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BIM Framework for Energy and Maintenance Performance Assessment for Facility Management

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BIM framework for energy and maintenance performance assessment for facility management

by

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Program of Study Committee:
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Iowa State University

Ames, Iowa

2016

This work is dedicated to

Adnan and Fatina,
My parents,
“My first teachers, the strong and gentle souls who supported, guided, and taught me to believe in myself and my dreams”

Zina
My super wife,
“The encouraging, loving, strong, and successful woman who brightens my life and pushes me to be better”

Leya
My adorable daughter
“The one who makes me forget my problems with one smile”

Sawsan, Suhad, Abdullah
My siblings
“The great supporters”

Heyam and Laila
My aunts
“The ones who supported me”

My Friends
“Having you is the greatest gift of all”

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ABSTRACT

Facility managers face many challenges during their day-to-day practices. Such challenges include identifying spaces within a facility with heating and cooling problems caused by systems faults and malfunctions. In addition, they lack the tools and methods to detect spaces within a facility that have deteriorated equipment and systems malfunction. On the other hand, Facility Management (FM) information systems are complex and provide high quality data. However, they lack interoperability and visualization capabilities and fail to support FM needs. This dissertation aims to detect spaces with faults and failures in buildings. It uses Building Information Modeling (BIM) and other FM information systems to determine intended energy performance and compare with actual energy consumption and other information stored in different FM systems. In addition, the dissertation aims to improve the quality of data collected, which is necessary for corrective and predictive maintenance actions through utilizing visualization and interoperability capabilities of BIM. To achieve that, a framework with different processes and approaches was developed. This framework links data between Industry Foundation Class (IFC) BIM, energy simulation results, Building Energy Management Systems (BEMS), and Computerized Maintenance Management Systems (CMMS) to detect spaces with faults and problematic behavior within a facility. The framework also implements IFC-BIM to link and present alarms reported by FM systems such as BEMS and CMMS. The framework was validated on a case study. The results show that the facility energy performance reflects the faults in its energy management systems. Furthermore, it helps detecting spaces with faults and maintenance needs. Moreover, the proposed framework showed efficiency increase in high-quality maintenance data collection. The framework contributes to the body of knowledge by providing facility managers with a framework that outlines how to

use energy simulation and data aggregated from other FM systems and BIM to locate and detect spaces with problematic behavior. In addition, it provides a schema that integrates corrective maintenance data in a 3D IFC-BIM environment. It also helps minimize the lead-time needed by facility managers to collect relevant high quality data and link it to problematic spaces and failed equipment.

CHAPTER 1. INTRODUCTION

According to the International Energy Agency (IEA), 30% of the world's total energy production is consumed by buildings (IEA 2008), with Heating, Ventilation, and Air Conditioning (HVAC) responsible for approximately 40% of building energy consumption (USDOE 2011). A recent study has shown that between 25-40% of the energy used by HVAC equipment is being wasted worldwide (Liu, et al., 2011), and about 5-20% of this wasted energy results from either faults in controlling systems or lack of maintenance (Roth, et al., 2005).

Previous studies have highlighted the importance of facility managers' role in reducing building energy consumption. Accordingly, facility managers constantly seek to find more efficient energy management methods (Bush and Maestas 2002). It has also become increasingly critical to detect and respond to maintenance needs in a timely fashion, but facility managers currently face many challenges that may impede achieving their goals (Per Anker Jensen and Tu 2015). Challenges facing facility managers include responding to and repairing facility failures in a timely fashion (Roper and Payant 2014), reducing a facility's energy consumption by managing it more efficiently, and making sure that sufficient information related to any maintenance issue or system failure is available (Motawa and Almarshad 2013). Moreover, lack of information support for FM teams can represent other challenges that often result in wasting large amount of time on non-productive tasks such as visualizing models, searching, and validating various information elements (Yang and Ergan 2015). These challenges may also include identifying facility spaces exhibiting problematic performance, isolating different types of problems, prioritizing problem impacts, and developing solutions for them (De Wilde 2014; Zhu 2006).

Currently, facility managers depend on several types of systems to operate and manage buildings. Systems such as Building Energy Management Systems (BEMS) allow facility managers to monitor and optimize a facility’s energy performance. BEMS are commonly connected to Direct Digital Controllers (DDC) that report failures and faults in building equipment. Another type of system used by facility managers is Computerized Maintenance Management Systems (CMMS) that are used to manage and store facility maintenance data. Unfortunately, information obtained from these systems may be scattered, unconnected, managed by different teams, and not readily available.

Energy simulation can be very effective in reducing energy consumption in buildings (Kim, et al., 2016), but real-life energy performance often differs from simulated performance (De Wilde 2014; Demanuele, et al., 2010; Menezes, et al., 2012). FM activities can contribute to such differences in several ways, including occupant behavior (De Wilde 2014; Haldi and Robinson 2008; Korjenic and Bednar 2012). Other ways that FM can contribute to simulation discrepancies include differences between actual BEMS settings and those assumed in the simulations (Dasgupta, et al., 2012; De Wilde 2014; Newsham, et al., 2012), equipment deterioration, and lack of maintenance (Reddy, et al., 2007; Williamson 2010).

Recent research studies have investigated the benefits to be expected by implementing Building Information Modeling (BIM) in FM (Becerik-Gerber, et al.. 2011; Dong, et al., 2014; Eastman, et al., 2011; Kelly 2013; Laine, et al., 2007; Motawa and Almarshad 2013; Teicholz 2013). One such expected benefit is BIM’s capability for sharing data among multiple systems during the FM phase (Becerik-Gerber, et al., 2011; Kelly 2013; Motawa and Almarshad 2013; Teicholz 2013). BIM has potential to support FM tasks by acting as a data repository, by locating equipment within a facility, and by coordinating information from multiple systems.

This dissertation develops a framework (Figure 1.1) that utilizes BIM technology to overcome some of its previous challenges by providing processes and approaches that achieve the following goals:

1- Optimizing the data collection process for corrective maintenance actions. It uses BIM as a data repository where it aggregates and presents maintenance-related information in response to failures or faults.
2- Locating problematic spaces within a facility by evaluating energy performance.
3- Collecting necessary information with respect to a specified space to identify causes of problematic performance.
4- Investigating the impact of occupancy activities on building systems and providing capability to consider such activities while locating system faults.

Dissertation Organization

This dissertation is organized into a paper-based format. It consists of four main research papers that complement one another to achieve the stated goals. The following discussion provides a brief description of each paper.

The first paper, entitled “A novel framework for BIM enabled facility energy management – a concept paper,” introduces the framework’s basic concept, to use BIM as a central data repository for operating buildings and managing their energy performance. The goals for this framework include achieving a dynamic BIM that can act on and react to BEMS and provide feedback to facility managers. This paper is an introductory study describing the concept of BIM as a coordinator for FM systems.

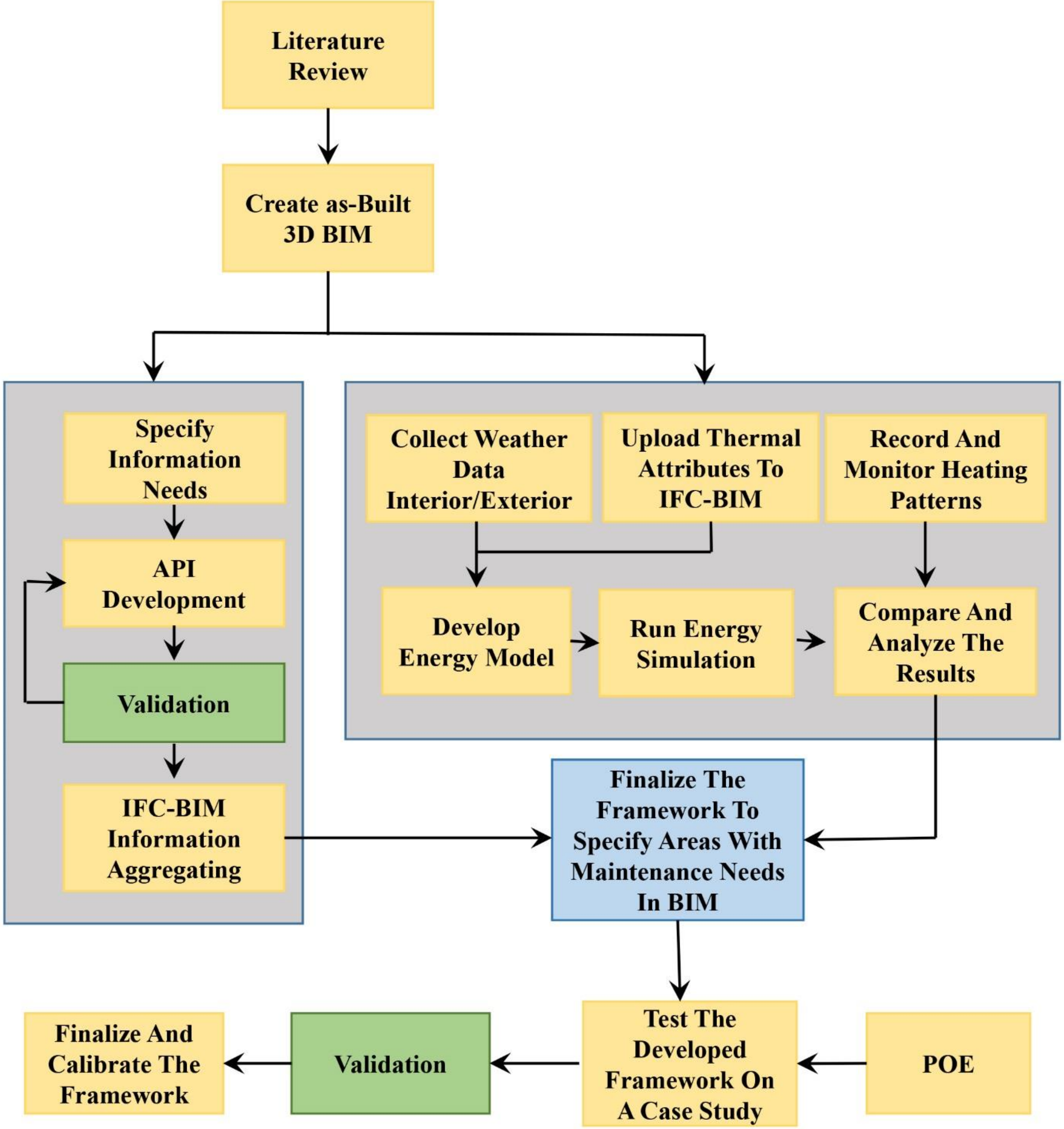

Figure 1.1: BIM framework for improving FM tasks

The second paper, entitled “IFC-BIM based facility management approach to optimize data collection for corrective maintenance,” develops a process for FM data collection using BIM as a data repository to improve the data collection process for corrective maintenance procedures. The goal of this paper is to provide facility managers with timely high-quality maintenance data in terms of accuracy and availability. Its contribution to the body of knowledge lies mainly in the area of BIM implementation during FM, with a particular focus on optimizing the data collection process for corrective maintenance of building equipment.

The third paper, “BIM-Energy simulation approach for detecting spaces with faults and problematic behavior” continues to build on the previous work. This paper describes development of a BIM based framework for identifying areas exhibiting faults and problematic behavior within a facility. This framework deals with BIM coordinate data collected by BEMS, design and construction data stored in the BIM, maintenance data stored in CMMS, and energy simulation results obtained from EnergyPlus based DesignBuilder software. The paper achieves two tasks: (1) establishing a system for collecting BEMS weather data to be used in energy simulations, and (2) developing an approach for identifying building spaces with problematic behavior and specifying possible causes of such behavior.

Finally, the fourth paper entitled “Implementing BIM - energy simulation framework to detect spaces within a facility with maintenance needs – case study approach,” validates the applicability of the framework through a case study. The paper includes a comprehensive literature review defining the underlying causes of an energy performance gap. Experimental tools and components described in the literature were also investigated, including Post Occupancy Evaluation (POE) and BIM for building energy management applications. The paper also presents the results of applying the proposed framework to a building case study and combines it with the results of a POE to identify actual reasons for performance gaps related to maintenance and equipment failure.

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CHAPTER 2. A NOVEL FRAMEWORK FOR BIM ENABLED FACILITY ENERGY MANAGEMENT – A CONCEPT PAPER

Firas Shalabi, and Yelda Turkan

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Abstract

Building Information Modeling (BIM) enabled facility management has gained increased interest in both academia and industry. Previous research has shown the importance of having dynamic BIMs that can react and interact with real-time data obtained from building sensors. The other sought benefits of BIM such as improving workforce efficiency, proactive maintenance planning, and improving maintenance records, which would lead to reduced energy and water consumption, are also acknowledged by both the academic community and the industry practitioners. However, BIM implementation for facility energy management activities, specifically for energy use monitoring, has not yet been explored, and one of the main reasons pertain to not having standards for BIM to be effectively used for facility energy management tasks. This paper provides a comprehensive literature review on BIM implementation and BIM requirements for facility management and facility energy management related tasks. In addition, it proposes a conceptual framework that enables to achieve dynamic BIM for building energy use monitoring activities. The proposed framework connects BIM database with building energy management systems, while enabling BIM to act as a central data repository and a visualization tool to achieve energy use monitoring related tasks. Finally, it summarizes the challenges to achieve dynamic BIM, and concludes with the expected benefits of

implementing dynamic BIM for building energy management as well as recommendations for future research.

Introduction

Energy Management is one of the most important tasks among Facility Management (FM) responsibilities. Building Energy Management Systems (BEMS) are used to operate, control and monitor energy use in buildings. BEMS are also used to manage buildings' environment and to control their heating, cooling, and lighting systems. However, many of BEMS capabilities, such as automated data sharing, are not yet fully achieved.

There is a growing interest in the Construction Industry in using Building Information modeling (BIM) throughout buildings' life cycle including Facilities Management (FM) practices. BIM implementation for FM applications, including energy management tasks, is considered an emerging field. Many benefits of implementing BIM in FM are sought during later phases of buildings' life cycle. Those benefits include the ability to extract and analyze data for various needs that could support and improve decision-making process, thus improve the energy performance during Operation and Maintenance (O&M) phase.

In this paper, a novel framework is introduced, where BIM is used as central data repository for operating buildings and managing their energy performance. This framework aims to achieve a dynamic BIM that can act and react with BEMS and provide feedback to operators and building energy managers. This framework is part of a larger study that will be implemented for educational buildings in order to test its performance.

The paper is organized as follows; the next section gives background on current building operation and energy management practices including BEMSs. Section 3 then reviews current BIM uses and presents a novel framework for using BIM during building operations and maintenance phase. Section 4 focuses on the challenges that this framework would face and proposes solutions for each identified challenge. Section 5 draws conclusions and discusses future research needs.

Current Building Energy Management Practices

Energy management is considered the top priority among the functional responsibilities in FM, followed by maintenance and repair (Sadeghifam et al. 2013; Underwood and Isikdag 2011; Yao 2013; Yiu 2007). Currently, tools such as Building Automation Systems (BAS) and BEMS are used to manage buildings' environment and control their heating, cooling, and lighting systems, i.e. to perform building energy management tasks. Those systems are defined as a collection of microcomputer systems consist of Direct Digital Control (DDC) controllers and their control devices, which operate under supervisory control equipment or software collectively. Their abilities include sharing data with individual controllers for coordination and optimization, linking control processes, and performing operation tasks and reports (Doty and Turner 2009). BEMS are considered an essential source of information for building energy performance assessment that is used to optimize building energy performance as well as to fix any problems in building systems. However, many of BEMS capabilities, such as automated data sharing, are not yet achieved, and the current BEMS practices lack continuous data flow throughout facility life cycle (O'Sullivan et al. 2004) (Figure 1). Furthermore, data to the O&M phase is input manually, which results sometimes in inaccurate and incomplete information (Kelly 2013) that would require facility managers to re-enter the missing data they need to operate BEMS and guarantee optimal energy performance.

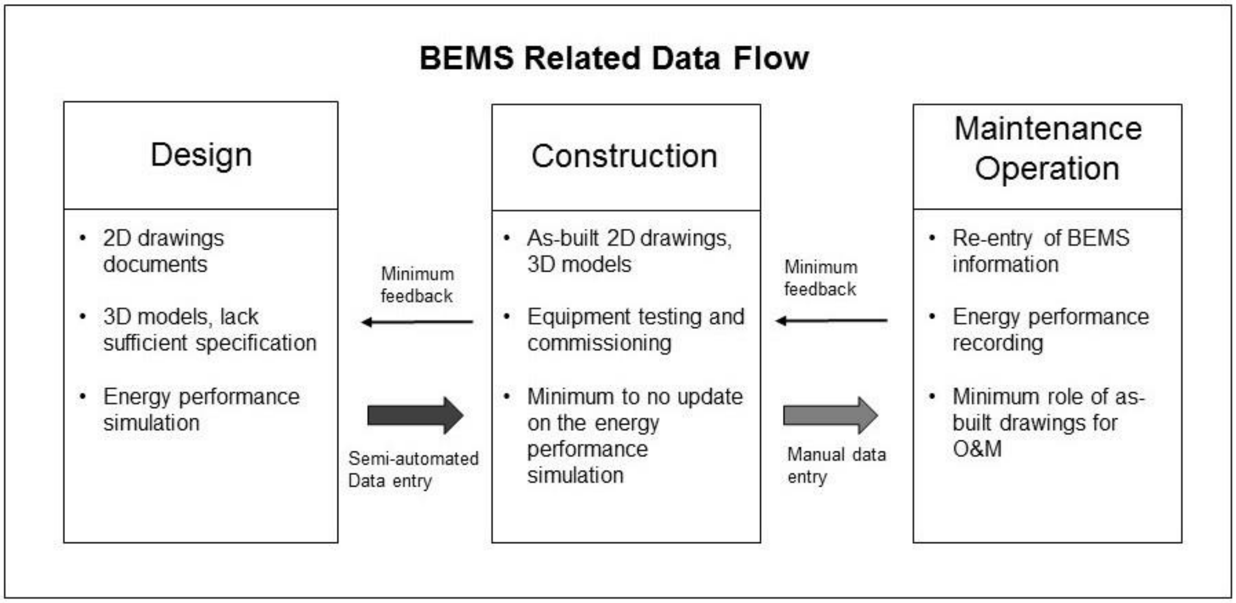

Figure 2.1: Energy management related data flow throughout building life cycle

Continuous feedback from BEMS during O&M is considered essential to maintain the planned operational and energy performances of buildings. In addition to imprecise commissioning and BEMS malfunctioning, not providing real-time data to BEMS are considered as the main reasons for buildings' performance deterioration. BEMS enable building energy performance monitoring, and help achieve energy savings of up to 40% (Claridge et al. 1994; Herzog and LaVine 1992; Salsbury and Diamond 2000). However, they are becoming more complex and difficult to operate for an average operator (Hyvärinen and Kärki 1996).

BEMS records and stores building energy use data collected from sensors (e.g., temperature, CO2, zone airflow, daylight levels, occupancy levels, etc.) as well as data from fault detection and diagnosis sensors (e.g. air handler units' controls, HVAC systems, valves controls and fans controls). Those sensors are numbered and organized based on their location in the building, and presented in list format. Sensor outputs, energy performance metrics (i.e. energy consumption), and other building performance metrics are presented in 2D histograms, tables and lists of tasks or in similar formats (Figure 2). Furthermore, maintenance records and other facility documents are kept in separate systems, not in BEMS, plus all these software have their own data structure that are not compatible with each other (Wang et al. 2013). As a result, when BEMS shows a problem for one of the building elements, facility energy managers and maintenance personnel need to obtain further information associated with that particular element. This requires them to check other systems such as building maintenance and warranty records. Finally, after gathering all necessary data, the problematic element needs to be located within the building, which maybe a tedious task, especially if the element is located in an area congested with other building elements such as pipes, ducts etc.

