LEVERAGING BIM FOR AUTOMATED FAULT DETECTION IN OPERATIONAL BUILDINGS

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ABSTRACT

Building Information Modeling (BIM) is an increasingly popular method for generating and managing facility information during the life cycle of a building, ranging from facility conceptualization, through design, construction and its operational life. Organizations involved in Facility Management (FM) have the opportunity to use BIM as a knowledge repository to document evolving facility information and to support decisions made by the facility managers during the operational life of a facility. This paper demonstrates the potential of using BIM to develop algorithms that automate decision making for FM applications. The potential of utilizing BIM as an analysis tool is demonstrated through the scenario of HVAC (Heating, Ventilation, and Air Conditioning) system failure in an operating facility. In case of a typical HVAC malfunction today, facility occupants record complaints in a ticketing database maintained by the FM organization. Upon receiving notification of HVAC system failure, facility inspectors visit the location to confirm the reported failure. Upon confirmation, facility managers review building plans and specifications to develop a detailed plan of action to repair any HVAC components suspected of damage. Based on the plan of action, inspectors visit the facility to inspect and, in case of damage, repair the appropriate HVAC system components. These FM practices – as currently implemented across the industry – are labor intensive, time consuming, and often rely on unreliable and outdated information. To address these shortcomings, the authors propose an alternative methodology of HVAC fault detection in operational buildings. The authors implement an algorithm that leverages complaint ticket data and automates BIM to determine potentially damaged HVAC system components. Based on the list of HVAC components suspected of damage, the algorithm develops a plan of action for the facility inspectors. Finally, the authors discuss the advantages of the proposed method as well as the challenges of implementing automated BIM-enabled decision making processes in the FM industry.

KEYWORDS

Facility Management, Building Information Modeling, Automation

INTRODUCTION

Facility Management

Facility Management (FM), as defined by the International Facility Management Association (IFMA), is a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, processes and technology. FM practices contribute to 5-10% of the gross domestic product in developed countries [Madritsch et al. 2009] and the total life cycle costs of a facility could be as much as 7 times higher than the initial investment costs [Seul-Ki et al. 2012]. Moreover, more than 85% of the total costs of ownership are spent on FM activities [Teicholz 2004]. Considering this significant cost associated with the operations and maintenance (O & M) phase of facilities, the importance of developing efficient FM practices is clearly understood in the industry and among owners. Since FM activities are information intensive and all related decision making processes involve vast amounts of data, having real-time and efficient access to information is essential to make the maintenance of the facility more feasible. However, due to communication gap between the contractor and the owner, FM processes are usually time consuming and laborious. Upon completion of a project, the contractor hands over to the owner an enormous amount of as-built information. Then, the owner/facility manager spends a significant amount of time and money on the documents to implement the information into a facility management system. This is mainly due to the incompatibility of the information systems supporting FM practices. According to NIST, the capital facilities construction industry wastes $15.8 billion annually due to interoperability inefficiencies, where $5.2 billion of it is attributed to the participants within the Architecture, Engineering, and Construction (AEC) industry and the remaining $10.6 billion loss is attributed to the owner/facility manager during the O & M phase of the facility [Newton 2004].

Building Information Modeling

The National Building Information Model Standard Project Committee defines Building Information Modeling (BIM) as a digital representation of physical and functional characteristics of a facility [BuildingSMART Alliance 2013]. BIM is a value creating process that involves the generation, management, and exchange of knowledge of a facility forming a reliable basis for decision making throughout its life cycle – from the conceptual, design, and construction phases, through its operational life and subsequent closure [East and Brodt 2007]. As a comprehensive digital database it is gaining acceptance as the preferred tool of communication during the design and construction phases. While the use of BIM is usually limited to design and construction, owners and facility managers have realized its potential and persist on inheriting BIM models for further use. The authors propose Figure 1, which illustrates the potential uses of BIM in different phases of any constructed project during its life cycle. The bold text in Figure 1 indicates the new potential areas and applications that the authors believe BIM can be highly beneficial and are continuously working on.

