integrated Workplace Management System (IWMS), etc. CMMS is utilized by facility maintenance organizations to record, manage, and communicate their day-to-day operations (Sapp, 2015). It can be deployed for asset management, inventory control, generation of service requests, managing work orders of different types, and tracking the resources (time and costs) of services and materials used to complete work orders (Parsanezhad & Dimyadi, 2014). CAFM system integrates a Computer-Aided Design (CAD) graphics module and a relational database software to provide various facility management capabilities (Sapp, 2015) including space management (e.g. administering room numbers, departments, usable heights, room areas etc.). It also provides means to collect data from a variety of sources through technology interfaces and link to other systems (such as CMMS) or human transfer processes. IWMS has many of the functionalities as CAFM system with an emphasis on estate portfolio and space management.

At present, software developers also developed different commercial FM software, like EcoDomus, Onuma system, FM: system (FM: interact), ARCHIBUS, IBM Tririga, BIM 360 field, etc. CMMS or FM system records data about equipment and property including maintenance activities, work orders, specifications, purchase date, expected lifetime, warranty information, service contracts, service history, spare parts and anything else that might be of help to management or maintenance workers. After comparing these current FM software, they have some common functions, such as space management, move management, asset management, maintenance management, etc. The majority have developed mobile applications to enable facility managers to securely access, update and report facility data in the field with a mobile device, which improves the productivity of FM. In addition, most FM software support COBie format, and some of them can integrate with GIS.

Even with the wide variety of software applications are available to meet the requirement of facilities management, there is no single application that would encompass the diversity of all FM requirements (Sabol, 2014). Bentley Systems are developing intelligent models to intake, organize, present the data of equipment and facility from varying software sources, and finally merge data into a single BIM model. Middleware solutions, such as EcoDomus, acting as a bridge between a BIM model and database. These systems have shown promise for sizeable organizations but are relatively expensive (Parsanezhad & Dimyadi, 2014).

(3) Integration of BIM Model and FM Software Using COBie

In 2007, COBie was created as a new way for designers and contractors to directly provide information of electronic operations, maintenance, and asset management. As a performance-based specification for facility asset information delivery, two types of assets are included in COBie: equipment and spaces. It is used for the information exchange between BIM and FM software. COBie attempts to utilize the open data format provided by IFC (Industry Foundation Classes) to bridge the gap among design, construction, and O&M by mapping commonality within the FM process. By approaching FM activities with an open standard and interoperable set of standardized attributes, users can then customize the data to meet their facility needs. Therefore, some large organizations and scholars start to study the information exchange and information management in O&M period. Some pay attention to investigate whether and how IFC and COBie can deliver the data and information about assets required by facility managers in a life cycle, such as Rasys et al. (2014), Patacas et al. (2015), Wetzel & Thabet (2015).

Recently, Autodesk Inc. has developed a plugin, COBie extension for Revit, to connect Revit and FM software using COBie. This plugin can be installed into Revit to get COBie-embedded BIM model, and simultaneously set some parameters and information of building components for facilitating maintenance, like warranties, spare part lists, equipment lists and product data sheets. In addition, the plugin can bi-directionally transmit COBie data in spreadsheet between FM software and BIM model for further facility information management.

Moreover, as-built drawings needed for effective maintenance and operations of facilities often contain errors and omissions, particularly electrical, control and instrumentation documentation. Therefore another plug-in, namely Autodesk Revit Model Checker, was developed to automatically check Revit models and help with verifying their compliance to BIM Requirements (Autodesk, 2015). With hundreds of different checks and the ability of batch checking against multiple models and their corresponding links, the Autodesk Revit Model Checker assists owners and design consultants in providing high quality Revit models for all of their BIM projects.

2.1.2 Condition Monitoring

Condition monitoring is defined as the collection and interpretation of parameters of the relevant building component and system for the purpose of identifying the state of system changes from normal conditions and trends of the health of the component. Actually, predictive maintenance is a key consequence of condition-based maintenance. Condition monitoring has become a plant optimization and reliability improvement tool rather than a maintenance management tool (Mobley, 2003). Fault monitoring systems play an important role in predictive maintenance (Miyagi & Riascos, 2006) because these systems monitor changing signs of machine under the operating condition of the machines. Moreira et al. (2015) studied a condition monitoring system using petri nets, and the significant result of his work was the assessment of the condition monitoring system architecture by simulating process and resource optimization, and eliminating the possible deadlocks. Similarly, PdM can be applied to buildings facility maintenance management. First of all, how to use sensor technology and map sensing data into BIM models are essential when applying PdM.