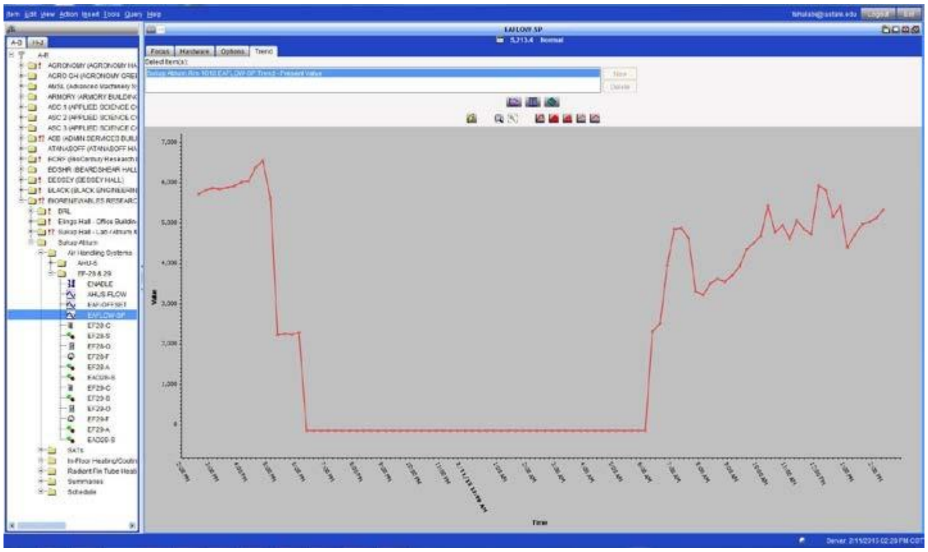

Figure 2.2: BEMS user interface

Overall, this makes it cumbersome to evaluate energy performance of an entire facility by gathering data from separate systems (Pietruschka et al. 2010; Yao 2013). Furthermore, it limits the possibility to react to any changes or possible problems in the system on time. It also prevents from developing a proactive maintenance strategy, which may increase energy losses due to system defects. For example, it is estimated that about 30% of the energy in commercial buildings is wasted because of degraded and poorly maintained equipment (Granderson et al. 2011).

A Novel Dynamic BIM Framework for Building Energy Management

There is a growing interest in the Construction Industry in using (BIM) throughout buildings' life cycle including FM practices. BIM supports a collaborative approach throughout the project's life cycle phases and engages multiple stakeholders in the project including architects, engineers, contractors, and the facility managers. Furthermore, BIM eliminates tedious and error prone data entry process, which leads to decrease/eliminate loss of project/facility information during project lifecycle (Figure 3) (Eastman et al. 2011).

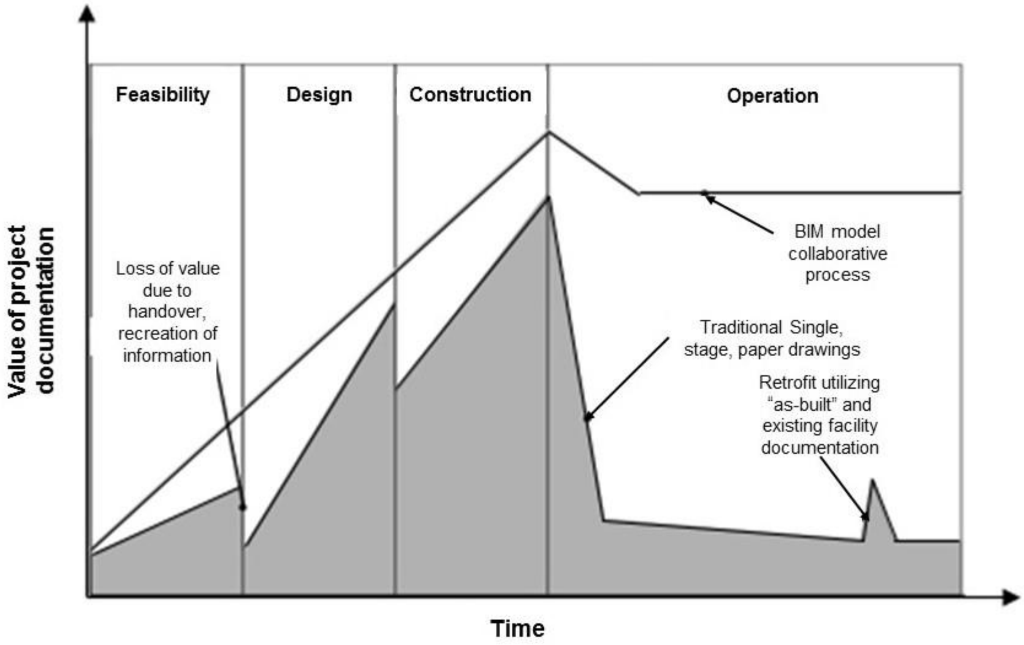

Figure 2.3: Documentation loss of value during project lifecycle (Eastman et al. 2011)

BIM implementation for FM applications, including building energy management, is considered an emerging field that lacks real case studies (Kelly 2013). However, most benefits of implementing BIM in FM are sought during later phases of buildings' life cycle, such as the ability to extract and analyze data for various needs that could support and improve decision-making process (Azhar 2011). Furthermore, BIM in FM applications can help increase the efficiency of work order executions by providing faster access to data and by improving the process of locating various facility elements with its user-friendly 3D interface (Kelly 2013). In addition, BIM implementation in FM and BEMS would help eliminate redundancy in data re-entry since BIM would act as a central data repository (Figure 4) that supports all activities throughout the buildings' life cycle from design to maintenance and operations (Fallon and Palmer 2007).

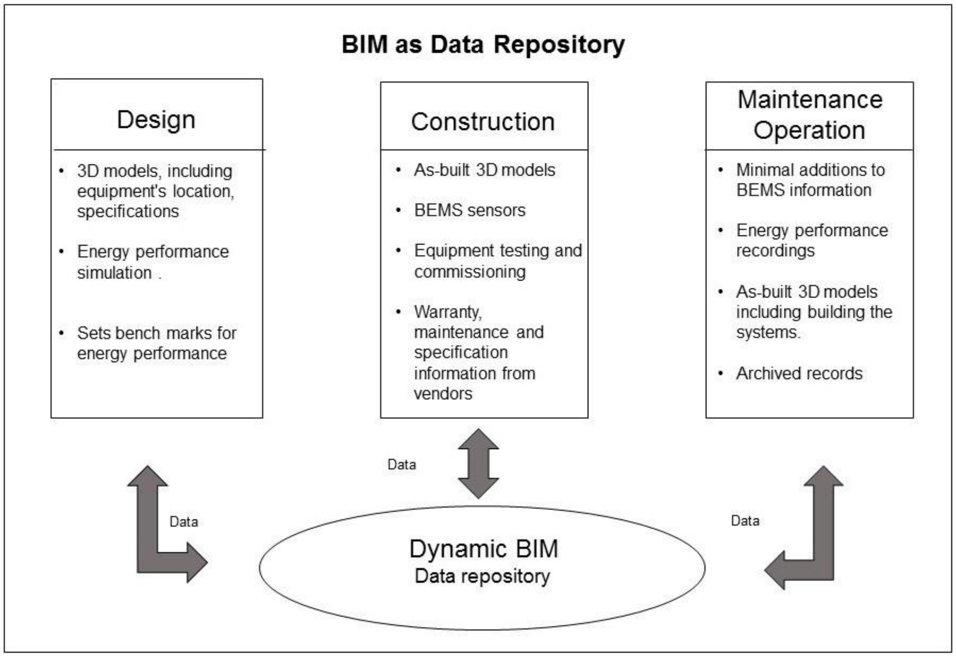

Figure 2.4: BIM as Data repository in buildings' life cycle

Dynamic BIM Framework

BIM implementation for energy management activities has been limited to green retrofit modeling and design simulations. This maybe a result of unforeseen productivity gains that can be realized from reduced equipment failure as well as the productivity increases that maybe realized through an integrated platform (Becerik-Gerber et al. 2011). A suggested step forward would be to integrate energy use data with BIM database for building energy use monitoring (Muthumanickam et al. 2014) in order to achieve a dynamic BIM (Figure 5). Having dynamic BIM models that reflect actual as-built conditions and contain real time building information gained increased interest lately (Akanmu et al. 2013). A dynamic BIM model has the potential to provide improved documentation, minimize the cost of facility operations and maintenance, serve as a useful reference for future projects, and improve proactive maintenance planning (Chen et al. 2014; Teicholz 2013). This, overall, would lead to reduced energy consumption as a result of having well maintained, efficient mechanical equipment.

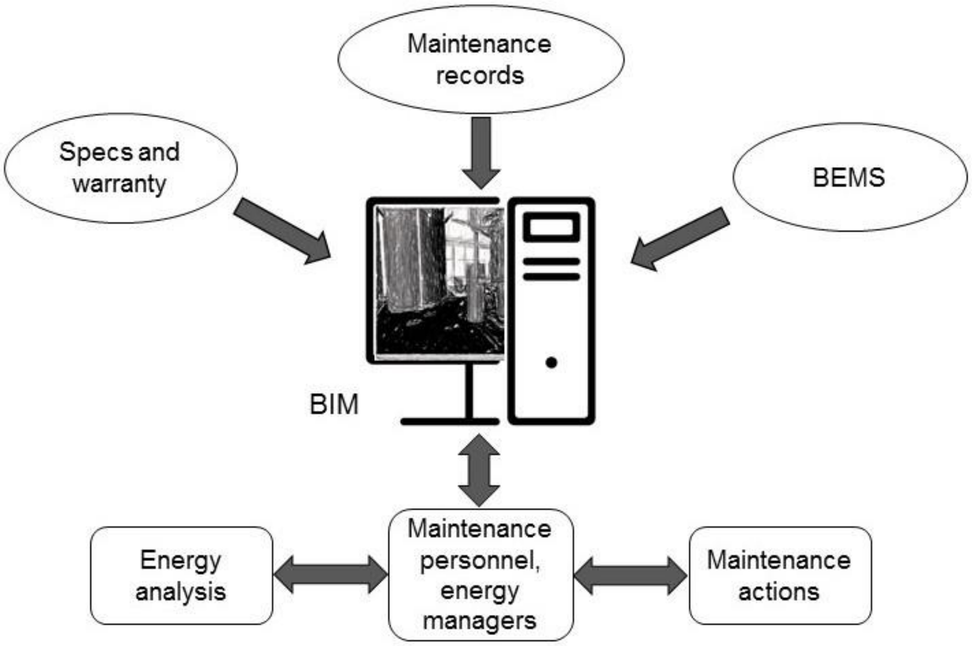

Figure 2.5: Dynamic BIM concept for FM

This paper proposes a novel framework that utilizes dynamic BIM models containing real time building information obtained from sensors and BEMS to improve facility energy management activities (Figure 6). This framework aims to integrate BIM with BEMS systems using a programming application to enable industry foundation classes (IFC)-based BIM files read and update their database based on the BEMS live feed. Visualization of BEMS data in user-friendly 3D BIM interface would enable facility energy managers to take timely actions about the problematic building elements, i.e. proactive maintenance, which would translate into energy savings.

In order to achieve the proposed framework, two programming applications will be developed; the first one is to link the BIM database with energy sensor output data, through

BEMS, thus to visualize real-time energy use as color coded 3D models and to link it to each model element, where building maintenance and records of warranties and other information are stored. This would allow comparing the collected data with historical energy consumption data, the design, or manufacturer claimed data and maintenance records simultaneously, which would help discovering any over consumption or flaws in the system in an efficient and timely manner. The second programming application will be developed to link BIM database with energy analysis programs, where energy consumption can be analyzed and over consumption can be detected.

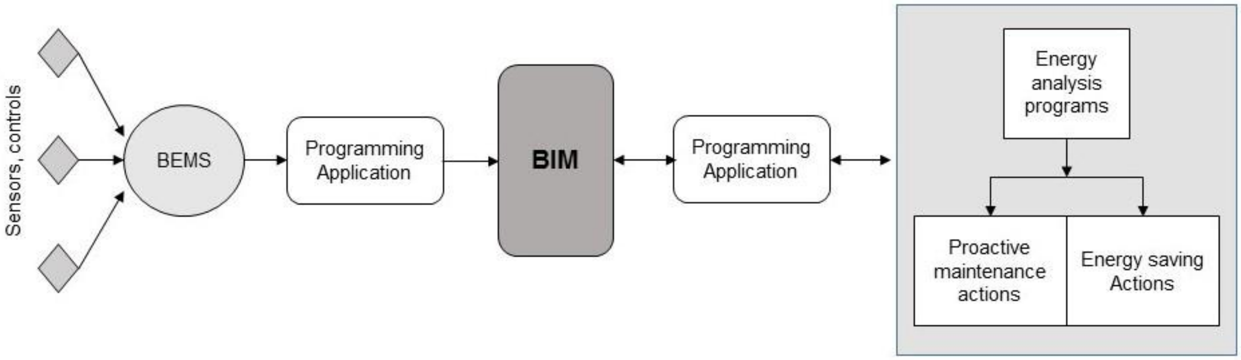

Figure 2.6: BIM - BEMS framework

Consequently, this should enable energy managers to detect any over consumption immediately, which would help them determine the reasons behind it faster. This would improve proactive maintenance plans and actions as it enables detecting defective or faulty equipment in a faster manner, so that they can be replaced immediately without causing more energy losses.

Dynamic BIM Challenges

In order for BIM to be used in facility and energy management practices it needs to be dynamic; and that is, reflecting actual conditions of a facility and presenting real time building information. However, achieving “dynamic” BIM is faced by a number of challenges, which can be grouped into three main categories: (1) lack of guidelines for the necessary information required for BIMs to be used in building energy management related tasks; (2) inaccuracy and/or incompleteness of as-built BIMs; (3) interoperability issues between BEMS and BIM authoring tools (Laine et al. 2007). In this paper, a framework that connects BIM with BEMS is being introduced to help overcome one of these challenges, the interoperability issue.

The first obstacle, the necessary information required for BIMs to be used for building energy management tasks, has been addressed and stated in the literature. Becerik-Gerber et al. (2011) suggested that three types of energy management related FM data should be incorporated into BIM: (a) equipment and systems, (b) attributes and data, (c) portfolios and documents. However, specifications and details of this FM data, such as type of equipment that should be included in the model and attributes and the level of detail of the building model, were not described. Furthermore, the Pennsylvania State University computer integrated construction research program report (2013) suggested that the following items should be identified, documented, and included in order to achieve dynamic BIMs: (a) type of building elements to be tracked (b) information display format (c) Level of Detail (LoD) required for each model element (d) properties and attributes of each element.

The second challenge pertains to inaccuracy and/or incompleteness of as-built BIMs. Several researchers suggested that early involvement of FM personnel in design and construction phases would be very beneficial for developing accurate and complete as-built BIMs (Teicholz 2013; Wang et al. 2013). However, such involvement remains limited due to lack of knowledge about BIM implementation for FM tasks (Kelly 2013), lack of specific data requirements (Becerik-Gerber et al. 2011; Kelly 2013), and interoperability issues (BIFM 2012). The issue related to inaccuracy of as-built BIMs (at object level), has been addressed both by researchers and industry practitioners. Several researchers emphasized the importance of having accurate and up-to-date as-built BIMs for FM tasks (Ahmed et al. 2014; Akinci 2015; Bosché et al. 2013; Son et al. 2014). Therefore, developing guidelines and requirements for BIMs to be used for building energy management practices is essential for achieving dynamic BIM and needs broader attention.

The third obstacle, interoperability issue, has been widely expressed by both researchers and industry practitioners. Interoperability enables to manage and communicate electronic data among collaborating firms, between different disciplines in individual companies and between different phases of a project, i.e. design, construction, maintenance, and business process systems (Gallaher et al. 2004). Interoperability issues between FM and BEMS programs and protocols are common and well known. Furthermore, there are interoperability issues between BEMS and BIM as well as between various programs that are used for building maintenance, building condition monitoring and document management. Typically, these programs have their own data structure and are not compatible with each other (Wang et al. 2013). The role of BIM for FM and BEMS within current practice is still unclear. However, as shown in Figures 5 and 6, there are possibilities for connecting BIM with various BEMS and other FM software. BIM would act as a central data repository that collects and stores data from various systems, and provide access to this data through a 3D, easy to use, user-friendly interface.

Conclusions and Future Research

BIM implementation for facility energy management practices has gained increased interest both in academia and in industry in recent years. The current energy management practices have several drawbacks such as lacking automated data sharing, requiring manual data entry during O&M phase, and not facilitating continuous data flow throughout facility life cycle. BIM enabled energy management facilitates extracting and analyzing data for various needs to improve decision-making process, which would translate into increased efficiency in work order executions and elimination of redundancy in data entry. Dynamic BIM models could improve documentation, minimize the cost of facility operations and maintenance, serve as a useful reference for future projects, and improve proactive maintenance planning which would lead to reduced energy consumption. Lack of guidelines to prepare BIM for BEMS, inaccuracy or incompleteness of as-built BIMs and interoperability issues between BEMS and BIM authoring tools are the main challenges that prevents from achieving dynamic BIM. In this paper, a conceptual framework that proposes to connect BIM with BEMS was introduced to help overcome the interoperability issue. The proposed conceptual framework will be implemented by developing a programming application to link BIM and BEMS and tested in future research. It is expected that it would help improve current facility energy management practice, and help save energy.

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CHAPTER 3. IFC-BIM BASED FACILITY MANAGEMENT APPROACH TO OPTIMIZE DATA COLLECTION FOR CORRECTIVE MAINTENANCE

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Abstract

Facility managers are required to collect high quality data to achieve corrective maintenance actions. Current Facility Management (FM) information systems are complex and provide high quality data. However, they lack interoperability and visualization capabilities. The goal of this study is to improve the quality of data collected that is required for corrective maintenance by utilizing visualization and interoperability capabilities of Building Information Modeling (BIM). To achieve that, an approach that implements Industry Foundation Classes (IFC) BIM to link and present alarms reported by FM systems such as Building Energy Management Systems (BEMS) and Building Automation Systems (BAS) with related data from Computerized Maintenance Management Systems (CMMS) was developed, and validated on a typical university building. The results showed efficiency increase in high-quality maintenance data collection. The proposed approach supplements the existing body of knowledge in FM domain by providing a schema that integrates corrective maintenance data in a 3D IFC-BIM environment. Moreover, it provides a process to minimize the corrective maintenance lead-time and link equipment failures to the related maintenance information. FM practitioners can use this approach to decrease the lead-time needed corrective maintenance responses, and focus their resources on productive maintenance tasks.

Keywords: IFC, Corrective Maintenance, BIM, CMMS, BAS, BEMS, Data Quality, Lead Time

Introduction

Building maintenance and repair is vital for the operation of the equipment in any facility. Building maintenance activities involve multiple stakeholders over a long time period, which require a comprehensive information system to capture and retrieve data related to building equipment (Motawa and Almarshad 2013; Nummelin et al. 2011). Currently, 25-40% of the energy used by heating and cooling equipment in buildings is being wasted worldwide (Liu et al. 2011). Furthermore, responding and repairing systems' failures in a timely fashion remains a challenge for facility managers (Roper and Payant 2014). Maintenance can be preventive, corrective, or predictive. While the information needed for preventive maintenance is typically available from manufacturers, information needed for corrective and predictive maintenance maybe harder to find and collect. In fact, having readily available sufficient information about the building elements and systems for any maintenance operation is considered a key challenge (Motawa and Almarshad 2013) when faced with a failure in the system.

In current Facility Management (FM) practice, Direct Digital Controllers (DDC) report failures and faults of building equipment to FM information systems namely Building Energy Management Systems (BEMS) and Building Automation Systems (BAS). These systems allow facility managers to monitor and optimize the performance of a facility as they provide reports for any defected or unreliable equipment in the heating or cooling system. Facility maintenance data, on the other hand, is typically kept and managed in a separate FM database called Computerized Maintenance Management Systems (CMMS). In order to be able to respond to system failures in a timely manner, it is not enough for FM information systems to operate sufficiently on their own. They also need to achieve automated data and information sharing with each other, in addition to optimizing the process for gathering maintenance related information. FM information systems (e.g. BEMS, BAS) detect and notify FM team when there is a fault in heating or cooling systems. After being notified, the maintenance team looks for the maintenance information to help solve the problem. FM and maintenance teams waste large portion of their time on non-productive tasks such as visualizing models, searching, and validating different pieces of information due to lack of information support (Yang and Ergan 2015).

Recent research efforts have focused on investigating Building Information Modeling (BIM) implementation and its possible expected benefits in O&M, including facility management, maintenance, and energy management (Becerik-Gerber et al. 2011; Dong et al. 2014; Eastman et al. 2011; Kelly 2013; Laine et al. 2007; Motawa and Almarshad 2013; Teicholz 2013). BIM is seen as a solution for sharing data among multiple systems especially during O&M phase of a facility (Becerik-Gerber et al. 2011; Kelly 2013; Motawa and Almarshad 2013; Teicholz 2013). BIM with its data repository capabilities has the potential to enable facility managers to minimize the lead-time of non-productive activities necessary for maintenance.