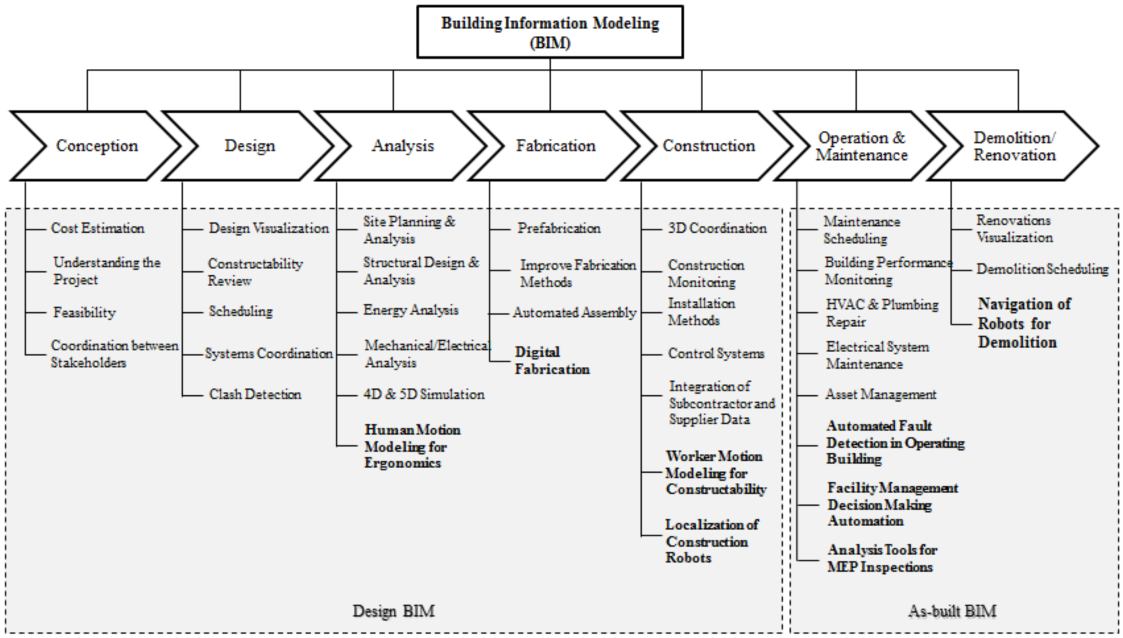


Figure 1- Potential applications of BIM during a facility's lifecycle

The use of BIM during the design and construction phases has received considerable attention in the AEC field from the professional community [Becerik-Gerber et al. 2012; Smith and Tardif 2009] as well as the research community [Azhar et al. 2008; Eastman et al. 2008; Goedert and Meadati 2008; Khemlani 2009] and has evolved into a mature practice. The use of BIM during design phase for maintainability, clash detection [Dunston and Williamson 1999; Eastman et al. 2008; Leite et al. 2009], and energy and sustainability analysis [Barnes 2009; Cho et al. 2010; Miller 2010; Stumpf et al. 2009] has shown significant promise. BIM has been proposed as a platform for multi-disciplinary collaboration [Singh et al. 2011; Tatum and Korman 2000] and project control [Hwang and Liu 2010] during construction. Several problems that occur with the current procedure for construction hand-over documents have also been investigated [East and Brodt 2007]. The process of capturing accurate as-built BIM data, for buildings in the construction and post-construction phases, has also received significant attention in recent years [Huber et al. 2011; Liu 2012; Woo et al. 2010].