(1) Sensor

The sensor technology of condition monitoring was firstly used for machines in the manufacture industry. According to Moubray (1997), vibration monitoring and lubricant analysis are the most effective, proven and validated techniques for condition monitoring in countless industries. In building condition monitoring, typical monitoring aspects of sensor include (1) temperature and humidity monitoring, (2) power usage- current monitoring, (3) water flow- pump performance, (4) air flow- filter clogs/ reduced performance, (5) leak detection -coolant system leaks, (6) air pressure- air compressor system failures and leaks, etc.

It should be noted that, not all information directly indicates the status of building components. Some of them directly present the status of building components, for example, decreasing illumination intensity shows the poor lighting condition. But some others are just external environment parameters, such as temperature, humidity and pressure. Therefore, we need to use failure prediction method to diagnose condition of building components and predict future failure time and service life time according to these parameters.

There have been already some studies on the combination BIM with sensor. But, embedding sensors to BIM model in the design phase and then using them for building monitoring have not been explored yet. Akanmu et al. (2014) proposed a cyber-physical system, which utilized sensors to link the virtual model with real world. However, there is lack of study on using sensor on BIM-based FM.

(2) Monitoring System Setting up

According to data processing procedure, we set up the monitoring system for condition data from sensor. The process is as following:

(1) Install sensors into building components according to different service systems.

(2) Pre-process obtained sensor data in control box through signal decoding, and some indicated condition parameters and external environmental parameters can be achieved.

(3) Map sensor data into BIM model for visualization using Revit. NET API (Application Programming Interface), which will be explained in next part.

(4) Finally store condition data into condition database (DB) for next FMM process, since BIM model cannot store all condition data. The monitoring system is showed in Figure 2.

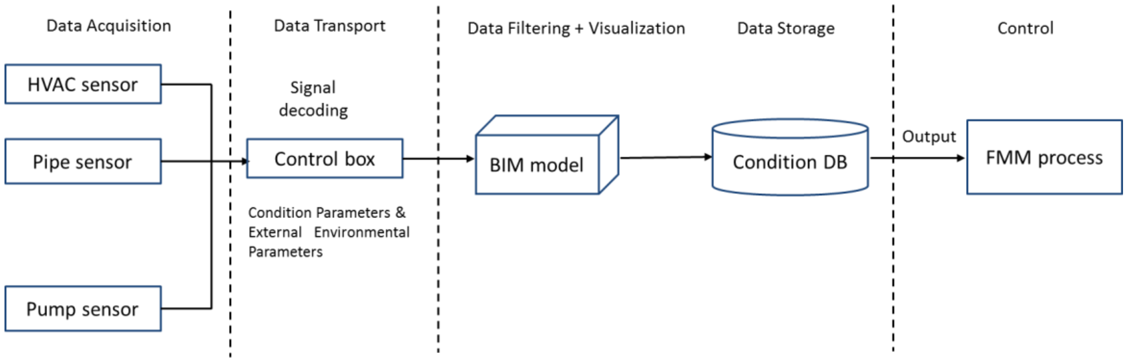

Figure. 2 Monitoring system in decision support system

(3) Mapping Sensor Data into BIM Model

Until now, Revit and other BIM design software have not had such functions to receive, store data from real time sensors and visualize them, so we need to develop a Revit plug-in to achieve dynamic sensor data. This plug- in is developed using Revit .NET API to extend the core functionality.

Firstly, there is no sensor type in IFC entity. In order to transfer sensor data into BIM model, sensors are set as *IfcSensor* type when we create the sensor family in Revit for a neutral data format. IFC data model is not only a standard format to describe building and construction industry data, it can also facilitate the interoperability among different software platforms. Entities such as *IfcSensor* and *IfcSensorType* can be used to represent sensors.