Therefore, this paper introduces a novel process, where BIM is used as a data repository to optimize the data collection process for corrective maintenance actions. It aims to provide facility managers with high quality maintenance data in terms of accuracy that is available when needed. It contributes to the existing body of knowledge in BIM implementation during FM with a focus on optimizing the data collection process for corrective building equipment maintenance.

The paper is organized as follows: a comprehensive literature review on current building maintenance practices, BIM implementation in FM practice, and the contribution is provided in the next section. The following section then introduces the proposed BIM-enabled facility management and maintenance optimization process. The validation and implementation of the proposed framework is provided in validation section. The final section draws conclusions and discusses future research needs.

Background

A comprehensive review on current FM systems and BIM implementation practices during Operations and Maintenance (O&M) phase is provided in this section.

Existing FM Systems and Practices

Facility managers rely on FM and maintenance information systems to operate and maintain their facilities. The details of both systems are provided below.

Facility Management Information Systems

Currently, tools such as BAS and BEMS are used to manage buildings' environments by adjusting and controlling their HVAC and lighting equipment to optimize building performance. These FM information systems, i.e. BEMS, BAS, are a collection of microcomputer systems consist of Direct Digital Controllers (DDC) and their control devices, which operate under supervisory control equipment and software collectively. Data sharing with individual controllers for coordination and optimization, linking control processes, and performing operation tasks and reports are among some of their capabilities (Doty and Turner 2009). Building sensors and controllers are connected to the BEMS or BAS system where they input data and report any flaws or equipment failures. However, current practices depend on manual data input during O & M phase. For example, when a new equipment is installed or a repair occurred, related data needs to be entered manually, which may result in inaccurate and/or incomplete information (Kelly 2013). Facility managers are required to look for and re-enter the missing data they need in order to operate their facility in an efficient manner.

Building controllers send feedback to BEMS or BAS system if any of the equipment is not working properly. In the meantime, facility managers can monitor, change any benchmark, or override the system decisions. When the system reports a fault or an error, facility managers need to report the problem to the maintenance personnel who in turn need to locate and inspect that particular element after gathering its maintenance information such as previous replacements and warranty information.

In order to meet and maintain the planned operational performance demand of buildings, facility managers are required to guarantee an up-to-date maintenance status of the HVAC equipment, which is dependent on the continuous feedback from the building sensors, controllers, and facility management information systems during O&M phase. Energy performance of buildings deteriorates overtime due to various reasons including lack of prompt response to faults/alarms reported by BAS and BEMS systems, imprecise commissioning, and BEMS/BAS malfunctioning. This would result in energy waste, and cause occupant discomfort and complaints (IFMA 2009).

DDCs report different types of data that are recorded by FM information systems. The data reported include weather and energy use (e.g., temperature, CO2, zone airflow, daylight levels, occupancy levels, etc.), alarm monitoring and data collected from sensors (e.g., equipment failure, high and low temperatures defective sensors and communication problems), and controllers (e.g. air handler units controllers, valves controllers and fans controllers) (Doty and Turner 2012). Typically, sensors are numbered and organized based on their location in the building, and presented in list format. However, data about their exact locations, the equipment affected by them and their maintenance history information are not stored in BEMS. Moreover, sensor outputs, energy performance metrics, and other building performance metrics are presented in 2D histograms (Fig. 1), tables, and lists of tasks or in similar formats, which requires manual and tedious data extraction and interpretation.

A BEMS hosts the results of a Fault Detection and Diagnostics (FDD) analysis and presents it to facility managers (Dong et al. 2014). Several FDD approaches have been developed to identify faults and deterioration in building equipment (Dong et al. 2014; Qin and Wang 2005; Sallans et al. 2006; Schein et al. 2006; Wang and Xiao 2006; Xiao 2004). FDD approaches are not in the scope of this study. Instead, it focuses on responding to faults reported by BEMS or BAS in a more efficient manner by providing higher quality maintenance data.

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Figure 3.1: A Typical BEMS Interface - Energy Consumption Histogram for a Heating Radiator (courtesy of Iowa State University)

Maintenance Information Management

Maintenance is vital for continuous performance of buildings. Facility managers use computerized solutions called Computerized Maintenance Management Systems (CMMS) for maintenance tasks, which have their own data structure that is not compatible with BEMS (Wang et al. 2013). CMMS are used to help assist with maintenance tasks that include maintenance planning, execution, assessment and improvement (Kullolli 2008). Maintenance process is supported by diverse resources, including documentation, equipment, personnel, availability of spare parts, etc. FM personnel including operators, technicians and facility managers are typical users of CMMS (Labib 2004). CMMS tools and technologies are becoming more advanced (Karim 2008), which increases the amount of data available for maintenance while actively increasing its quality (Markeset and Kumar 2003; Tretten et al. 2011). It also increases the accuracy of maintenance data required for decision making with the assumption that the collected data is relevant, used correctly, and is of high quality. The quality of data is extremely important, as accurate information is vital for decision making (Aljumaili et al. 2012). One important factor that affects the quality of maintenance data is the user's interaction with maintenance systems and tools (Aljumaili et al. 2012; Labib 2004). Despite the fact that CMMS is capable of executing the tasks it has been designed for, it often lacks the capability to communicate the output data and support the user needs, resulting in errors and data quality issues (Aljumaili et al. 2012).

Overall, CMMS does not provide a user friendly interface, which needs to be improved (Aljumaili et al. 2012). The reason is that they are not designed for facility managers' specific needs (Labib 2004; Uday Kumar et al. 2014). Problems with current CMMS include limited access to necessary documentation, incompatibility with other FM systems, manual data input requirements, lack of user-friendly interface, and high complexity (Kumar et al. 2014). The CMMS interface (Fig. 2) lacks easy and direct access to various information that is necessary to determine the type or location of alarms received. For example, if an Air Handler Unit (AHU) has a problem, CMMS can look it up based on its manufacturer or the service request (Fig.2.), but they cannot link it to other equipment that is connected to the AHU, previous maintenance actions applied to the HVAC system, or alarms received from other systems regarding to that AHU. In addition, CMMSs interface present the information in list format that does not help operators visualize any problems. Previous research on CMMS identified visualization and interoperability with other FM systems as the two main areas that need to be improved to allow for seamless data transfer among various FM systems (Aljumaili et al. 2012; Uday Kumar et al. 2014).

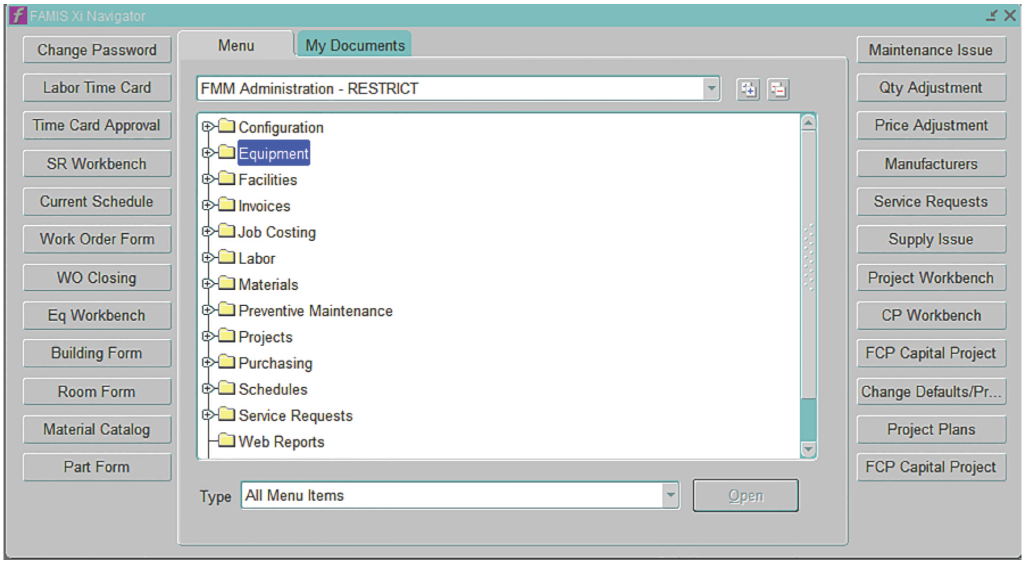


Figure 3.2: A Typical CMMS Interface (courtesy of Iowa State University)

Overall, facility managers find themselves required to master, operate, and gather data from multiple systems on a daily basis, which makes it cumbersome to evaluate and improve the performance of an entire facility, while keeping it maintained within the limited maintenance budget (Pietruschka et al. 2010; Yao 2013). Consequently, this limits the possibility to react any changes or possible problems in the system in a timely and efficient manner. It also prevents from developing a predictive and proactive maintenance strategy, which may increase energy losses and costs associated with systems' deficiencies. For example, it is estimated that about 30% of the energy in the US commercial buildings is wasted because of degraded and poorly maintained equipment (Granderson et al. 2011). In addition, deferred facilities maintenance costs have increased $5.5 billion since 1988 and still increasing according to the report published by the US Association of Higher Education Facilities Officers and the National Association of College and University Business Officers (Kaiser and Davis 1996).

BIM Implementation during O&M Phase

BIM supports a multi-domain and multi-layer collaborative approach throughout a facility's life cycle. It engages multiple stakeholders in the project including architects, engineers, contractors as well as facility managers and operators. BIM helps eliminate tedious and error prone data entry process, which leads to decrease/eliminate loss of project/facility information during project lifecycle (Al-Shalabi and Turkan 2015; Eastman et al. 2011). Other capabilities include effective data sharing between various stakeholders. The benefits of these capabilities have been proven for design and construction phases. However, effective BIM use during O&M phase of a facility has not yet been achieved. Previous research on BIM use in FM and O&M can be categorized into two groups: (1) studies that developed BIM frameworks to streamline the existing processes and systems, (2) studies that developed BIM-based approaches to replace current processes to capture, store, and retrieve facility data in an efficient manner.

Examples of the first group of studies include augmented reality based operations and maintenance (AR-based O&M) support (Lee and Akin 2011), 2D barcode BIM-based facility management system (Lin et al. 2012), 3D based facility maintenance and management system (Chen et al. 2013), and BIM-based facility maintenance management system (Lin and Su 2013). These studies fall within the same scope of this research in terms of streamlining the existing O&M processes and are complimentary to it. However, it differs from the previous work by focusing on developing a new process that improves corrective maintenance actions by minimizing lead-time to collect required information.

Examples of the second group of studies include: using BIM to generate customized templets to capture maintenance work related changes (Akcamete 2011), a knowledge based BIM system using case-based reasoning for building maintenance (Motawa and Almarshad 2013), fault-tree analysis for failure root cause detection (Lucas et al. 2012; Motamedi et al. 2014), and using BIM for HVAC troubleshooting (Yang and Ergan 2015). However, none of the studies in this group focused on developing algorithms to streamline the existing processes to collect necessary information for corrective maintenance actions without replacing the existing processes.

BIM Implementation in FM: Potential and Challenges

BIM adoption in FM, including building maintenance, is still in its early stages (Kelly 2013). This is mainly due to the limited awareness of expected BIM benefits for FM among facility management professionals, lack of data exchange standards and unproven productivity gains illustrated by case studies. BIM benefits in FM are sought during O&M phase includes the ability to extract and analyze data for various needs that could support and improve decision making process (Azhar 2011). Furthermore, BIM in FM applications can help increase the efficiency of work order executions by providing faster access to data and by improving the process of locating various facility elements via its user friendly 3D interface (Kelly 2013). In addition, carrying BIM from design to O & M phase would help eliminate redundancy in data re-entry since BIM would act as a central data repository (Fig.3) that supports all activities throughout the buildings' life cycle (Fallon and Palmer 2007).

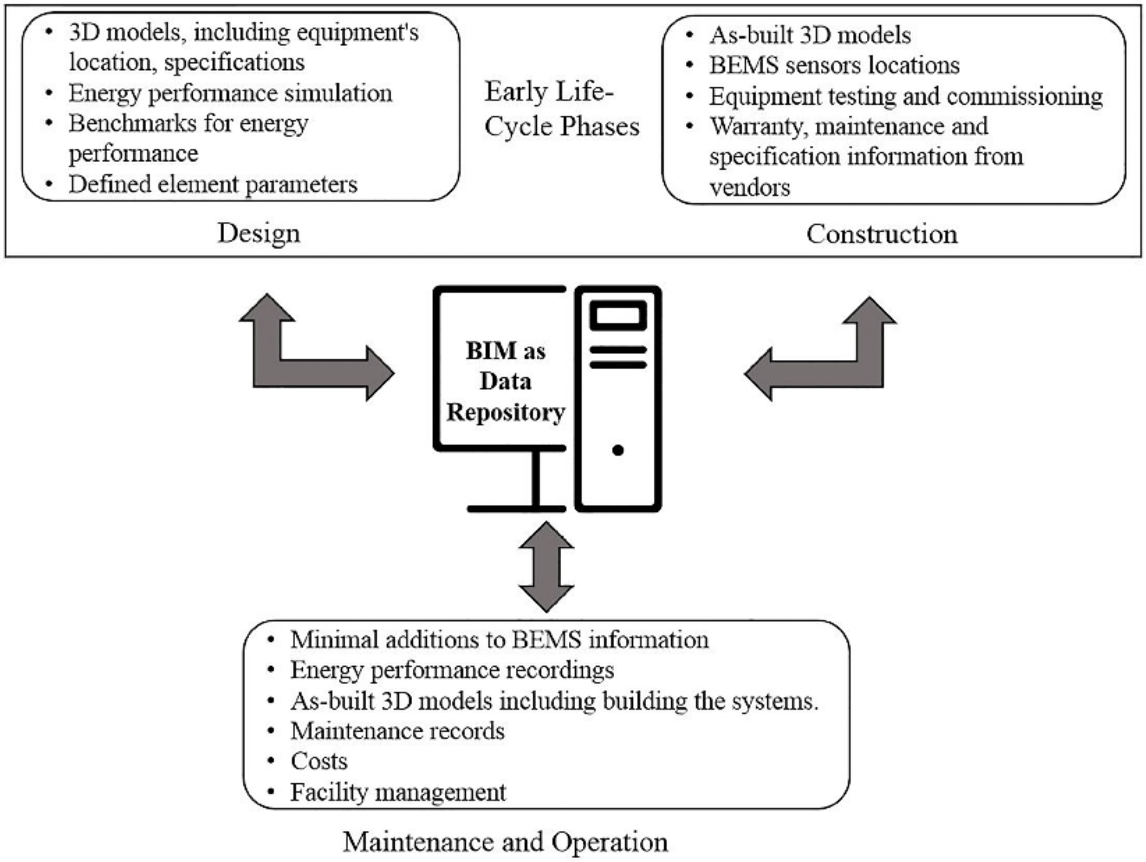


Figure 3.3: BIM Use throughout the Facility Life-Cycle

However, there are still many challenges regarding BIM implementation in FM. Unproven productivity gains that can be realized from reduced equipment failure as well as the productivity increases that maybe realized through an integrated platform (Becerik-Gerber et al. 2011) are the two major challenges that prevents from BIM implementation in FM. In addition, lack of facility managers' input regarding their needs upfront early in the process, fragmented data, data interoperability, and lack of data transparency throughout the building life cycle are among some of those challenges.

BIM Data Handover from Construction to FM

According to a study conducted by the National Institute of Standards and Technology (NIST) (Gallaher et al. 2004), inadequate interoperability and incompatibility between systems result in $15.8 billion total added cost in the construction industry. The industry also realized this problem and started developing data exchange guidelines and standards to support reliable and consistent data exchange. Construction Operation Building information exchange (COBie) (East 2007) is a major standard in the building industry, which supports information collection during design and construction phases and handover to the facility management stage. COBie format is internationally recognized FM related, non-geometric information standard for the exchange of information using IFC format (East and Carrasquillo-Mangual 2012). Even though additional data is still needed to manage facilities than what is provided by COBie, several studies have shown its value and capabilities (EcoDomus 2013; Nisbet 2008; Onuma ; William East et al. 2012). In addition to COBie, some other information exchange standards are also under-development such as HVAC information exchange (HVACie), which explicitly describes capture and delivery of HVAC information through the building life cycle. Building Automation Modelling information exchange (BAMie), Life Cycle information exchange (LCie) and several others are currently being developed (BuildingSMART 2015). Nevertheless, all information exchange (East 2007) standards tackle the information handover process, not daily O&M actions and issues.

Existing Industry Solutions

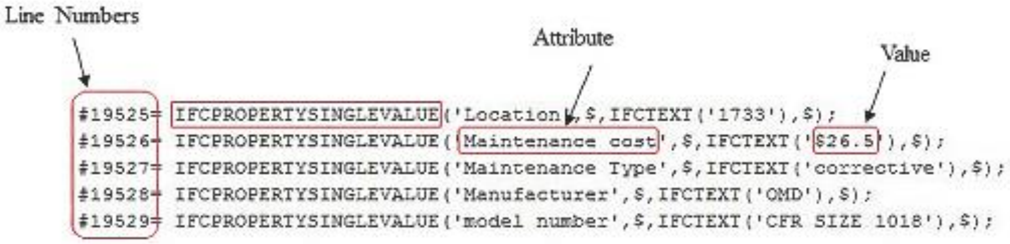
Various Computer Aided Facility Management (CAFM) solutions have been developed and introduced to incorporate BIM data into FM by using interoperable functions of BIM authoring tools. However, most contemporary CAFM systems still use 2D environments and mainly focus on space management and asset management tasks. In addition, they require manual query and update routines (Aspurez and Lewis 2013; Parsanezhad and Dimyadi 2014). Examples of those systems include ARCHIBUS (ARCHIBUS 2015) and FM:Interact (FM:Systems 2015). Also, a different level of relatively expensive solutions exists and known as Middleware solutions, e.g. EcoDomus (EcoDomus 2015). A middleware solution is a software that allows two different software packages to exchange information and connect applications (Aspurez and Lewis 2013). EcoDomus has been used and developed for some buildings by the General Services Administration (GSA) such as NASA Langley Pilot study, and Camden ANNEX life cycle BIM project. In the NASA Langley pilot study, EcoDomus is used to query, transmit, synchronize data between CMMS and BIM, and visualize them in EcoDomus environment. The Camden ANNEX study was developed to integrate BIM, CMMS, and BAS in EcoDomus (Teicholz 2013).

Above mentioned solutions focus on the turnover process of new construction projects to facility management using COBie, and mainly serve newly constructed facilities, not existing ones. Furthermore, open source file formats such as IFC are used to transfer data from construction to O&M, not to exchange data between O&M applications and tools used daily basis. In addition, no off-the shelf BIM portal (Jordani 2010) that links BIM and works with FM applications seamlessly has been developed yet. For example, EcoDomus solutions are developed for each specific project (Kensek 2015; Khemlani 2011). Furthermore, the current solutions hyperlink data between BIM and other systems (i.e. CMMS or BEMS), they do not present and/or retrieve faults detected by BEMS/BAS along with the associated information.

Industry Foundation Classes (IFC) for O&M

Currently, the Industry Foundation Classes (IFC4) (BuildingSMART 2013) is considered a major data exchange schema standard for BIM. IFC schema was developed to help overcome the interoperability issue among various software used in the building industry. IFC files contain data about building objects and connections between those objects. Each IFC file is made of object classes, relation classes and resource classes. Object classes identify an IFC object, its ownership, and functional units. Relation classes define the multiple relations between object classes and their functional units while resource classes describe functional units through a set of attributes (Vanlande et al. 2008). Most of the performance data is included in IFC as functional units. Previous research has focused on extracting and managing building component information using IFC files during design and construction, and proposed solutions for design evaluation, construction cost estimating and construction management (Hu and Zhang 2011; Jeong and Ban 2011; Zhang and Hu 2011; Zhiliang et al. 2011). Furthermore, managing information using IFC files during FM phase started to gain more attention in recent years, and research efforts led to development of methods such as IFC-based indoor path planning (Lin et al. 2013), and 3D Indoor Emergency Spatial Model (Tashakkori et al. 2015).