Potential benefits of implementing BIM in the O & M phase is widely accepted among researchers [Motawa and Almarshad 2012], and related research indicates great tendency in the industry to gain advantage of the new and unique opportunities that as-built BIM offers [Becerik-Gerber et al. 2012]. Wireless Sensor Networks have been integrated with BIM to monitor physical and environmental conditions during the operation stage of the building [Eastman et al. 2008]. Opportunities for utilizing BIM for facility management have also been investigated with focus on supporting maintenance planning [Akcamete et al. 2010] and identifying useful information in a BIM model needed by facility managers [Anoop et al. 2011]. The concept of Facilities Management Classes (FMC) - a collection of object class definitions for representing the information used in carrying out FM activities – has been developed to support the sharing and exchange of information among FM applications within an integrated environment [Yu et al. 2000]. BIM has the potential to improve communication and interoperability in FM by eliminating inefficiencies and streamlining the O & M systems for facilities [Akcamete et al. 2010]. However, despite the clear benefits of using BIM in FM practices, research related to utilizing BIM in FM is still in its infancy. The authors believe that developing and introducing

BIM based applications for FM is essential for increasing the adoption of BIM in the O & M industry. The authors identified the facilitation of decision making for FM purposes as one of the main areas where the use of BIM can be highly beneficial.

MOTIVATION – HVAC SYSTEM FAILURE

For the purpose of this study, the authors have investigated the process of inspecting and repairing damaged HVAC equipment as implemented at UM Plant Operations. UM Plant Operations office is the resource for all facility maintenance services at the University of Michigan. The office provides around-the-clock building maintenance, operation and environmental monitoring for over 30 million sq. ft. of facilities that serve the university campuses, hospital and health centers. One of the main tasks of the office is the maintenance and repair of the Mechanical, Electrical, and Plumbing (MEP) systems and equipment – from electric outlets or thermostat in an office, to a 1200-ton centrifugal chiller – including HVAC systems.

Upon HVAC system failure, the facility occupants report deterioration in performance to UM Plant Operations office's ticketing database. UM Plant personnel, responsible for HVAC maintenance, reconcile the reported malfunction with the facility's paper plans, blueprints, specifications, and inventory documentation. The personnel then try to localize the potentially failed equipment and generate a plan of action based on their judgment and experience. The plan of action is used as a guide by field personnel to inspect the HVAC system for failed equipment and repair if failure is detected. This process – as currently implemented across the industry – is labor intensive, time consuming, and often susceptible to unreliable or outdated information.

While executing the maintenance and repair tasks, FM personnel need real-time access to vast amounts of facility information. By using BIM models instead of paper blueprints, FM personnel can reconcile real components with corresponding 3D models and guide themselves through the system to promptly execute the plan of action. Integrating BIM with FM databases also makes the repair process more efficient by providing personnel with relevant information such as specifications and history of failure of equipment. While real-time visualization of equipment information and topology helps FM personnel in streamlining their operations, the authors believe that the true potential of BIM is realized as an analytical tool to support decision making in FM. The authors propose automating the process of fault detection and generation of the plan of action for field inspectors – as described in the following section – thus enabling prompt access to relevant information regarding failed equipment and saving considerable repair time and effort.

METHODOLOGY

HVAC Distribution Network Model

The research presented in this paper was conducted by investigating the HVAC system of the G.G. Brown Building at the University of Michigan, shown in Figure 2 (a). The authors created a BIM of the investigated building based on the as-built plans. Figure 2 (b) shows a section of the BIM with its HVAC equipment. For reasons mentioned before, it is highly recommended that owners inherit the as-built BIM of the building from the contractor upon completion of the project.

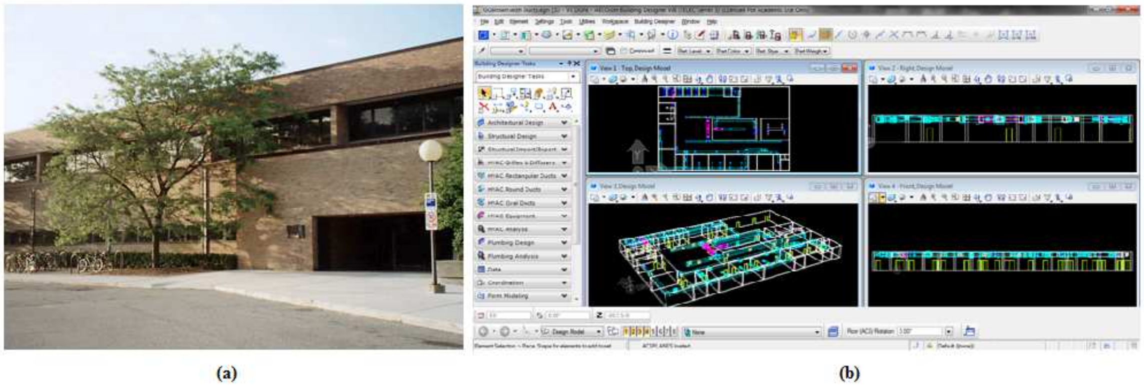


Figure 2 - (a) The G.G. Brown Building and (b) HVAC BIM of a section of the building