Secondly, we create shared parameters for each sensor. Shared parameters can be added to families or projects in Revit, which gives users the flexibility to add specific data that is not predefined in the family file or the project template. Since sensor is created as a new family, we can use shared parameters for storing the data. However, shared parameters in BIM model can only record transient monitoring data, thus the whole sensor data will be then stored in the condition DB eventually (Figure.2).

These sensor data is subsequently merged into BIM model and processed for visualization through the new plug-ins in Revit. Finally all the sensor data can be easily accessed in BIM model for condition assessment.

2.2 Application Layer

2.2.1 Condition Assessment Module

The real time monitoring of these sensor data is crucial for assessing the status of building component under different environmental conditions. After getting condition data from sensor, the common process (Ahluwalia, 2008) of condition assessment is as following.

(1) Identify the component list of deficiencies that should be assessed in each building system.

(2) Set a condition index scale which is used to assign a value that represents the component condition. This scale is used to represent the numeric values related to the linguistic representation. The scale is from 0 to 100; where 0 is failure and 100 is excellent condition. Another method is defining the condition using five degree: very good, good, fair, poor, and unacceptable, which is usually used in FM software, e.g. Maximo and ARCHIBUS.

(3) Calculate the condition index of each component.

(4) Set a relative weight for each component in the same building system.

(5) Calculate the condition value of each building system.

To support the maintenance work, sometimes FM staff needs to conduct condition survey in person for more accurate condition assessment. The above assessment method is also suitable for manual condition survey.

2.2.2 Failure prediction module

Since facility maintenance faces problems of random failure and inherent deterioration of building component, predictive decisions based on condition monitoring, condition assessment and the prediction of the trend of building system deterioration are critical for maintenance decision making and planning.

In fact, failure prediction is divided into two steps. 1) Determination of the pace trend considering the factors accelerating or decelerating the trend of deterioration of components; 2) Analyzing the sequence of deterioration from a higher level condition to a lower condition using following three types of methods (Table 1).

(1) Prediction Scheduling

Prediction scheduling is made before conducting prediction to get more accurate prediction, reduce system processing task and save forecast cost. Set a trigger in the monitoring system to indicate the timing (T_1) of taking prediction actions. In other words, when sensor data crosses threshold limits, which is determined based on the historical condition data and historical maintenance records, a trigger will be touched and FM manager will use the DSS to predict the future failure curve.

(2) Failure Prediction Methods

The deterioration trends vary in different building components and different systems. This module not only presents the prediction process, but also acts as a method pool to provide suitable methods of deterioration prediction for different components. These methods can be classified in three categories; deterministic models, statistical/stochastic models and Artificial Intelligence (AI) models (Tran, 2007). This area has been studied by many researcher and part of research achievements are showed in Table 1.

Table 1. Different failure prediction methods for building components

Methods Type	Method	Author and Year	Building Component
Deterministic Models	Linear Methods	Kliener & Rahani, 2001 Lou et al., 2001	Water mines & pavements
	Exponential Deterministic Models	Mishlani & Madanat, 2002	Pipe
Statistical Models	Markov Chain	Madanat & Ibrahim, 1995 Baik et al., 2006 Sharabah, et al., 2007 Cinlar et al., 1977	Bridges Sewers Building assemblies Creep of concrete
	Gamma Process	Lawless& Crowder, 2004	Fatigue crack growth
Artificial Intelligence	Artificial Neural Network	Sinha & Pandy,2002	Sewer constructions
	Fuzzy Set Theory	Cattan & Mohammadi, 1997	Bridge deterioration
	Case-Based Reasoning	Sinha & Pandy,2002	Oil & gas pipe lines

The table indicates knowledge in forecasting deterioration method at the building component level to recommend FM manager to choose right methods. These suggested prediction methods are used combining with condition assessment result and monitoring condition data. The outcomes of this module include the failure curve, the coming time point of failure (T_2), and the remaining service time (T_2-T_1). The historical maintenance records from FM software, as-built model, condition survey data from condition DB, as well as this module outcome, will be used for next application module.

2.2.3 Maintenance Planning and Budget Allocation Module

(1) Maintenance Planning

Maintenance work involving time and resources (labor, tools, material and capital) often encounter scheduling problems. Maintenance planning usually consists of various work orders, such as setting maintenance priority, handling maintenance request and resident complaints. Providing an optimal maintenance plan by using an optimization approach can help reduce time, labor, and financial expenses, as well as further enhance facility reliability, ultimately reducing the likelihood of sudden damages in a facility.