Attributes of each object in an IFC file are defined as *IFC-PROPERTY-SINGLE-VALUE* with a unique line number in object classes (Fig. 4), and each one has a different attribute and assigned value that can be modified based on the data obtained from BEMS and CMMS. Those attributes are connected to that specific object through an *IFC-PROPERTY-SET* that has a name, i.e. a resource class, which can be predefined, and a set of *IFC-PROPERTY-SINGLE-VALUE* line numbers (Fig. 5).



```
#19525= IFCPROPERTYSINGLEVALUE('Location',$,IFCTEXT('1733'),$);
#19526= IFCPROPERTYSINGLEVALUE('Maintenance cost',$,IFCTEXT('$26.5'),$);
#19527= IFCPROPERTYSINGLEVALUE('Maintenance Type',$,IFCTEXT('corrective'),$);
#19528= IFCPROPERTYSINGLEVALUE('Manufacturer',$,IFCTEXT('OMD'),$);
#19529= IFCPROPERTYSINGLEVALUE('model number',$,IFCTEXT('CFR SIZE 1018'),$);
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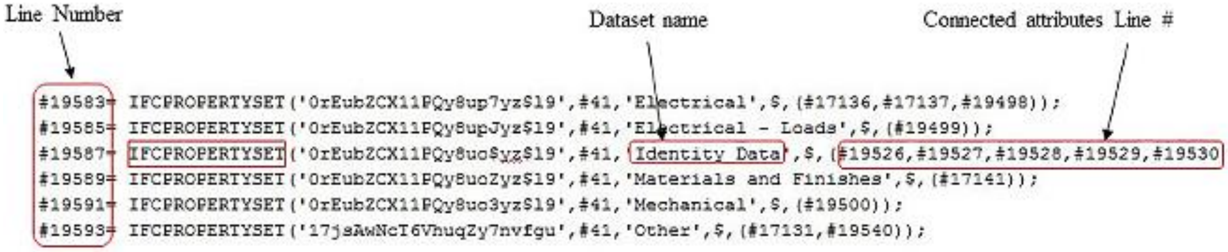
Figure 3.4: IFC Attributes



```
#19583= IFCPROPERTYSET('0rEubZCX11PQy8up7yz$19',#41,'Electrical',$,(#17136,#17137,#19498));
#19585= IFCPROPERTYSET('0rEubZCX11PQy8upJyz$19',#41,'Electrical - Loads',$,(#19499));
#19587= IFCPROPERTYSET('0rEubZCX11PQy8uo$yz$19',#41,'Identity Data',$,(#19526,#19527,#19528,#19529,#19530
#19589= IFCPROPERTYSET('0rEubZCX11PQy8uoZyz$19',#41,'Materials and Finishes',$,(#17141));
#19591= IFCPROPERTYSET('0rEubZCX11PQy8uo3yz$19',#41,'Mechanical',$,(#19500));
#19593= IFCPROPERTYSET('17jsAwNcI6VhuqZy7nvfgu',#41,'Other',$,(#17131,#19540));
```

Figure 3.5: IFC Property Sets

Process framework

The main objective is to develop an automated approach that collects detected alarms from FM systems such as BEMS and BAS, and retrieves corresponding maintenance information from CMMS to support corrective maintenance actions for facility equipment. The main focus is on equipment that is connected to BEMS or BAS systems including mechanical equipment, and alarms from sensors such as equipment failure alarms.

Data exchange between different facility management systems (i.e. BEMS, CMMS) during operations is carried out manually to the most part. The proposed approach implements IFC-BIM as a data repository and an exchange mechanism between BEMS and CMMS. The architecture of the new approach is shown in Figure 3.6. Data retrieved from BEMS is linked to IFC-BIM objects to highlight and retrieve the previous maintenance data from the record (if kept in BIM). If the maintenance record is not readily available in BIM, then the proposed approach retrieves the maintenance data from the CMMS system, and attaches it to the IFC-BIM file.

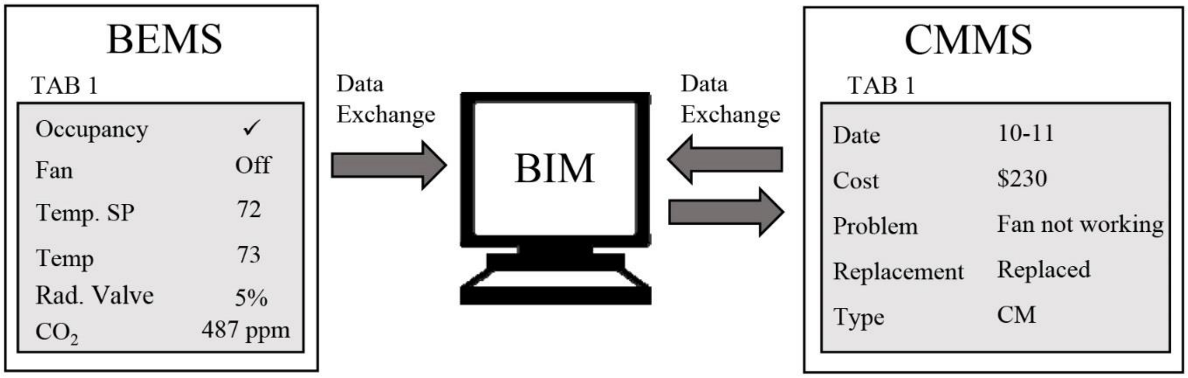
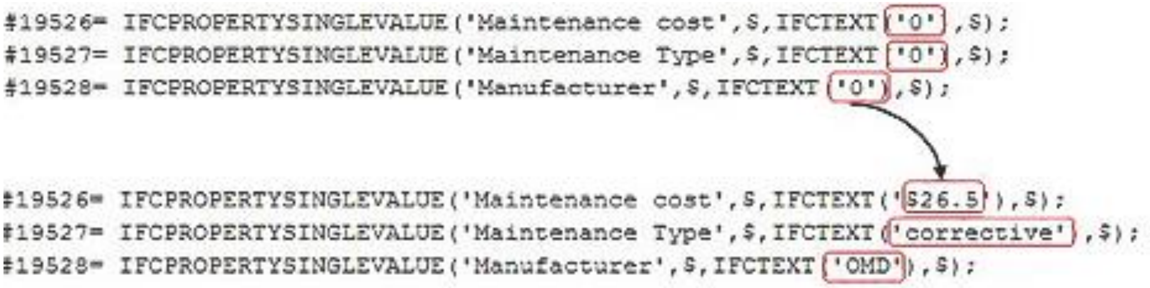


Figure 3.6: Process Architecture

In the IFC file, each piece of equipment has multiple IFC-PROPERTY-SETs and each set contains multiple IFC-PROPERTY-SINGLE-VALUEs. Different types of data collected from BEMS and CMMS are categorized in different IFC-PROPERTY-SETs and corresponding IFC-PROPERTY-SINGLE-VALUEs. For example, the IFC-PROPERTY-SINGLE-VALUEs data location and serial number belong to “Identity Data” property set, while maintenance costs, warranty date, and other maintenance information belong to “Maintenance Data” property set. Consequently, once a single value is defined in the IFC file, the corresponding IFC-PROPERTY-SET should be mapped and defined. After that, other IFC-PROPERTY-SETs can be defined and further IFC-PROPERTY-SINGLE-VALUEs data can be modified or retrieved.

A unique IFC-PROPERTY-SET and IFC-PROPERTY-SINGLE-VALUE with unique line numbers are important to attach maintenance information to its corresponding element or piece of equipment. In order to do so, each attribute should be given a value (e.g. 0, none, etc.) in the corresponding field when modeling, i.e. it should not be left blank (Fig. 7). This is because IFC format tends to optimize the file by combining IFC-PROPERTY-SINGLE-VALUE attributes with no values into shared property sets, which disables not only the ability to differentiate between different elements and their attributes, but also the possibility to update them.



```
#19526= IFCPROPERTYSINGLEVALUE('Maintenance cost',$,IFCTEXT('0'),$);
#19527= IFCPROPERTYSINGLEVALUE('Maintenance Type',$,IFCTEXT('0'),$);
#19528= IFCPROPERTYSINGLEVALUE('Manufacturer',$,IFCTEXT('0'),$);


#19526= IFCPROPERTYSINGLEVALUE('Maintenance cost',$,IFCTEXT('$26.5'),$);
#19527= IFCPROPERTYSINGLEVALUE('Maintenance Type',$,IFCTEXT('corrective'),$);
#19528= IFCPROPERTYSINGLEVALUE('Manufacturer',$,IFCTEXT('OMD'),$);
```

Figure 3.7: IFC-PROPERTY-SINGLE-VALUE Original IFC File with Given Values

As shown in (Fig. 8), when an alarm is received from BEMS for a specific equipment, its type is determined. Then, it is fed into the IFC-BIM file with data including location, BEMS ID and/or Serial Number. Serial Number and BEMS ID are unique to each piece of equipment; therefore, the equipment can be identified easily within IFC-BIM through its BEMS ID and/or serial number. Maintenance IFC-PROPERTY-SET is defined using serial numbers and made ready for adjustments.

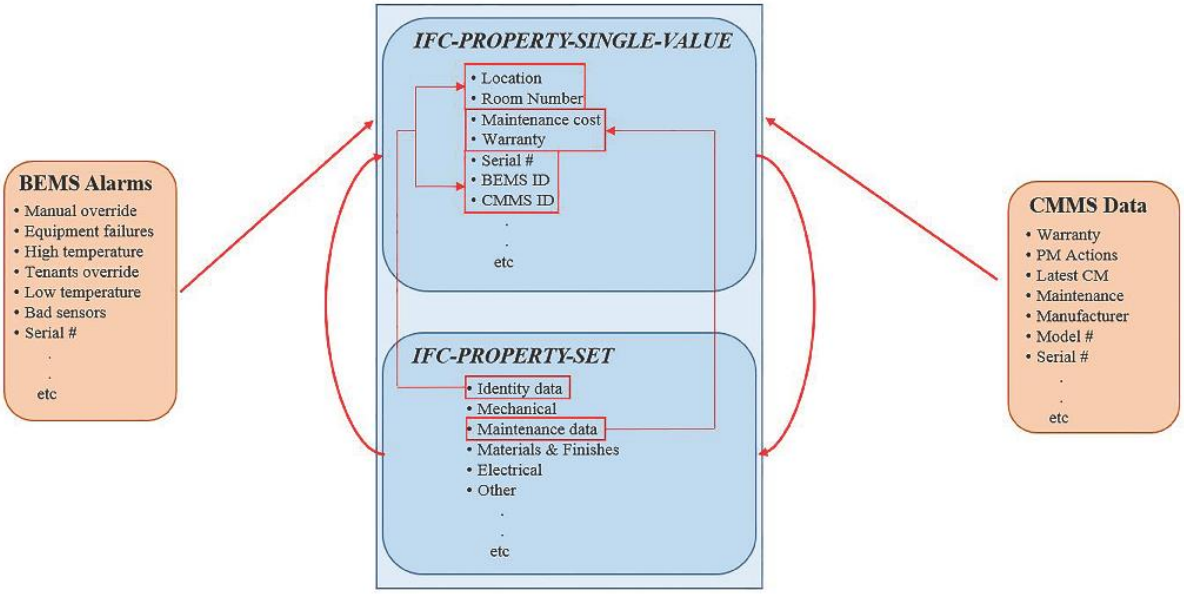


Figure 3.8: The Process Schema

It should be noted that IFC-BIM file allows adding various IFC-PROPERTY-SETs and IFC-PROPERTY-SINGLE-VALUEs to any element. The serial number that was defined earlier helps in defining the related maintenance data in CMMS, which then can be copied to the right maintenance IFC-PROPERTY-SET, and presented in BIM.

In summary, the proposed approach utilizes the serial and element ID numbers of building equipment to retrieve any required operation or maintenance data. To achieve that, it modifies the unique IFC-PROPERTY-SINGLE-VALUEs that are connected to IFC-PROPERTY-SETs in IFC-BIM file. Each set or single value is linked to a specific equipment and space in the model. The approach was validated with real-life data collected from an educational building. The implementation process along with the preliminary results are included in the following section.

Implementation

In order to implement and validate the proposed approach detailed in the process framework section, an API was developed using C# programming language. The API utilizes open source IFC 4 for the BIM, .XLS files for the BEMS and CMMS files. The API's interface (Fig. 9) allows the user upload any data that was acquired from the BEMS and CMMS in .XLS format. The user then assigns the IFC file to the API. The API's logic achieves two main functions (Fig. 10); first, it takes the object(s) name from the .XLS file and performs a "search and replace" procedure for the assigned attributes in IFC-BIM. If one attribute is missing, the algorithm would generate that particular attribute and add its value to the object's IFC-PROPERTY-SET through the resource class. If previous maintenance information of a dysfunctional object/equipment is not included in the IFC file, the API will conduct a "search and find" process in the CMMS file using the serial number and the CMMS ID that is connected to the object, locate it in the IFC-BIM file, and attach it to the pertinent object.

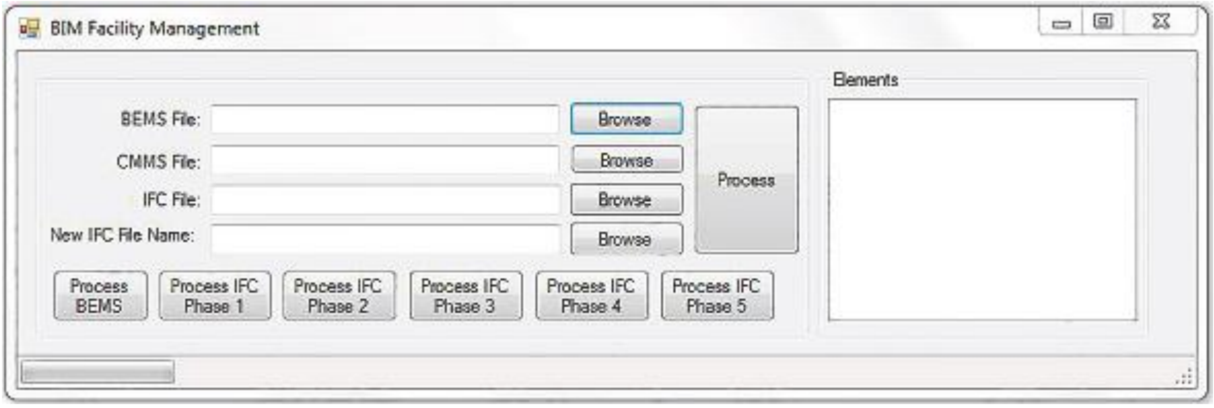


Figure 3.9: API User Interface

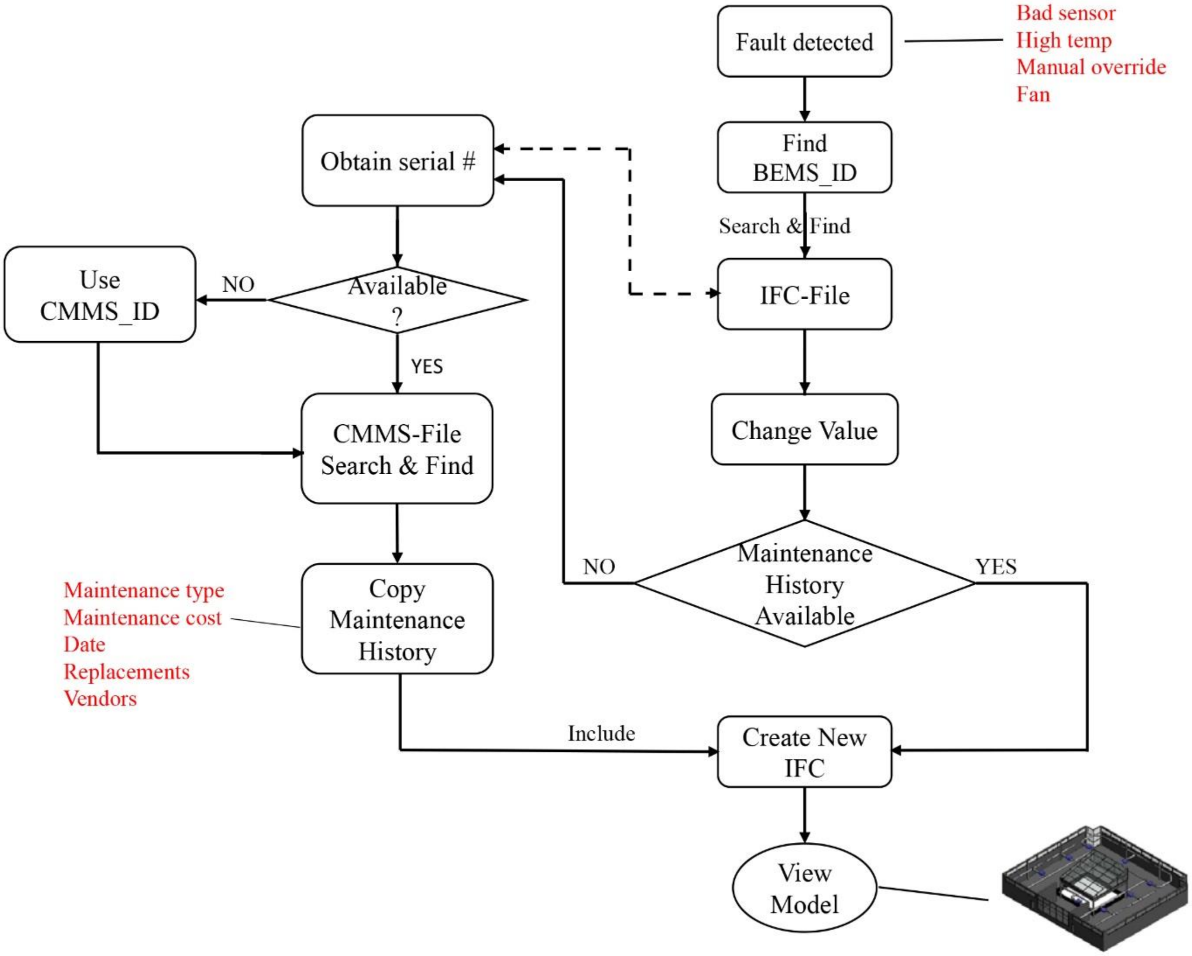
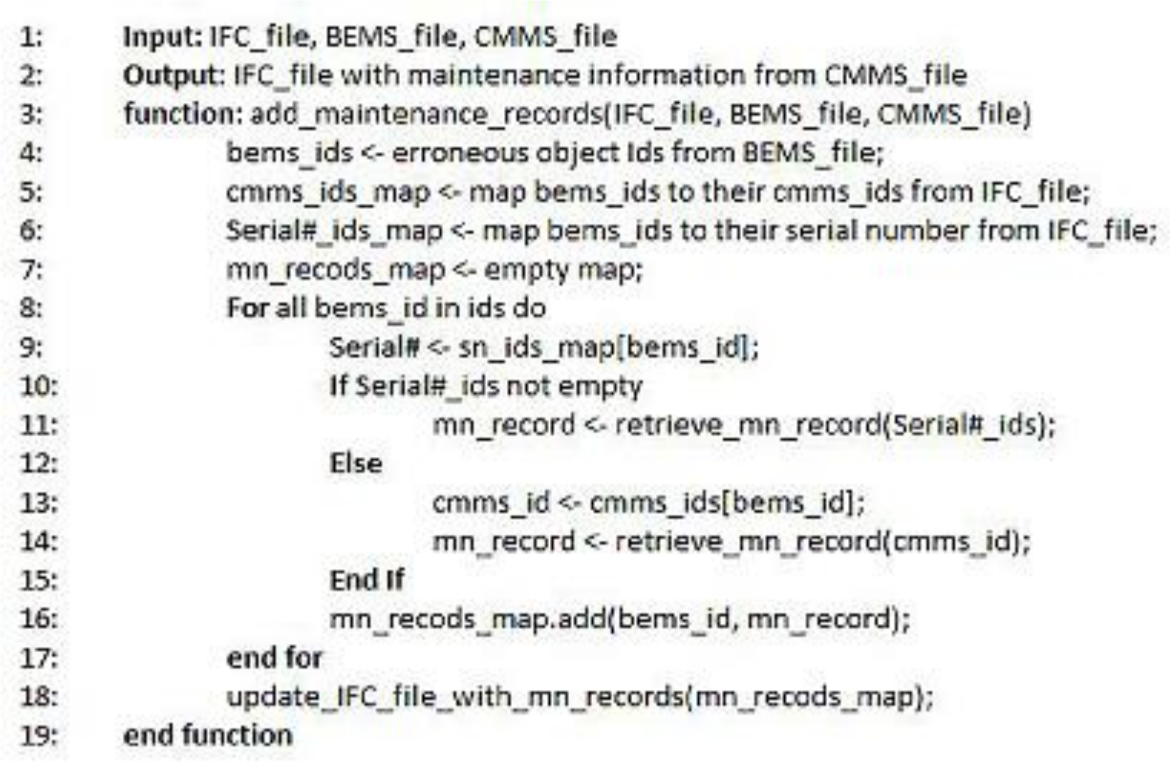


Figure 10: Algorithm Design

The pseudo code of the algorithm is presented in Figure 11. The algorithm updates IFC-BIM of the intended building with the maintenance records obtained from CMMS. If BEMS reports a malfunction for a system element, the BEMS_ID for that element is recorded (line 4 in Fig. 11). The BEMS_ID is then mapped with the corresponding Serial# or CMMS_ID in the IFC_File for the same element (lines 5, 6 in Fig. 11). In the CMMS maintenance records file, either the CMMS_ID or the Serial_# is used to find the intended element with the corresponding maintenance information (lines 9-15 in Fig. 11). The algorithm then retrieves the corresponding maintenance data using the predefined attributes in the IFC_File (line 16 in

Fig. 11). Finally, a new IFC_File is generated with all the necessary maintenance data of the dysfunctional element (line 18 in Fig. 11).