The HVAC BIM is used to extract and store the distribution system logic as a tree network by traversing the various HVAC distribution paths – starting from the central HVAC unit and ending at the occupant rooms. HVAC components (supply ducts, heating/cooling coils, air blower units, etc.) are modeled as nodes and their physical layout determines the tree network precedence. One such HVAC distribution system and its corresponding tree network are shown in Figure 3 (a) and 3 (b), respectively. The problem of automatically detecting faults in the system then reduces to localizing the nodes that have most probably failed for a given set of reported complaints. It is important to note that the fault detection method presented is limited by the use of occupant room temperatures, HVAC distribution topology, and activity status as contextual parameters. The implementation of a fault detection algorithm that also considers the functional characteristics of the nodes in the HVAC distribution tree as contextual parameters is likely to improve the performance of the fault detection system.

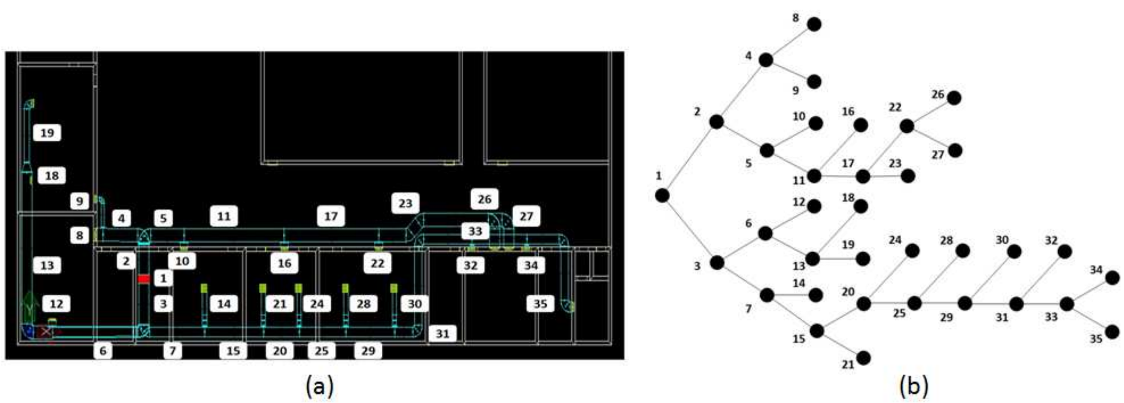


Figure 3 - (a) An HVAC distribution system and (b) its corresponding tree network model

HVAC Malfunction Ticketing and Deterioration Model

The authors propose a web-based ticketing system, as shown in Figure 4 (a), which can be accessed by all occupants. Upon experiencing deteriorated performance, the occupant submits the information requested in the web-form, including room number, set (desired) temperature, and current (observed) temperature. The ticketing system also monitors and records the outdoor weather and temperature conditions when the complaint was submitted.