According to the failure time point T_2, we decide the maintenance timing T_2' (T_2'<T_2) and give the initial maintenance plan based on work orders. And then we adjust the maintenance plan according to priority and budget limitation. For example, when two work orders have time conflict, the priority is given to more important work, which will cause more serious impact if it breaks down.

In this module, the work flow of a maintenance work order is presented in Figure.3. When the maintenance timing T2' is up, firstly FM manager applies BIM technology for positioning damaged component in BIM model. Next, FM staff inspects the component condition in site and decides maintenance type (repair or replacement). For replacement action, BIM also enables maintenance staff to navigate by the shortest path for reaching spare parts. After maintenance finished, the maintenance record will be updated in FM system for corresponding components. In the process, the maintenance plan is visualized in FM software. This module can also adjust maintenance plan dynamically if the prediction result has any change.

(2) Budget Allocation

According to Figure. 3, each action in maintenance generates maintenance cost in terms of time and resources, and we totally calculate all of them to get cost of each maintenance work order. Based on annual budget or semiannual financial report, the FM manager can adjust maintenance budget according to the actual situation. Additionally, FM manager needs to keep reserved funding for handling emergency events. For example, in Hong Kong, typhoon usually appears every year and damages many facilities and equipment in a building. Based on PdM, FM managers can have inventory list of spare parts in advance and thus do not need to store more spare part to take up more money and space.

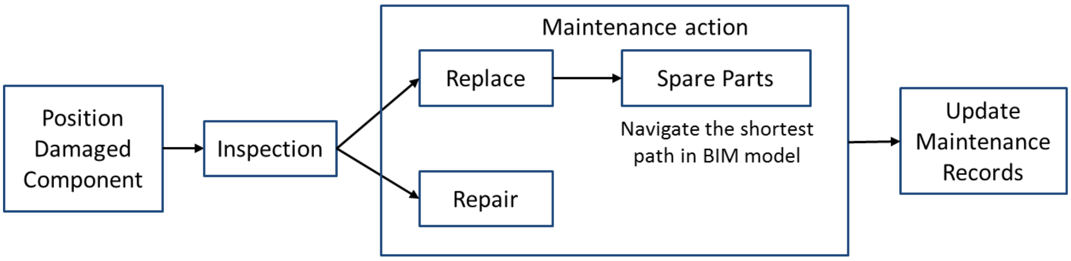

Figure. 3 Work flow of a maintenance work order

3. DISCUSSION

This framework benefits facility managers in several aspects to solve problems existing in maintenance of modern buildings. These aspects are as follows: (1) Pre-plan and pre-schedule maintenance work for building components and sophisticated systems under a complex operating environment. (2) Capture real time condition data from sensor for more accurate maintenance. (3) Avoid the risk of catastrophic failure and eliminate unplanned forced outage of components or systems. (4) Leverage the advantages of BIM to make maintenance tasks more convenient (e.g. position damaged component). (5) Increase the percentage of predictive maintenance actions to decrease the maintenance cost, the quantity and space of the spare parts required for emergency repairs.

In the future, this system will also need to integrate or cooperate other related systems including geographic information systems (GIS) and enterprise resource planning systems (ERP). Besides, in order to gain control over facility data at all stages, project managers and facility managers can embed sensor into their system for spatial sensing and imaging technology. Mobile devices and solutions (e.g. ARCHIBUS Mobile Framework) are also necessary for FM managers and technicians.

In the BIM-based facility maintenance management, the biggest utilization value of BIM is taking the advantage of data mining technology to find the useful information to reduce cost and optimize maintenance plan. That will be our future main work.

4. CONCLUSIONS

Getting appropriate and reliable information about a facility (e.g. product data, warranties and predictive maintenance schedule) is pivotal for enabling facility managers to support decision making, planning and execution of activities, particularly during O&M period. This paper aims to apply effective monitoring system and predictive maintenance to building components using BIM-based FM. It presents a conceptual framework of BIM-based and data-driven decision support system for facility maintenance management. Three functional modules are illustrated and recommendations are given for facility managers to conduct predictive maintenance using this framework.

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