```
1:    Input: IFC_file, BEMS_file, CMMS_file
2:    Output: IFC_file with maintenance information from CMMS_file
3:    function: add_maintenance_records(IFC_file, BEMS_file, CMMS_file)
4:        bems_ids <- erroneous object Ids from BEMS_file;
5:        cmms_ids_map <- map bems_ids to their cmms_ids from IFC_file;
6:        Serial#_ids_map <- map bems_ids to their serial number from IFC_file;
7:        mn_recods_map <- empty map;
8:        For all bems_id in ids do
9:            Serial# <- sn_ids_map[bems_id];
10:           If Serial#_ids not empty
11:               mn_record <- retrieve_mn_record(Serial#_ids);
12:           Else
13:               cmms_id <- cmms_ids[bems_id];
14:               mn_record <- retrieve_mn_record(cmms_id);
15:           End If
16:           mn_recods_map.add(bems_id, mn_record);
17:       end for
18:       update_IFC_file_with_mn_records(mn_recods_map);
19:   end function
```

Figure 3.11: API Pseudo Code

However, it should be noted that a minimum number of defining attributes such as equipment serial numbers, BEMS IDs and CMMS IDs should be available and attached to each specific piece of equipment in all systems for the proposed approach to work. This means that any element in the IFC-BIM file that misses any of the defining attributes cannot be linked, thus their attributes cannot be updated in the IFC-BIM file.

An ideal scenario to implement the process presented above would require having an IFC-BIM that includes equipment BEMS IDs, serial numbers, and/or CMMS IDs, and this model would be handed over to facility managers after the commissioning phase. That is why the research team developed an algorithm that updates the IFC-BIM with BEMS and CMMS ID numbers to mimic the ideal scenario. It is important to note that in a perfect world, facility managers should be involved when deciding on the specific attribute data, i.e. BEMS and CMMS IDs, which needs to be included in the model.

The proposed approach was tested for a complex environment using the HVAC system of a building located at Iowa State University (ISU) campus. For the matters of this experiment, the target maintenance attributes that were used from the CMMS system included warranty information, previous malfunctions, previous replacements, manufacturer, maintenance cost, maintenance type, and maintenance description. Those attributes may change depending on the facility type and facility manager needs. Furthermore, identification data that includes equipment serial numbers, BEMS IDs, and CMMS IDs were used to help identify and link the corresponding information between the two systems. BEMS attributes that were used in these experiments were limited to DDC reports and alarms of equipment failures that are directly related to maintenance actions. BEMS and CMMS data can easily be exported in .XLS format, which is easy to implement in a variety of programming languages including C#.

Data

BEMS and CMMS data were provided by ISU facility management department in .XLS format. The proposed approach was first tested for the HVAC system in a typical university building, King Pavilion. The building is a 22,317 sq. ft., (2073.3 m^2) two story, LEED platinum university building located at ISU main campus (Fig. 12). It is part of the college of design and houses studio spaces. This building was chosen for multiple reasons: 1) the majority of the building information and models were available, and it is still being used as studio spaces as it is intended in the original design; 2) the HVAC system used in the building is simple yet complex enough for validation purposes. The building has all the major centralized HVAC components, has only one thermal zone, and includes terminal units with simple design. 3) All maintenance documents were available in the CMMS.

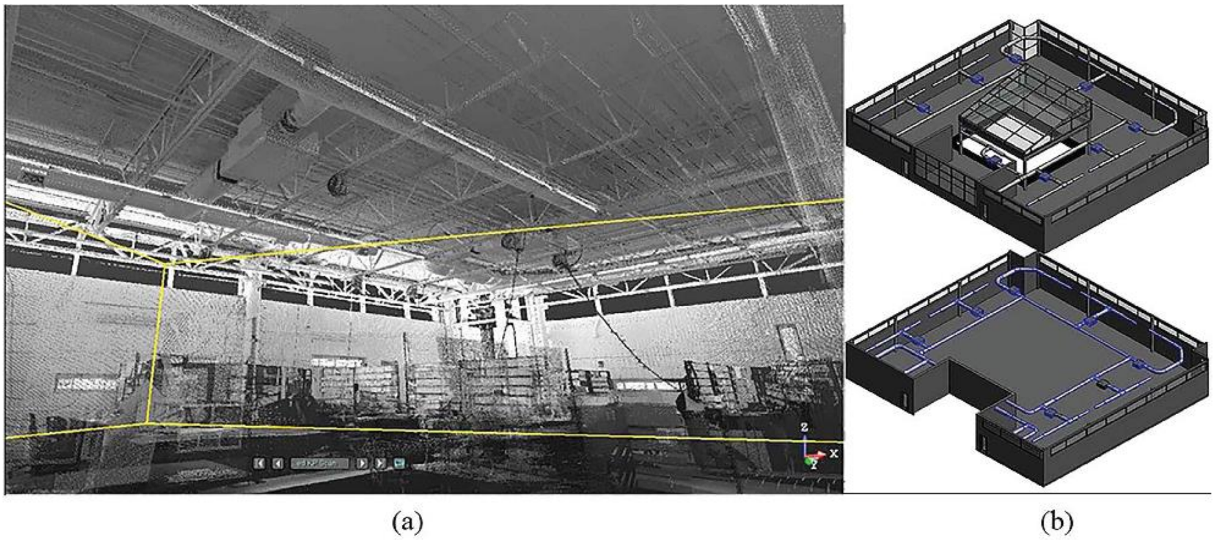


Figure 12: King Pavilion building 3D point cloud (a), and 3D As-built BIM (b)

An accurate 3D as-built BIM of the building was not available to the research team, thus one was developed using laser scan point clouds captured using a Trimble TX5 laser scanner. Eight scans were taken to cover each story, sixteen scans in total for the whole building. Autodesk Revit Scan-to-BIM plugin was used to model the building's structural and the HVAC components from the 3D point cloud. BEMS attributes, and their names were added to each object manually during the modeling process. The model was then converted into IFC format. Tekla BIMsight software (Tekla-corporation 2013) was used to visualize the changes in 3D environment as it prevents from data loss for IFC format.

BEMS system used by ISU is Metasys from Johnson Controls (Johnson-Controls 2015) which is one of the commonly used BEMS systems in educational buildings. The CMMS software used by ISU is called FAMIS from Accruent, LLC (Accruent.LLC 2015). A DDC system with more than 250 sensors is installed and connected to the BEMS in the building. The data was acquired in .XLS format from the BEMS system for one-month period. The operation data of the past six years was acquired from the CMMS system, which included serial numbers, CMMS IDs, warranty dates, serving spaces, in addition to previous maintenance cost, type, task, description and work numbers.

Preliminary Results and Discussion

The system components included are energy recovery ventilator (ERV), condensate pump, fan coil unit (FCU), hood exhaust fan (HEF), hot water pump, heat exchanger unit (HXU), exhaust fan, supply fan and 15 terminal air boxes (TAB). All of these components are equipped with multiple controllers and sensors.

Table 1 summarizes the alarms collected for one-month period from BEMS for the equipment listed above. During the one-month period, four alarms were reported indicating failure of the following equipment: an ERV, a condensate pump and two of the main TABs with BEMS ID numbers ERV1, CDP1, TAB-012, and TAB-015 respectively. These failures were successfully detected by building sensors and reported in the BEMS output file. For those two TABs, as seen in Table 2, the fans were dysfunctional which caused temperature increase within that space, thus there was another alarm for increased temperatures. The proposed approach successfully identified and located these malfunctions in the IFC-BIM file.

Table 3.1. Alarms Collected by BEMS

Equipment	Alarm received	Alarm Type
Energy Recovery Ventilator	Yes	Turned off
Condensate Pump	Yes	Not running
Fan Coil Unit (FCU)	No	
Hood Exhaust Fan (HEF)	No	
Hot Water Pump	No	
Heat Exchanger Unit (HXU)	No	
Exhaust Fan	No	
Supply Fan	No	
TAB 012	Yes	Fan not working
TAB 015	Yes	Fan not working

Table 3.2. Reported TABs Alarms

TAB#	001	002	003	004	005	006	007	008	009	010	011	012	013	014	015
Occupancy	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Fan	√	√	√	√	√	√	√	√	√	√	√	×	√	√	×
Temp. SP	73	73	73	73	73	73	73	73	73	73	73	73	73	73	73
Temp.	75	74	75	73	73	74	75	73	73	72	75	78	73	74	77
Rad. valve	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CO_2	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√

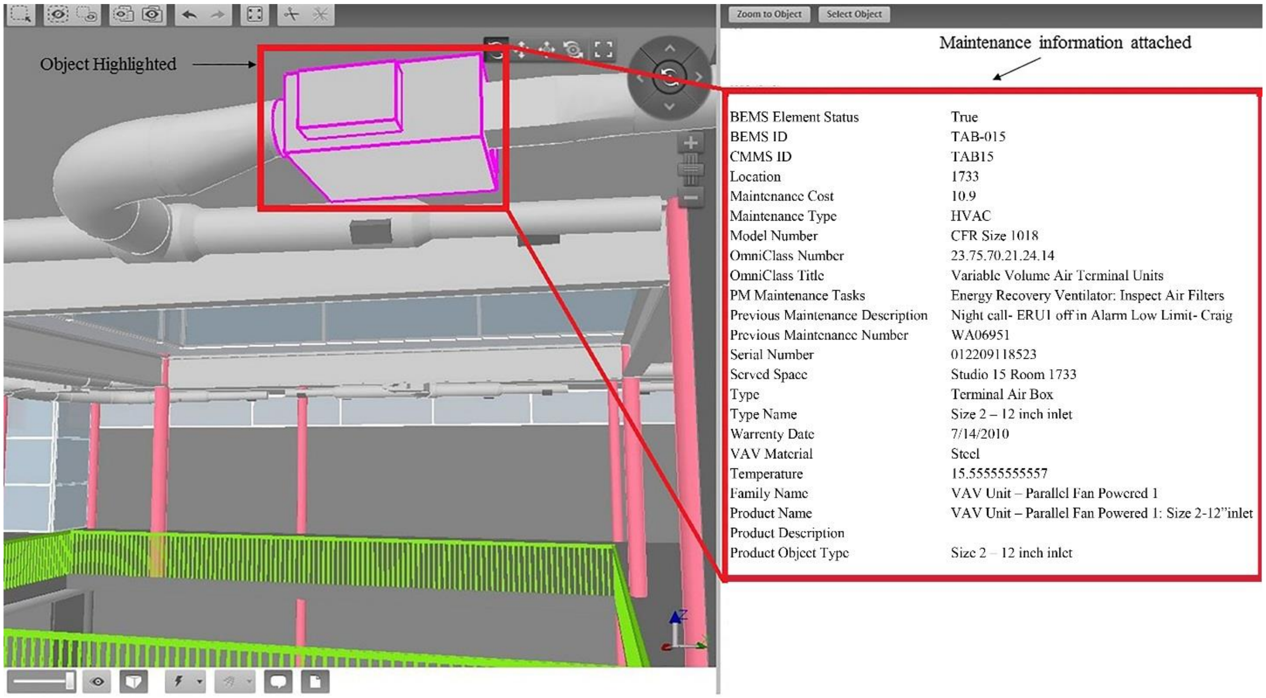
√: Properly functioning, ×: Not functioning

Therefore, maintenance data of all dysfunctional elements were retrieved successfully as shown in Table 3. It shows that three elements have a history of sudden failures, and they needed corrective maintenance actions in the past. This information would be available to the maintenance personnel while inspecting the element through IFC-BIM interface, which would help reduce the time for looking for other causes (e.g. for the ERV the maintenance team might check the keypad first). Furthermore, guidelines on design and maintenance of building equipment, such as (ASHRAE 2008), ((Agle and Galbraith 1991; McDowall 2006), are typically included in CMMS and can be transferred to IFC-BIM file using this method.

Table 3.2. Maintenance Information Retrieved from CMMS

Categories	ERV	CDP	TAB 12 FAN	TAB 15 FAN
Maintenance Type	CM	CM/Plumbing	PM	CM
Maintenance Cost	228.5	114	86.3	10.9
Maintenance Date	04-13-2013	10-15-2013	10-10-2014	6-9-2014
Maintenance actions	Replace Keypad, recalibrate	__	Replace fan	Inspect filters, turn off alarm, energy recovery ventilator check
Manufacturer	VENMAR CES	BELL & GOS	ENVIRO TEC	ENVIRO TEC
Warranty	expired	Expired	expired	expired

Tekla BIMsight was used to visualize the new IFC file created using the proposed approach (Fig.13). Tekla BIMsight software was selected because it conserves all the maintenance information transferred from the CMMS and BEMS files during the file conversion process. The location of the TAB-015 was defined and highlighted in the 3D model. Having related maintenance information and required guidelines in a 3D environment would help maintenance personnel locate equipment easily while improving their understanding of the problem. In addition, it would reduce the time and effort spent on collecting information, and it would help improve efficiency in corrective maintenance tasks.



BEMS Element Status	True
BEMS ID	TAB-015
CMMS ID	TAB15
Location	1733
Maintenance Cost	10.9
Maintenance Type	HVAC
Model Number	CFR Size 1018
OmniClass Number	23.75.70.21.24.14
OmniClass Title	Variable Volume Air Terminal Units
PM Maintenance Tasks	Energy Recovery Ventilator: Inspect Air Filters
Previous Maintenance Description	Night call- ERU1 off in Alarm Low Limit- Craig
Previous Maintenance Number	WA06951
Serial Number	012209118523
Served Space	Studio 15 Room 1733
Type	Terminal Air Box
Type Name	Size 2 – 12 inch inlet
Warrenty Date	7/14/2010
VAV Material	Steel
Temperature	15.55555555557
Family Name	VAV Unit – Parallel Fan Powered 1
Product Name	VAV Unit – Parallel Fan Powered 1: Size 2-12”inlet
Product Description	
Product Object Type	Size 2 – 12 inch inlet

Figure 13: Final IFC-BIM with Maintenance Information

Conclusions

Facility managers depend heavily on FM information systems such as BEMS and CMMS for corrective maintenance actions. Current FM information systems lack improved visualization and interoperability capabilities to allow for seamless operation and data transfer during O&M phase. BIM is sought to enhance current FM practices by improving interoperability, visualization, and fragmented data challenges. Previous research either developed BIM frameworks to streamline the existing FM processes or developed approaches to replace current processes. However, there is no study to date which has focused on using

BIM for FM to minimize lead-time needed to collect high quality data for corrective maintenance actions.

This paper presented an automated process that responds to alarms received from BEMS or BAS systems by retrieving historical maintenance data required for corrective maintenance. The contributions include 1) a schema that enables the integration of data required for corrective maintenance in 3D IFC-BIM environment, and 2) a process to link alarm reports of equipment failures and the related maintenance information from CMMS system using IFC-BIM.

The proposed process was validated in terms of data relevance, and for being readily available when needed. The results showed that the process was able to collect any type of information needed by facility managers for corrective maintenance. In addition, it can include other information such as maintenance guidelines for different pieces of equipment. It can help facility managers and maintenance teams with collecting related data and information for corrective maintenance actions in an efficient and timely manner using current systems and processes. The process shows that BIM does not need to be inclusive, which means that data can be aggregated from different systems, and temporarily written into IFC-BIM on an as needed basis. Furthermore, information can be accessed and edited by the responsible FM personnel who have the access right to edit and/or collect necessary information for O&M actions. Future work should focus on determining the different needs of various O&M crews to provide more specific data needed by particular crews. In addition, it should focus on making bi-directional data transfers from IFC-BIM to FM systems and vice versa.

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CHAPTER 4. BIM-ENERGY SIMULATION APPROACH FOR DETECTING SPACES WITH FAULTS AND PROBLEMATIC BEHAVIOR

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Abstract

Heating and cooling consumes the majority of energy in buildings. Faults and problems in heating and cooling systems waste up to 20% of heating and cooling energy. Identifying spaces with heating and cooling problems within a facility remains a major challenge for facility managers. This study aims to detect spaces with potential problems by using BIM to utilize data collected by facility management systems to determine the intended energy performance and compare it with actual energy performance and other maintenance and alarms occurred in the building. To achieve that, this study developed a framework that links related data between Industry Foundation Class (IFC) BIM, energy simulation, Building Energy Management Systems (BEMS), and Computerized Maintenance Management Systems (CMMS) to detect spaces with faults and problematic behavior. The framework achieved detecting specific spaces in the building with hidden problems and faults. The paper supplements the body of knowledge in the area of facilities energy management by providing a framework to use energy simulation and other FM systems to locate and detect spaces with problematic behavior. Furthermore, it enables facility managers to collect relevant high quality data from spaces with problems. Facility managers can utilize this framework to plan their maintenance plans based on the poor behavior of specific spaces within the building.

Keywords: IFC, Predictive Maintenance, BIM, BEMS, CMMS, Energy Performance

Introduction

Buildings consume more than 30% of the world’s total energy (IAE 2008). Heating, Ventilation, and Air Conditioning (HVAC) accounts for approximately 40% of buildings’ energy consumption (USDOE 2011). However, 5% to 20% of HVAC energy consumption goes to waste is due to faults and lack of maintenance (Roth et al. 2005). It became more important for facility managers to find more efficient ways for managing building energy (Bush and Maestas 2002). However, facility managers face many challenges to achieve their goals (Per Anker Jensen and Tu 2015) that includes identifying problematic spaces in a facility, isolating different types of problems, prioritizing the impact of those problems, and developing solutions for these problems (Zhu 2006).

Energy simulation can be very effective to help reduce energy consumption in buildings (Kim et al. 2016). However, building energy analyses are mostly conducted during design stages, and the results of these analyses are not typically used while operating the building. Facility managers’ ability to identify problematic areas and isolate problems is limited due to numerous interconnected Facility Management (FM) systems and their multi-layer information content. Nevertheless, BIM provides facility managers with an opportunity to manage and coordinate the information collected from these systems. In addition, it supports engaging multiple stakeholders, and enables collecting various information throughout the project life cycle.

This study proposes a new BIM-based framework to identify problematic areas in a facility by evaluating its energy performance by comparing its BEMS monitoring and energy simulation results. In this framework, BIM coordinates data collected by Building Energy Management Systems (BEMS), geometrical data stored in BIM, maintenance data stored in

Computerized Maintenance and Management System (CMMS), and energy simulation results generated by EnergyPlus™ based DesignBuilder software. Detailed tasks include (1) establishing a methodology to collect BEMS data and use it for energy simulation, and (2) developing a framework to identify building spaces with problematic behavior and specifying possible causes. In order to assess the feasibility of the framework, data was collected from an unoccupied building where areas with problematic behavior were located, and possible causes were identified using its maintenance history data.

This paper is organized as follows: comprehensive literature review on BIM for energy management, building energy management systems, BIM for FM, and current maintenance practices is provided in the next section. The proposed framework is detailed in the following section. The following section then presents the results of the experiments conducted. The final section draws conclusions and discusses future research needs.

Background

BIM for Building Energy Management

Energy-modeling and current energy modeling tools are complex and time consuming (Crawley et al. 2008), because of the process of gathering and accurately entering the necessary building description data that is required for simulation. Traditionally, the modeler enters all the data manually to describe the building. It is important to note that the modelers make simplifications on the proposed geometric design to minimize the complexity of the energy modeling and information gathering. Programs such as DOE-2.2 and EnergyPlus™ that were developed and used to predict energy consumption in buildings require laborious data entry and complex to use (Heiple and Sailor 2008; Zhu 2006). Currently, BIM is used to efficiently plan, design, and manage buildings. While energy modeling needs data such as R-values, conductivity and thicknesses, BIM offers intelligent objects of a building structure that can include such data (Shalabi and Turkan 2016) for all building elements such as exterior/interior walls, roofs, windows, doors, floors, and their orientation.

Different energy-simulation accuracy levels can be achieved based on BIM Level of Details (LOD). The most accurate simulation can be achieved after completing the building and finalizing the construction decisions. When used with other Facility Management (FM) systems, using energy simulations while operating the building not only helps in detecting energy overconsumption, but it also helps in defining causes for that overconsumption (Al-Shalabi and Turkan 2015). Such causes may include lack of maintenance for one or more building element, users' behavioral actions, or both. The previous research on BIM for building energy management can be categorized into three groups: (1) studies that developed methods and algorithm to use BIM to predict energy performance depending on the results obtained from energy simulation tools such as DOE and EnergyPlus™. (2) Studies that investigated data exchange between BIM and energy simulation tools. (3) Studies that developed applications for using BIM for energy management.