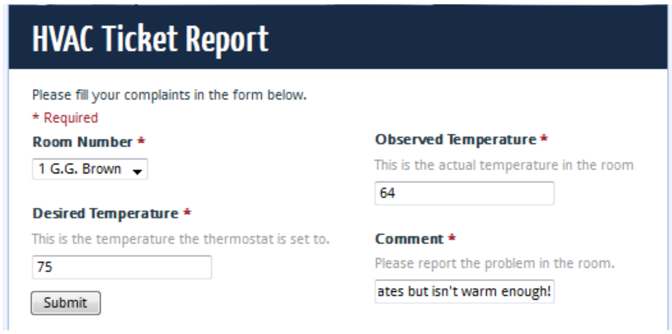
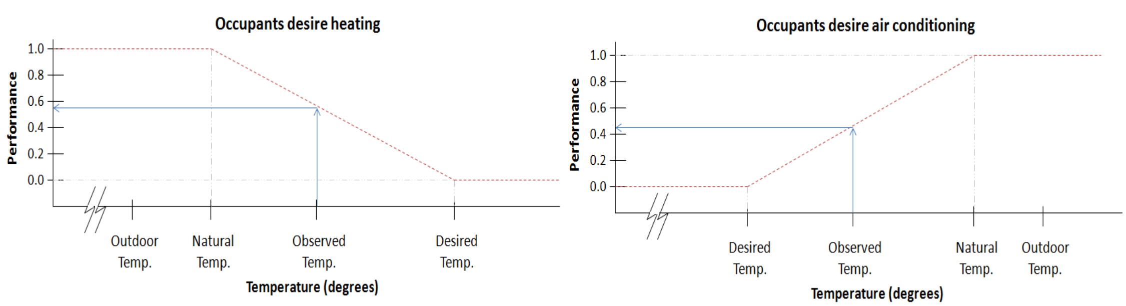


Figure 4 - Web-based ticketing system form to record occupant complaints

The deterioration in HVAC performance is modeled as shown in Figure 5 (a) and 5 (b) for heating and air conditioning, respectively. The outdoor, observed, and desired temperatures of the occupant's room are inherited from the ticketing system. The natural temperature of the room is the temperature of the room without any HVAC supply for a given outdoor temperature. The natural temperature is a function of outdoor temperature and the materials used in constructing the facility and can be determined by recording a series of observations when the HVAC unit is turned off. The deterioration model maps the HVAC performance to a scale of 0 to 1, with 0 being representative of perfect performance and 1 being representative of total failure. If observed temperature is equal to desired temperature, it is considered as a perfectly functioning system. If observed temperature is equal to natural temperature, it is considered as a total failure of the HVAC system. The authors model the performance between the desired and natural temperatures as a linear deterioration. The occupied rooms, where deterioration in performance may be reported, are the leaf nodes of the HVAC distribution tree network.



(a) (b)

Figure 5 - HVAC performance deterioration model for (a) heating and (b) air conditioning

Fault Detection Algorithm

The authors adopt an algorithm [Leckie and Dale 1997] that uses the information-theoretic minimum message length principle to locate faults in the HVAC tree-structure network model. The inputs of the algorithm are the HVAC distribution tree-network, the HVAC performance at the leaf nodes, and the probability distribution of HVAC performance at the leaf nodes for two cases – when the occupant room corresponding to the leaf node is 1) affected by HVAC failure, and 2) unaffected by HVAC failure. For each occupant room (leaf node), the probability density function of HVAC performance—if the occupied room is affected by HVAC failure—is modeled by observing the reported performance metrics over several historic instances of HVAC failure. The authors assume that if HVAC failure does not affect the occupant room, then the occupant will not report deteriorated performance and the default performance of such leaf nodes are assumed to be 0 (perfect).

A set of observed HVAC leaf node performances could be the result of several possible fault combinations. For each such possible fault combination, the algorithm first constructs a message that explains the fault combinations and the performances. The algorithm then selects the fault combination with the minimum message length to be the most plausible fault combination [Leckie and Dale 1997]. The algorithm localizes a set of HVAC components that are most likely at fault for the deteriorated performances observed in the system. A detailed discussion on the adopted minimum message length algorithm [Leckie and Dale 1997] is beyond the scope of this paper.

HVAC System Repair Workflow

The authors developed a BIM plug-in application, shown in Figure 6, to assist HVAC facility inspectors in determining their plan of action. Upon querying, the application extracts the HVAC distribution tree networks corresponding to the facility from its BIM model. The application acquires the tickets corresponding to the facility and generates leaf node performance measurements using the deterioration models. The application invokes the fault detection algorithm and determines the set of HVAC components that are most likely at fault. The application then generates the plan of action by requesting the inspector to repair the components suspected to be at fault – starting from those farthest away from the root of the HVAC distribution tree.