The first group focused on developing BIM for energy modeling during design phase. Cho et al. (2010) developed a strategy that uses BIM technology to include sustainable fixtures to predict energy generation. Another study focused on optimizing energy performance using a multi-objective generic algorithm that uses the results from BIM-based energy simulation (Chen and Gao 2011). Other researchers used BIM to analyze the annual energy consumption and CO_2 emissions of a single house (Raheem et al. 2011). Kim et al. (2013) developed an IFC-BIM based energy simulation process that runs in DOE 2.2. In addition, they developed a semantic material name matching system that finds standardized materials names and their associated material property values (Kim et al. 2013). Several researchers focused on developing requirements and guidelines for using BIM for building energy modeling and management. Such studies include developing guidelines for using BIM for building energy modeling (Reeves et al. 2012), and studying key BIM-server requirements for information exchange in energy efficient building retrofit projects (Jiang et al. 2012). In a different line of work, Oh et al. (2011) developed a method that uses EnergyPlus™, and genetic algorithm to determine the optimal design option for various glazing options. In addition, they developed an application to exchange data from gbXML to EnergyPlus-IDF file. These studies complement, and fall within the same scope of the study presented here, in terms of developing the energy model using BIM. However, this study differs from the previous work by focusing on using BIM and energy simulations for actively managing building energy performance during building operation phase.

The second group investigated information exchange between HVAC systems and energy simulation tools. Bazjanac (2008) investigated the interoperability between IFC-BIM and building energy analysis tools. This work focused on transferring geometry and HVAC information from IFC-BIM into EnergyPlus™. O'Sullivan and Keane (2005) presented a graphical user interface to input necessary data about HVAC system into BIM-based building energy simulation using IFC format. These studies are similar to the work presented here in terms of the methods they use to develop the energy model. However, they differ from this study as they developed methods for information exchange, which is not in the scope of this study.

The third group focused on the applicability and usability of building simulation tools in different life-cycle stages of a building. Katranuschkov et al. (2014) developed an energy enhanced BIM (eeBIM) framework with the goal of closing the gap for existing data and tools from building design and operation to enable an efficient life-cycle energy performance estimation and decision-making. Attia surveyed selection criteria of building simulation tools between various stakeholders on construction projects, the results showed a broad range of differences between designers and simulation tools (Attia 2010). Difficulties in implementing BIM by industry practitioners is described by Arayici et al. (2011), which included difficulties such as reinventing the workflow, training their staff, assigning responsibilities, and changing the way buildings are modeled. (Katranuschkov et al. 2014) described the importance of developing a framework that enables integration multiple resources (e.g. weather, occupancy, material data, etc.) and the interoperability between energy analysis, cost analysis, CAD, FM and building energy monitoring tools. They also highlighted the importance of combining various construction and FM related data in typical BIM to be efficiently applied to tasks such as energy simulation and FM. Kim et al. (2016) built on this work by developing a model for mapping IFC-BIM material information to building energy analysis was developed. Shalabi and Turkan (2016) developed an approach for optimizing data collection from IFC-BIM to be used for corrective maintenance actions. However, none of these studies considered using energy simulation techniques for energy management during building operation phase. This study builds on the work in this group by developing an approach that integrates energy simulation results, actual energy performance monitored by BEMS, and other FM data such as maintenance to move toward more active building energy management and maintenance.

Building Energy Management Systems

BEMS adjust and control buildings HVAC and lighting equipment to manage their environment while optimizing their energy performance and occupants' thermal comfort. BEMS is defined as a collection of microcomputer systems consist of Direct Digital Controllers (DDC) and their control devices, which operate under supervisory control equipment and software collectively. Their capabilities include data sharing with individual controllers for coordination and optimization, linking control processes, and performing operation tasks and reports (Doty and Turner 2009). BEMS is connected to building sensors and controllers that report any flaws or dysfunctions in the system or its equipment.

Building controllers send feedback to BEMS or BAS system if any of the equipment is not working properly. Facility managers receive alarms from BEMS about any dysfunctions or failure, and they can monitor, change any benchmark, or override the system decisions. When maintenance or replacement is needed, facility managers report the problem to the maintenance personnel who in turn need to locate, inspect, and gather the required maintenance information regarding that element.

Facility managers work to achieve and maintain the planned operational performance of buildings, and to guarantee an up-to-date maintenance status of the HVAC equipment, which is dependent on the continuous feedback from the building sensors, controllers, and energy management strategies during building operation phase. Energy performance of buildings deteriorates overtime due to various reasons including lack of prompt response to faults/alarms reported by BEMS systems, imprecise commissioning, and BEMS malfunctioning. This would result in energy waste, and cause occupant discomfort and complaints (IFMA 2009).

BEMS reports different types of data that are recorded by FM information systems. The data reported include weather and energy use (e.g., temperature, CO2, zone airflow, daylight levels, occupancy levels, etc.), alarm monitoring and data collected from sensors (e.g., equipment failure, high and low temperatures defective sensors and communication problems), and controllers (e.g. air handler units controllers, valves controllers and fans controllers) (Doty and Turner 2012). Typically, DDCs are numbered and organized based on their type, function, and location in the building, and presented in list format. However, data about their exact locations, the equipment affected by them and their maintenance history information are stored in different systems. Furthermore, building performance metrics such as sensor outputs, and energy performance metrics are presented in 2D histograms, tables, and lists of tasks or in similar formats, which requires tedious data extraction and interpretation processes to benefit from this data.

A BEMS hosts the results of Fault Detection and Diagnostics (FDD) analysis and presents it to facility managers (Dong et al. 2014). Several FDD approaches have been developed to identify faults and deterioration in building equipment (Dong et al. 2014; Qin and Wang 2005; Sallans et al. 2006; Schein et al. 2006; Wang and Xiao 2006; Xiao 2004). This study differs from FDD approaches as it analyzes energy simulation results using real weather data measured by the building systems and then compares the results to actual energy performance of a building.

BIM Implementations in FM

FM personnel manage HVAC systems and other building components using multiple systems. Their goal is to maintain a thermally comfortable environment for occupants, and to guarantee the functionality of the building while remaining in operation budget. Two of the major systems used in the FM practice are BEMS and CMMS.

FM systems interact with multiple users and stakeholders directly and indirectly during building operation including occupants and FM staff (Roper and Payant 2014). Occupants' actions affect the energy consumption and the reported faults by BEMS concern facility managers (Doty and Turner 2009). Some well-known problems caused by occupants include: the use of space heaters during winter which wastes cooling power while increasing the plug loads (Beltran et al. 2013); and blocking thermostats and sensors with furniture or appliances which gives false readings to FM systems. The lack of manpower in FM affects maintenance and energy consumption of a building greatly (Roper and Payant 2014; Teraoka et al. 2014). As a result, building operators feel overwhelmed by the number of fault alarms they need to address, and they focus only on critical faults and complaints made by occupants. Furthermore, facility managers may take temporary fixes that resolve the issue but lead to more energy waste or allow for further faults to emerge (Teraoka et al. 2014).

Throughout the facility life cycle, BIM supports a multi-domain and multi-layer collaborative approach, and engages multiple stakeholders in the project including architects, engineers, contractors as well as facility managers and operators. Using BIM leads to decrease information loss of project during its lifecycle (Al-Shalabi and Turkan 2015; Eastman et al. 2011). Effective data sharing between various stakeholders is among the capabilities of BIM, which has been proven for design and construction phases. However, effective BIM applications during the operation phase of a facility have not yet been achieved.

BIM adoption in FM is still in its early stages (Kelly 2013). This is mainly due to the limited awareness among FM professionals about the expected BIM benefits for FM, lack of data exchange standards and unproven productivity gains illustrated by case studies. BIM benefits in FM are sought during the operation phase, such benefits include extracting and analyzing data for various needs to support and improve decision making processes (Azhar 2011). Furthermore, BIM in FM applications can provide faster access to data and improve the process of locating facility elements via its user friendly 3D interface, which help increase the efficiency of work order executions (Kelly 2013). In addition, carrying BIM from design to operation phase would allow BIM to support all activities throughout the buildings' life cycle (Fallon and Palmer 2007)

Previous research on BIM use in FM developed BIM frameworks to streamline the existing processes and systems. Such studies include augmented reality based operations and maintenance (AR-based O&M) support (Lee and Akin 2011), 2D barcode BIM-based facility management system (Lin et al. 2012), 3D BIM-based facility maintenance and management system (Chen et al. 2013), (Lin and Su 2013). These studies compliment the research presented here in terms of streamlining the existing FM processes and systems. However, this study differs from the previous work as it uses energy simulations and energy performance monitoring to improve building energy management by detecting systems dysfunctions.

Several other studies developed BIM-based approaches to replace current processes to capture, store, and retrieve facility data in an efficient manner. Such studies include using BIM to generate customized templets to capture maintenance work related changes (Akcamete 2011), a knowledge based BIM system that uses case-based reasoning for building maintenance (Motawa and Almarshad 2013), fault-tree analysis for failure root cause detection (Lucas et al. 2012; Motamedi et al. 2014), and using BIM for HVAC troubleshooting (Yang and Ergan 2015). However, none of the studies in this group focused on developing approaches to provide facility managers with solutions that are proactive to improve the performance of their buildings.

While BIM is sought to benefit the FM practice, there are still many challenges regarding BIM implementation in FM. Two of the major challenges that prevents from BIM implementations in FM include unproven productivity gains that can be realized from reduced equipment failure, as well as the productivity increases that maybe realized through an integrated platform (Becerik-Gerber et al. 2011). Furthermore, fragmented data, data interoperability, and lack of data transparency throughout the building life cycle are among some of those challenges.

Maintenance in FM

Maintenance can be preventive, corrective, or predictive. Corrective maintenance is considered as reactive type of maintenance that responds to a failure or to a breakdown (Motawa and Almarshad 2013). Preventive and predictive maintenance are considered as proactive maintenance that prevents from a failure or a breakdown of building equipment (Palmer 1999). Preventive maintenance is scheduled and predefined for regular intervals to guarantee a continued optimal performance (Rikey and Cotgrave 2005). Unlike corrective maintenance, preventive maintenance reduces non-planned work and allows estimating the overall maintenance budget (Flores-Colen and de Brito 2010). Predictive maintenance is a condition-based maintenance that is useful for reducing life-cycle costs and achieving more efficient maintenance budgets (Hermans 1995). Corrective maintenance is usually an emergency action that leads to unavoidable extra costs. It is important to minimize the occurrences of this type of maintenance (Flores-Colen and de Brito 2010).

Proposed Framework

Facility managers depend on various systems to guarantee a functioning building with minimum shutdowns. Due to the complexity of buildings, the massive amount of data collected from facility management systems, and the multiple factors that affect a building's performance, it has become cumbersome for facility managers and building operators to detect and specify spaces with abnormalities or malfunctions in buildings' systems.

The main objective of the proposed approach here is to detect faults that are causing excess energy consumption, human discomfort, or work overload on HVAC systems. The nature of such faults is usually hidden and undetected by BEMS alarming systems. The focus of the study is on heating and cooling equipment that are operating in spaces monitored and managed by BEMS.

Corrective maintenance actions are critical to the building performance as they may cause losses in equipment, affect occupants comfort, and result in unexpected costs. The proposed approach for building energy consumption monitoring enables to identify degraded equipment before they fail. Since BIM is not all-inclusive, data can be aggregated from other FM systems as needed and included in BIM (Figure 4.1). This allows facility managers to compare, analyze, and visualize information collected from various systems to detect faults and link it to its possible causes.

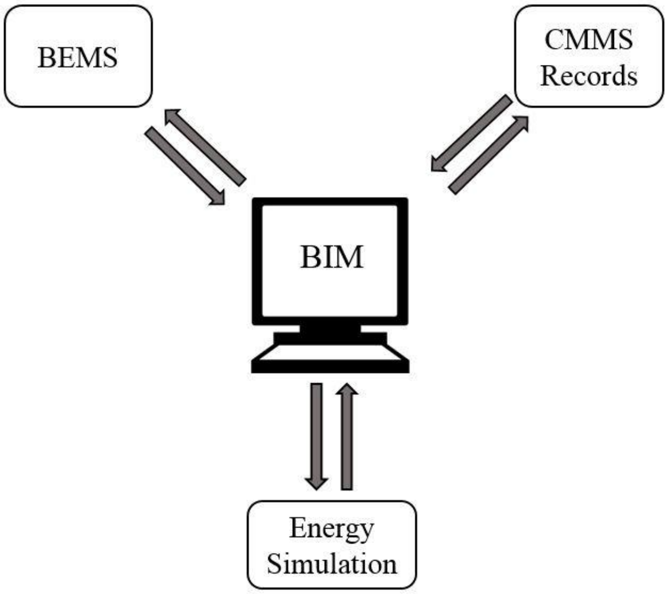


Figure 4.2: Role of BIM in building monitoring system

In the proposed framework, BIM coordinates data collected and produced by three systems i.e. BEMS, CMMS, and energy simulation outputs. BEMS records and keeps interior and exterior weather data that are considered essential to run accurate energy simulations. In addition, it records heating and cooling patterns by controlling heating and cooling outlets such as radiators' valves, TAB fans speeds, fresh air intake, etc. BIM is capable of storing valuable and essential information including energy simulation output data, geometrical data, materials properties, walls assembly, internal loads, HVAC systems and components, and operating strategies and schedules (Katranuschkov et al. 2014; Kim et al. 2016; Maile et al. 2007). In addition, it has the ability to present information from other systems about the building equipment's previous behavior, and maintenance needs.

Figure 4.2 shows the overall problematic spaces detection framework. The proposed framework consists of three major levels that are detailed below:

- *Building Information Level*: At this level, building data is collected, retrieved from different systems, and stored in BIM as detailed in (Shalabi and Turkan 2016). The collected data is divided into geometry, materials and assembly data, BEMS alarms data, and CMMS data. Geometry and assembly information are typically stored in BIM, while BEMS and CMMS data needs to be collected and temporarily stored in BIM to detect spaces with faults.
- *Energy Simulation Level:* Weather data that was collected and stored by BEMS in the previous level is used. The weather data includes exterior dry bulb temperature, relative humidity, dew points, atmospheric pressure, wind speed, and wind direction. This data is used to create the weather file that is needed to run the simulation. In addition, building information data from the previous level is loaded to develop the energy model; such data include building orientation, openings, HVAC systems, materials conductivity, walls assembly, and thicknesses. The energy simulations are then performed and the results are reported to the next level.
- *Analytical Comparison Level:* At this level, actual heating and cooling patterns are compared with heating and cooling load results of energy simulations for each space. If there is a discrepancy or a major flaw between the two, this highlights the need for a closer observation of that particular space. This will allow facility managers to have a better idea about the possible causes of the fault since they will be looking at a particular area depending on the nature of the simulation result and the information collected from other systems.

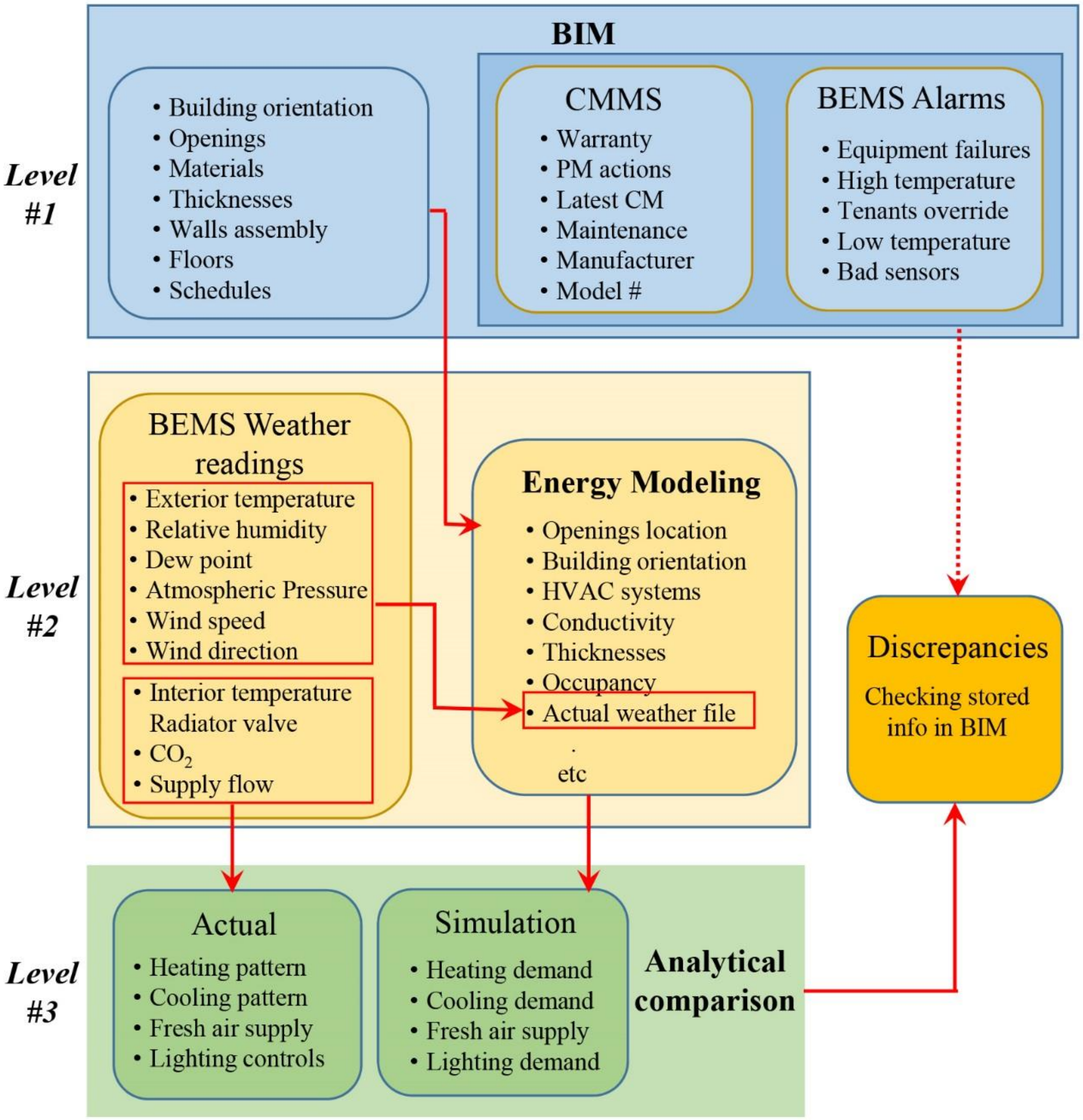
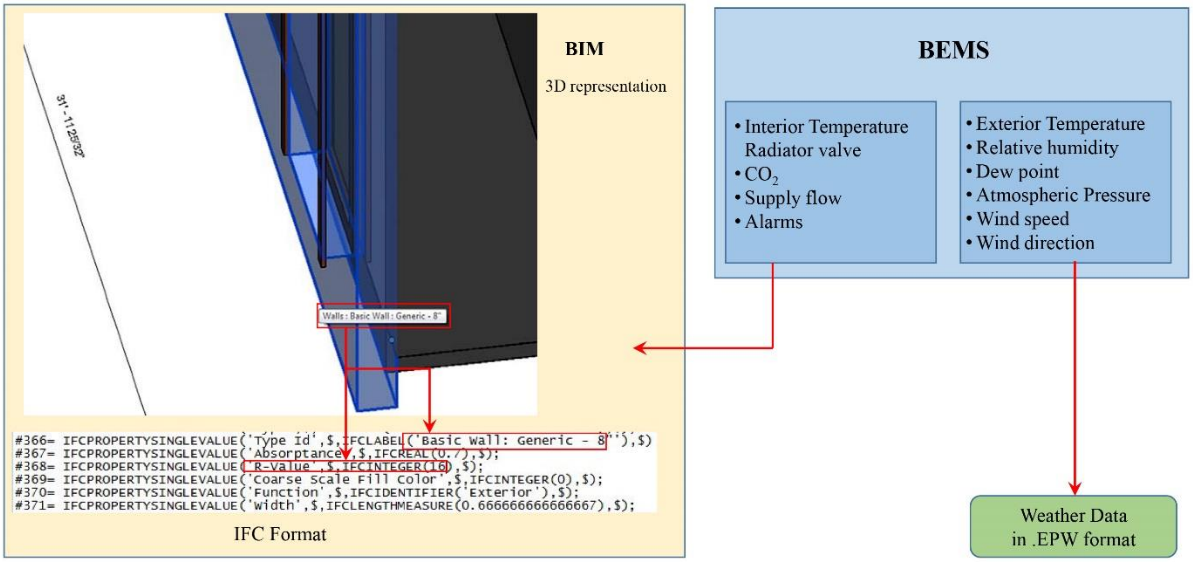


Figure 4.3: Overview of the proposed framework

Level 1: Building Information Aggregation

Data and information from multiple systems are needed to manage and operate a facility. In the proposed framework, building geometric information and materials data are stored in IFC-BIM from the handover and commissioning phase. All thermal properties of wall assemblies can be stored in IFC-BIM as IFC-PROPERTY-SET with different properties as IFC-PROPERTY-SINGLE-VALUEs. Such data is automatically generated by a BIM software (e.g. Revit) when provided during the modeling process. Data that are collected from other systems, such as BEMS and CMMS, can be aggregated into IFC-BIM either manually or using automated systems. Accurate evaluation of building equipment energy consumption requires recording local weather measurements, which is the norm in most modern BEMS systems. Therefore, three types of data are exported from the BEMS including alarms caused by equipment faults, actual heating and cooling systems loads, and weather data e.g. external dry bulb temperature to be utilized in BIM and energy modeling process. . Figure 4.3 illustrates this level in detail.

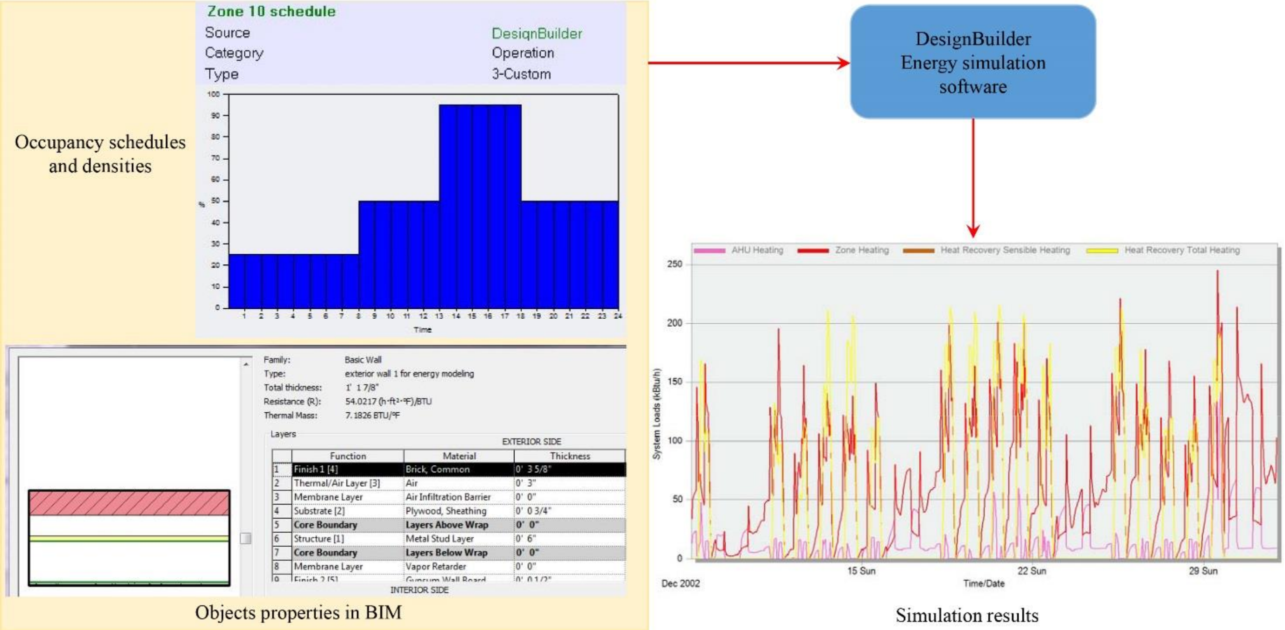


```
#366= IFCPROPERTYSINGLEVALUE('Type Id',$,IFCLABEL('Basic Wall: Generic - 8"'),$)
#367= IFCPROPERTYSINGLEVALUE('Absorptance',$,IFCREAL(0.7),$);
#368= IFCPROPERTYSINGLEVALUE('R-Value',$,IFCINTEGER(16),$);
#369= IFCPROPERTYSINGLEVALUE('Coarse Scale Fill Color',$,IFCINTEGER(0),$);
#370= IFCPROPERTYSINGLEVALUE('Function',$,IFCIDENTIFIER('Exterior'),$);
#371= IFCPROPERTYSINGLEVALUE('Width',$,IFCLENGTHMEASURE(0.666666666666667),$);
```

Figure 4.4: Level 1 - Aggregation of Building Information

Level 2: Energy Simulation Level

Energy simulation tools such as EnergyPlus^{TM} and DOE-2.2 are dependable but complex to use tools. At this level (Figure 4.4), data collected from other systems and stored in BIM is used to develop the energy model. The energy simulation tool can collect properties of the building envelope such as walls thicknesses, assemblies, and differentconductivity values from IFC-BIM. In addition, various occupancy schedules and occupancy densities are created and inserted into the energy simulation tool. In this study, EnergyPlus^{TM} based user interface software DesignBuilder was used to run the energy simulations.



Zone 10 schedule

Source	DesignBuilder
Category	Operation
Type	3-Custom

Family:	Basic Wall
Type:	exterior wall 1 for energy modeling
Total thickness:	1' 1 7/8"
Resistance (R):	54.0217 (h·ft²·°F)/BTU
Thermal Mass:	7.1826 BTU/°F

Layers

EXTERIOR SIDE

	Function	Material	Thickness
1	Finish 1 [4]	Brick, Common	0' 3 5/8"
2	Thermal/Air Layer [3]	Air	0' 3"
3	Membrane Layer	Air Infiltration Barrier	0' 0"
4	Substrate [2]	Plywood, Sheathing	0' 0 3/4"
5	**Core Boundary**	**Layers Above Wrap**	**0' 0"**
6	Structure [1]	Metal Stud Layer	0' 6"
7	**Core Boundary**	**Layers Below Wrap**	**0' 0"**
8	Membrane Layer	Vapor Retarder	0' 0"
9	Finish 2 [5]	Gypsum Wall Board	0' 0 1/2"

INTERIOR SIDE

Figure 5: Level 2 - Energy Simulation Level

HVAC thermal zones are divided into smaller spaces reflecting the actual HVAC outlets e.g. TABs and radiators. This simulation, corresponding to the actual as-built BIM data that uses actual occupancy schedules and densities, differs from the energy simulation that is conducted during design stage at macro level. The energy model used for the simulation is tuned to match the actual operating schedules and the various set points (e.g. temperature, humidity, CO_2, etc.) of the BEMS that controls the buildings climate.

Level 3: Analytical Comparison

Energy simulations that are conducted using energy models reflecting actual building operating schedules and various BEMS schedules produce a separate energy consumption load, i.e. separate heating and cooling loads, for each space with a HVAC outlet. BEMS tracks the duration and amount of energy usage for each HVAC equipment outlet such as amount of energy heating radiators provide. The simulation results mimicking the building envelope characteristics, operation schedules, occupancy, set points, etc. are compared to the actual heating and cooling loads delivered to building. After performing an analytical comparison between the results, the following scenarios can be considered (Table 4.1). The first scenario deals with cases demonstrating a constant behavior; i.e. the heating or cooling outlet is not corresponding to the changes of heating and cooling demand. This suggests either a malfunctioning valve or a broken controller. The second scenario covers cases with above normal behavior, i.e. the heating or cooling outlet responds to the demand but excessively. This suggests an occupant behavior such as opening a window or covering a radiator by furniture, or an override of the set points in BEMS. The third scenario deals with cases demonstrating a below normal behavior; i.e. the heating and cooling outlet is responding to the demand but insufficiently. In this case, the heating or cooling does not satisfy the space needs. This suggests broken sensors that reports current temperatures, broken valves in the heating or cooling outlet, or a heating an external heating source that affects the temperature sensors. Finally, scenario four examines irregular patterns; i.e. the actual consumption does not follow a pattern. In this case, the problem can be in the central unit, in the simulation itself, BEMS readings, or BEMS programming. However, the last scenario is not in the scope of this study.

It should be noted that the developed framework is not designed to detect irregular behavior in the system equipment to improve FM tasks as it provides a methodology to monitor, maintain and reduce energy consumption of a building. The framework does not detect a particular piece of equipment that causes energy overconsumption but identifies which space inside the building is performing poorly and the equipment connected to this space.

Table 3: Analytical comparison outcomes

HVAC behavior	Explanation	Potential causes
Unresponsive	Constant value and pattern, no response to change in demand	• The valve is broken • The controller is not working • An operator override
Excessive	Excessive response to the heating and cooling demand	• Occupant behavior • Furniture blocking the HVAC outlet • A change in the set point
Insufficient	Insufficient heating or cooling is provided to the space, but follow the demand pattern	• Reporting sensors problem • Valves or its controller • Heating source and medium
Irregular	Not following the demand	• Out of scope

Experiments

The proposed framework was implemented on data collected from a two story educational building. The building has a central heating boiler that is connected to fourteen different radiators that are operated separately (Figure 4.5). Each radiator is responsible for heating one of the fourteen spaces within the building. In each space, there are sensors measuring humidity, dry bulb temperature, and CO_2 for mechanical ventilation. All fourteen spaces are in the same thermal zone. In order to unify the conditions among which the building is operating, the building was unoccupied during experimental data collection, which took place over the winter break and was approximately one month. BEMS did not show any alarms or reported any malfunctions in the building components during this period.

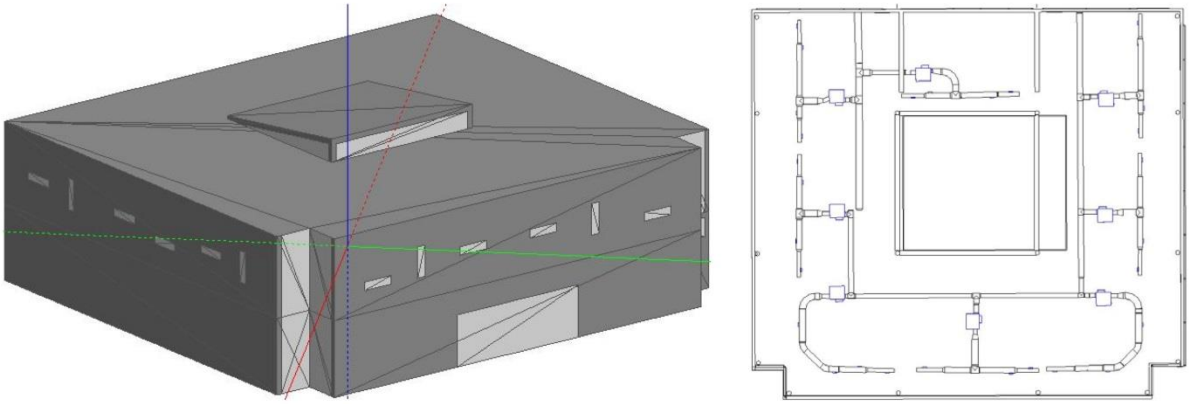

(a) (b)

Figure 6: (a) 3D BIM based energy model of the building (b) HVAC units' distribution

Geometric information for the BIM based energy model of this building was developed using laser scan point cloud captured using Trimble TX5 laser scanner. Eight separate scans were conducted to cover each story of the building, sixteen scans for the whole building. Autodesk Revit Scan-to-BIM plugin, a semi-automated modeling tool, was utilized to model HVAC and structural components from the point cloud accurately.

Materials data that is captured from the handover documents and the building commissioning verification results was uploaded to the BIM model and then to the energy simulation software. The materials data included thermal properties of architectural elements and characteristics of the HVAC system (Table 4.2). Weather data for the energy simulation were recorded onsite using the sensors of the BEMS systems. Based on those sensors readings, BEMS react and operate the heating and cooling equipment in the building.

Table 4.4: Materials data uploaded from BIM to energy simulation software

Building envelope components	Description	Thermal properties
Exterior walls	Composite wall system, frame, masonry, concrete, insulation, cladding	R-19
Roof	Concrete, insulation entirely above deck, composite	U-0.063
Floor/Slab	Steel frame, concrete on deck	U-0.052
Windows/doors	Combination of Low-E clear with high visible transmittance with aluminum frame	U-value COG 0.35 U-factor unit 0.48 SHGC 0.62 Visibility Transmittance 0.74
Shading devices	Overhangs	
HVAC system	Hot water radiators, VAV system with gas absorption chiller, gas fired boiler	
Energy recovery	Sensible Energy Recovery	94% effectiveness

The energy simulation parameters were set to imitate the actual conditions and circumstances under which the building was operated. In the energy model, the open space is divided by virtual partitions to obtain space-focused simulation results. Each space has hot water radiator, TAB, CO2, relative humidity and dry bulb temperature sensors.

The simulation results were compared with the heating radiators valve's behavior, which is controlled by BEMS, in that specific area/space. In nine spaces, the heating radiator valve demonstrated regular behavior (Figure 4.6), i.e.it responded by opening the valve in accordance

to the heating demand.

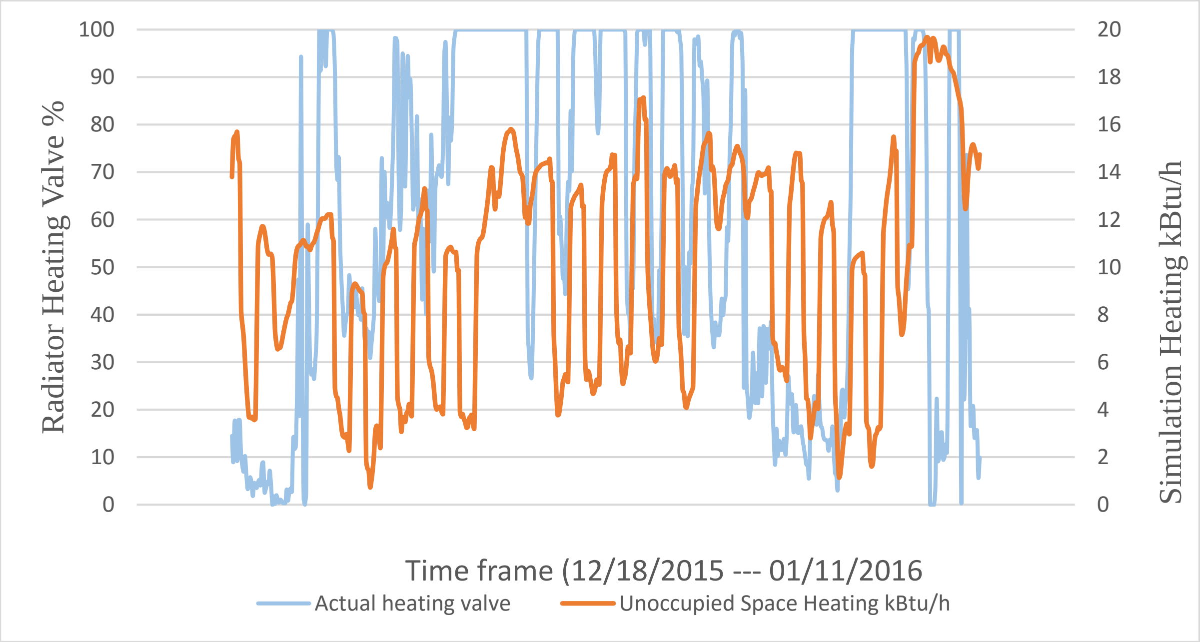


Figure 4.7: Actual heating vs simulation heating comparison for Space# 3

It should be noted that Figure 4.6 represents the pattern and the timing of heating the building, not the amount of heating energy released by the radiator. In Figure 4.6, note that when the heating demand defined by the simulation increases suddenly, the valve opening increases to the maximum in order to compensate the loss of heat. This adaptation is desired by the heating system as it heats the building as needed. On the contrary, the actual valve decreases its opening in response to decreasing demand that was predicted by the simulation. Facility managers usually present the actual heating pattern in BEMS using 2D graphs. The heating patterns typically cover short periods of 24 hours. This makes it cumbersome for facility managers to detect undesirable behavior especially when they cannot compare it to an ideal behavior.

However, five spaces in the building showed different behavior that varied between not responding at all to heat demand variations and demonstrating inadequate response. In Figure 4.7, space #12 response was constant by not responding to any demand variation at all and the radiator valve was closed all the time. In space #9, the valve responded but was not able to open more than 5%. Space #1showed below normal response as well, as it responded to the variations in demand but insufficiently (Figure 4.8).

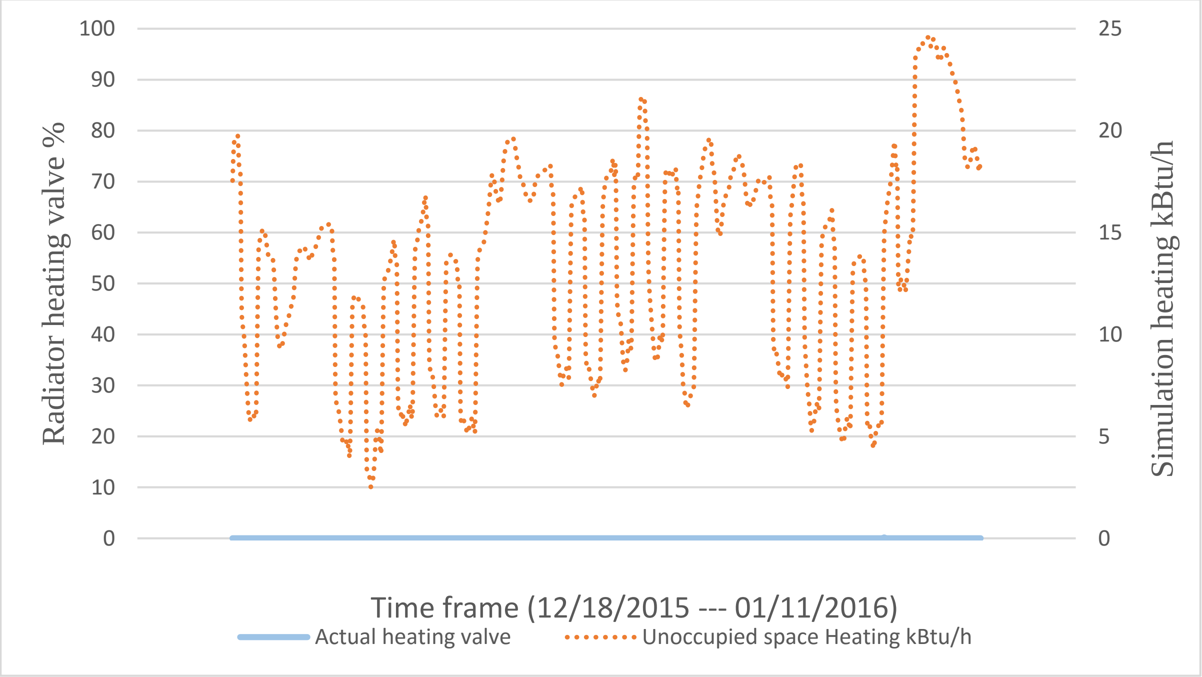


Figure 4.8: Actual heating vs simulation heating comparison for Space #12

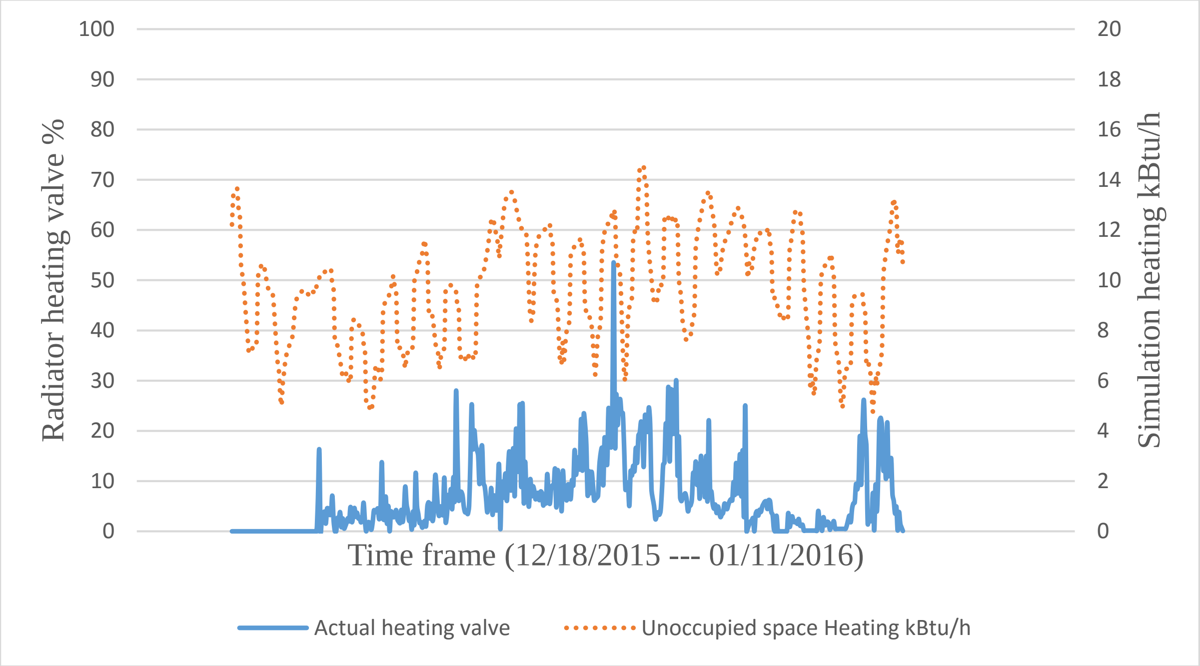


Figure 4.9: Actual heating vs simulation heating comparison for Space #1

This approach provides facility managers a closer look on how the building equipment and systems are performing in a given time period. This allows them to specify spaces with energy overconsumption or irregular behavior for further analysis or steps such as looking at other systems, maintenance history, occupants comfort, etc.

Conclusions and Future Work

Significant amount of the HVAC energy consumption is wasted due to faults in HVAC systems and lack of maintenance. Facility managers are aware of the importance of finding efficient ways to manage and reduce the energy consumption in their facilities. Current FM systems are operated by different teams and lack interoperability capabilities, which results in poor data coordination and management. In addition, facility managers face challenges in identifying problematic spaces in a facility, isolating different types of problems, and prioritizing the impact of those problems. BIM is capable of coordinating different FM and energy management systems. This would provide a comprehensive perspective of building spaces, its equipment, and information to facility managers. Previous research either developed methods to use BIM to predict energy performance during design phase; investigated information exchange from BIM to simulation tools; or developed methods for energy management during design phase. However, none of these studies focused on using BIM and energy simulation tools for locating problematic spaces in a facility, and collecting high quality data for the selected spaces to help perform required maintenance actions.

This paper presented a framework that uses BIM to compare energy simulation results obtained using actual HVAC pattern with historical BEMS and maintenance information. The contributions include 1) a methodology to compare actual HVAC behavior with heating and cooling demand 2) a framework that defines spaces with undesired energy performance and collects high quality data from spaces that require maintenance.

The proposed framework was validated in terms of detecting problematic spaces, identifying possible causes and collecting relevant data from that specific space. The results showed that the framework was able to detect spaces with undesired energy performance within the building. The nature of the faults cannot be detected by the automated BEMS alarming system. Comparing the intended energy performance with the actual performance of the building HVAC equipment highlights faults and problems in buildings. When comparing actual performance with intended performance, the results can include one of four cases: unresponsive, excessive, insufficient, or irregular. Specific causes can be related to each case. BIM provides an environment where facility managers can manage, coordinate, and present facility information. Future work should focus on testing the effects of occupants on the ability to use energy consumption for fault detection. In addition, methods should be developed to automate using energy performance comparisons to detect faults and problems in buildings.

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CHAPTER 5. BIM-ENERGY SIMULATION FRAMEWORK TO DETECT SPACES WITHIN A FACILITY WITH MAINTENANCE NEEDS – CASE STUDY APPROACH

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To be submitted to Procedia Journal

Abstract

The actual energy performance of a facility often may fail to match its predicted simulated performance, resulting in an energy performance gap. Such a mismatch may be caused by many factors related to all phases, including the Facility Management (FM) phase, of a building life cycle. Equipment deterioration and system malfunctions are other possible causes. Facility managers, however, may lack tools and methods for detecting spaces within a facility with deteriorated equipment and system malfunctions. This paper describes a framework that validates BIM and aggregated FM information in BIM with detailed energy simulation using a case study approach. An educational building was used to compare actual heating patterns with predicted heating demand under two different building conditions: occupied and unoccupied. The results were compared with a survey conducted to study occupants' behavior within the building. The results show that the framework can detect spaces within the facility with mismatched energy behavior. Reasons for such a mismatch detected by this framework include energy management system malfunction, hardware dysfunction, and unexpected occupant behavior. It is concluded that BIM provides a viable tool for FM, and comparing actual and predicted heating demand can help in locating spaces with abnormal performance, detecting systems malfunctions, and specifying hardware maintenance.

Introduction

There is growing evidence within the building industry to suggest that buildings' actual energy performance may differ from predicted energy performance; such a difference is referred to as a "performance gap" (De Wilde 2014; Demanuele, et al., 2010; Menezes, et al., 2012). While it is permissible to have some discrepancy between predicted and actual performance resulting from factors like predictions uncertainties and the scattered nature of actual measured data, evidence shows that the discrepancy is often unacceptably large. It is important to narrow this gap if buildings that maintain performance and meet expectations, such as Net Zero Energy Buildings, are to be delivered (Almeida, et al., 2010; Zhang and Gao 2010).

The most common perspective from which to study energy performance in terms of heating and cooling is annual energy use, although energy performance can also be studied using monthly, weekly, daily, or hourly data (De Wilde 2014). For the purposes of this paper, hourly data were collected and daily heating patterns studied over a period of two months. Typically, the performance gap describes the difference in predicted energy performance of the design intent (from the design stage) with measured energy performance (operational phase) in a building over a period of year. However, this study is concerned with using actual real-time data input measured in the building to simulate and compare predicted heating performance (operational phase) with the actual measured heating patterns (operational phase).