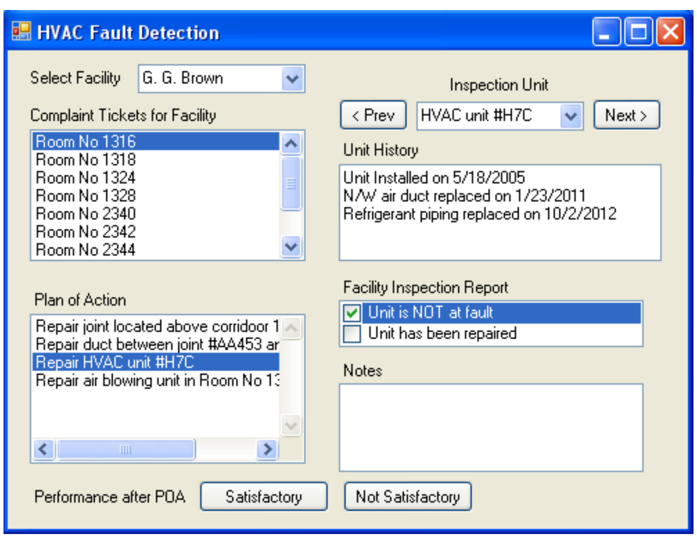


Figure 6 - The developed BIM plug-in application

For each component suspected to be at fault, the inspector either 1) finds the equipment to be faulty, repairs it, and reports it as repaired, or 2) finds no-fault in the equipment and reports it to be undamaged. After investigating all such components, the inspector returns to the rooms where deteriorated performance was recorded and monitors the HVAC performance. If the HVAC performance is not found to be satisfactory in some rooms, the inspector generates new tickets for all such rooms. The plug-in then modifies the HVAC tree-network by eliminating those nodes corresponding to the list of components that were deemed to be undamaged and/or repaired by the inspector. The sub-trees originating at these nodes are attached to the node's parents. The plug-in then utilizes the newly generated HVAC tree-network and ticket data to determine a plan of action for the inspector to follow. This process is repeated until the HVAC performance is deemed satisfactory by the occupants. The authors propose using this BIM plug-in on a tablet device at the job site, which will highly reduce the time and effort spent by the FM personnel by eliminating the need to go through all the paper plans and blueprints at the main office.

SUMMARY AND CONCLUSION

The use of BIM in the AEC industry is largely restricted to the conception, design, and construction phases of a building's lifecycle. In the O & M phase, BIM can be used by FM personnel as a database to document evolving facility information. The authors believe that the true potential of BIM in FM is realized by using the BIM database to automate decision making tasks. The potential of using BIM to automate decision making by using the scenario of HVAC system failure has been demonstrated in this paper. One method to model the HVAC distribution system and the deteriorated HVAC performance which are used by the fault detection algorithm is also presented. The authors deployed a fault detection algorithm that uses the minimum message length principle to localize those HVAC components most likely at fault. Based on the fault detection algorithm, a workflow method is presented that uses the developed BIM plug-in to generate the facility inspectors' plan of action. This BIM plug-in guides the HVAC repair operations and eliminates the time and effort spent by FM personnel to manually do the same based on their judgment and experience.

Limitations and Future Work

The authors assume that occupants experience either perfect or deteriorated HVAC performance and do not consider rare cases where HVAC over-performs. The HVAC performance deterioration is modeled as a linear mapping but in reality, 'performance' is a subjective term and the deterioration model experienced by most occupants is not necessarily linear. The probability density function of HVAC performance under failure is developed by observing performance metrics corresponding to failure history. However, historic patterns of HVAC performance in case of failure may not be an accurate representation of future performance under similar conditions. The accuracy of the fault detection algorithm in identifying the HVAC components at fault compared to the accuracy of manually doing the same (based on judgment, knowledge, and experience) is unknown and must be investigated. Development of BIM applications on tablet devices is also in its early stages and should be investigated by the software vendors, since FM personnel can highly benefit from its advantages.

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