In this paper, the benefits of a developed "BIM-energy performance in FM" framework are investigated using case-study research methodology. When compared to research methods such as surveys and interviews, a case study seems the most appropriate investigation method for determining the benefits of new information technologies (Bakis, et al., 2006; Barlish and Sullivan 2012), because case studies provide information about a particular project using the actual project's data. In contrast, experimentations, surveys, and interviews may be ineffectual because presence of a new system may influence variables that cannot be extracted from the original context. In addition, surveys and interviews should not be used alone because they are subject to perception, subjectivity, and general estimation. This paper includes two major parts:

- A literature review defining the causes of the performance gap and some of the concepts used in this study, such as Post Occupancy Evaluation (POE), Performance gap, and BIM for Building energy management.
- The results of a building case study using a BIM-energy simulation framework for maintenance and energy management.

Literature Review

Performance Gap Causes

The literature suggested various causes for the performance gap that can be grouped into three main categories (De Wilde 2014): causes related to the design phase, causes related to the construction phase, and causes related to the facility management phase. While such causes may vary from one building to another, they are usually a combination of several issues.

During the design phase, discrepancies may result from miscommunication about energy performance targets between clients and the design team, or among the design team members themselves (Newsham, et al., 2009). Another main source of discrepancy is designers who cannot accurately predict the functions of the building, e.g., operational conditions, that might significantly change (Dasgupta, et al., 2012; Korjenic and Bednar 2012; Menezes, et al., 2012; Newsham et al. 2012). Other problems include issues with the energy saving technology itself , since equipment might not perform as well as specified (Newsham, et al., 2009; Turner and Frankel 2008), and advanced systems specifically might be particularly prone to underperformance (Newsham, et al., 2012). In addition, energy-saving systems and their controls are complex (Zero Carbon Hub 2010) and increasingly dependent on software for their operation, adding another layer of complexity (America, et al., 2012). Defects in modeling and simulation procedures might also cause a performance gap. Use of incorrect methods or tools can result in false predictions (Menezes, et al., 2012). Accuracy of a modeling process depends on the modeler’s or analyst’s ability to apply the right knowledge and skill set to the process (Dwyer 2013). Finally, several sources of modeling input, such as weather conditions, occupancy schedules, occupancy activities, etc., might remain uncertain during the design phase and this may affect the results of the simulation, (Menezes, et al., 2012; Turner and Frankel 2008).

The second category of discrepancy occurs during the construction phase. Defects in the construction quality of a building, such as airtightness, insufficient insulation, and incompatibility with specification, are often responsible for poor energy performance (Menezes, et al., 2012; Newsham, et al., 2009). Further discrepancies could also be introduced through change orders and value engineering (Bell, et al., 2010; Turner and Frankel 2008). It should be noted that construction phase effects are hard to detect and usually require visual inspection to establish actual issues (De Wilde 2014).

At the facility management phase, after the building is commissioned and in use, many factors start to contribute to the performance gap. The main such factor cited in the literature is occupant behavior different from the assumptions (De Wilde 2014; Haldi and Robinson 2008; Korjenic and Bednar 2012; Menezes, et al., 2012). Several studies related to modeling and understanding occupant behavior have been conducted (Chung and Park 2010; Haldi and Robinson 2008; Ryan and Sanquist 2012; Yu, et al., 2011). They indicate that actual operation of a building is typically different from assumptions made during its design, both in terms of BEMS setting of the actual control attributes as well as the broader scope of FM (Dasgupta, et al., 2012; De Wilde 2014; Lee and Lee 2009; Menezes, et al., 2012; Newsham, et al., 2012; Turner and Frankel 2008). A BEMS in a building consists of a complex network of sensors that may not be consistently guaranteed to operate and register data properly. In addition, there may be a lack in coverage in terms of observing the overall state of the building, as well as a lack of standardization and continuity of monitoring, analysis, and control throughout the building's life cycle (De Wilde 2014; O'Sullivan, et al., 2004). Another reason for the performance gap is due to building system deterioration that may lead to mismatch between predicted and actual performance over time (Reddy, et al., 2007; Williamson 2010). Finally, lack of mechanisms for routine maintenance can negatively affect building performance. Routine Post Occupancy Evaluation (POE) can use past building performance to improve current building performance (De Wilde 2014; Menezes, et al., 2012).

Facility managers can control energy consumption of a building by monitoring its central HVAC equipment (Menezes, et al., 2012). Facility managers' good supervision practices can result in efficient energy performance and minimized waste (Bordass, et al., 2001). Such practices include recommissioning exercises, energy audits, and POE (Way and Bordass 2005).

Post Occupancy Evaluation

Post-occupancy evaluation (POE) is a structured process that uses qualitative and quantitative measures to evaluate the performance of a building after it has been built and occupied. POE is considered essential for obtaining detailed information on occupancy, occupant behavior, and thermal comfort (Bell, et al., 2010; De Wilde 2014; Menezes, et al., 2012). However, it should be noted that occupant behavior is complex and may be hard to capture, and there is no standard POE methodology in this area to date (Wei, et al., 2013). The scope of POE includes three aspects: feedback, feed-forward, and benchmarking (Cooper 2001). Feedback is concerned with building performance from a business productivity perspective, while feed-forward measures energy savings for project procurement. Benchmarking aims to measure the building energy performance and improve it. This study focuses on the benchmarking aspect; feedback and feed-forward aspects lie outside its scope.

BIM for FM and Energy Management

Throughout a facility life cycle, BIM supports a multi-domain and multi-layer collaborative approach and engages multiple stakeholders in the project, including architects, engineers, and contractors as well as facility managers and operators (Eastman, et al., 2011; Teicholz, et al., 2011). BIM has proven its capabilities for effective data sharing between different stakeholders during design and construction (Becerik-Gerber, et al., 2011). It also has been shown to lead to decreasing information loss of a project during its lifecycle (Al-Shalabi and Turkan 2015; Eastman, et al., 2011). However, effective application of BIM during the FM phase has not yet been achieved.

Facility managers control HVAC systems in buildings (Menezes, et al., 2012) to maintain a thermally comfortable environment while maintaining an efficient energy performance. To achieve such goals, facility managers can use systems such as Building Energy Management Systems (BEMS) and Computerized Maintenance Management Systems (CMMS). FM systems interact both directly and indirectly with occupants and FM staff (Roper and Payant 2014). Occupants' interaction sometimes cause problems by, for example, using space heaters in winter (Beltran, et al., 2013) or blocking thermostats and sensors with furniture, causing false sensor readings (Wei, et al., 2013). Lack of FM manpower often can cause different types of problems (Roper and Payant 2014; Teraoka, et al., 2014), i.e., the FM staff can be overwhelmed by the number of faults and alarms that require attention, and as a result they may focus only on crucial issues and occupant complaints while ignoring issues that may not be perceived by occupants. FM staff may make temporary fixes to resolve complaints, perhaps resulting in energy waste or emergence of other faults (Teraoka, et al., 2014).

BIM implementation in FM is still in its infancy stage (Kelly 2013). The main reasons for the lack of BIM implementation includes limited awareness of the expected benefits of BIM for FM among facility managers, lack of data exchange, and lack of demonstrated productivity gains (Becerik-Gerber, et al., 2011; Kelly 2013). Potential benefits of BIM for FM activities include extracting and analyzing data to support and improve the decision making process (Azhar 2011). Other benefits include increasing the efficiency of work order executions through providing faster access to data, and improving the process of locating facility elements using a 3D display interface (Kelly 2013).

Previous research on BIM use in FM either developed BIM frameworks for streamlining existing processes and systems, or developed BIM-based approaches to replace current processes for efficiently capturing, storing, and retrieving facility data. Examples of the first type include augmented reality-based operations and maintenance (AR-based O&M) support (Lee and Akin 2011), 2D barcode BIM-based facility management systems (Lin, et al., 2012), 3D based facility maintenance and management systems (Chen, et al., 2013), and BIM-based facility maintenance management systems (Lin and Su 2013). The second type of studies include: using BIM to generate customized templates for capture of maintenance work-related changes (Akcamete 2011), a knowledge-based BIM system using case-based reasoning for building maintenance (Motawa and Almarshad 2013), fault-tree analysis for failure root cause detection (Lucas, et al., 2012; Motamedi, et al., 2014), and using BIM for HVAC troubleshooting (Yang and Ergan 2015). However, none of the studies in this group focused on developing approaches that provide facility managers with active solutions to improve performance of their buildings.

This study aligns itself with the first group of studies in terms of streamlining the existing FM processes and systems. However, it differs from previous work by using a case-study approach to implement a framework where energy simulations and energy performance monitoring are used to improve building energy management by detecting systems dysfunctions.

BIM implementation in FM still faces many challenges. Such challenges include fragmented data, data interoperability, and lack of data transparency throughout the building life cycle (Becerik-Gerber, et al., 2011; Kelly 2013; Shalabi and Turkan 2016; Yang and Ergan 2015). Furthermore, unproven productivity gains that can be realized from reduced equipment failure, as well as the productivity increases that may be realized through an integrated platform are among these challenges (Becerik-Gerber, et al., 2011).

One of the main tasks that facility managers must tackle is managing energy consumption. Currently, BIM is used to efficiently plan, design, and manage buildings. It also offers intelligent objects of a building structure that can include data needed for energy simulation (Kim, et al., 2016; Shalabi and Turkan 2016) for all building elements such as exterior/interior walls, roofs, windows, doors, floors, their orientations, R-values, conductivities, and thicknesses.

Previous research on BIM for energy management can be categorized as follows: (1) Studies on developing methods and algorithms in which BIM depends on energy simulation tools such as DOE and EnergyPlus^{TM} to predict energy performance during the design phase. (2) Studies investigating information exchange from BIM into energy simulation tools during the life cycle. (3) Studies on developing applications where BIM is used for energy management purposes.

The first category of studies, in which BIM is used to predict the energy performance, was comprised of several pilot studies. Such studies include developing a method that uses BIM to take account of sustainable fixtures in predicting energy generation (Cho, et al., 2010). Another study used a multi-objective generic algorithm using BIM energy simulation to optimize energy performance (Chen and Gao 2011). A different study used BIM to analyze the annual energy consumption and CO_2 emissions in a single house (Raheem et al. 2011). In addition, an IFC-BIM based energy simulation process that runs in DOE 2.2 was also developed (Kim, et al., 2013). Using multiple tools, Oh et al 2011, used developed an application for exchange of data from gbXML to an EnergyPlus-IDF file. Reeves et al, provided guidelines for using BIM in building energy modeling (Reeves, et al., 2012), while Jiang, et. al, studied key BIM-server requirements for information exchange in energy-efficient building retrofit projects (Jiang, et al., 2012).

Several studies were concerned with information exchange. This included investigating the methodology and interoperability of IFC-BIM and building energy analysis tools (Bazjanac 2008). Another study developed a graphical user interface to input HVAC systems information into IFC-BIM to be used for building energy simulation (O'Sullivan and Keane 2005).

The third category focused on the applicability and usability of building simulation tools in different life-cycle stages of a building. Examples of studies that fall within this category include developing an energy-enhanced BIM (eeBIM) framework that aims to close the gap between existing data and tools used during the design and FM phases to enable an efficient life-cycle energy performance estimation and decision-making (Katranuschkov, et al., 2014). Attia surveyed a selection criteria of building simulation tools used among different stakeholders on construction projects (Attia 2010). Katranuschkov et al. (2014) focused on BIM for FM in their research. They emphasized the importance of integrating multiple necessary resources such as weather data with energy analysis tools, cost analysis, CAD, FM, and building energy monitoring tools. In addition, they described the importance of using BIM to aggregate construction and FM data to be applied in energy simulation and other FM tasks. By building on this work, Kim et al. (2016) developed a model for mapping IFC-BIM material information to building energy analysis . Shalabi and Turkan (2016) developed an approach for optimizing data collection from IFC-BIM to minimize the lead-time needed for corrective maintenance actions. None of these previous studies used the case study approach and this study complements current literature by employing a case-study methodology to implement and validate frameworks and methods that use BIM for energy management and assessment in buildings.

Case Study Location: King Pavilion

The case study took place in King Pavilion building, a LEED platinum certified educational facility located at Iowa State University main campus. The building consists of two stories with total floor area of 22,317 sq. ft., (2073.3 m^2). As part of the College of Design, the King Pavilion houses 14 studio spaces, a common space, and a small central atrium. All the building information and models are fully available to the research team, including the maintenance history, BEMS data, BIM model, and construction and commissioning documents. It is important to note that, no changes were made on the original design, meaning that the systems and spaces function as designed. The HVAC system of the building is complex enough for the purposes of the study. The entire building has only one thermal zone, and each studio space has a separate heating and cooling outlet.

The studio spaces inside this building are numbered from one to fourteen. The building is shared between four groups of students based on their studying disciplines. The students use the building regularly, and each student uses a particular desk during the semester. Each group of students shares the same occupancy schedule. Table 5.1 presents the details about the student groups and their corresponding spaces and schedules (Figures 5.1 - 5.7). For example, the first group that is located in studios 1, 2, 3, and 4 follow schedules 1-1, 1-2, and 5-1.

Table 5.1: Student groups studio distribution

Group Number	Disciplines	Studio Spaces	Occupancy Schedules
1	General Design	1, 2, 3, 4	1-1, 1-2, 5-1
2	Interior Design	5, 6, 7	2-2, 5-1
3	Landscape	8, 9	3-1, 5-1
4	Architecture	10, 11, 12, 13, 14	4-1, 4-2, 5-1

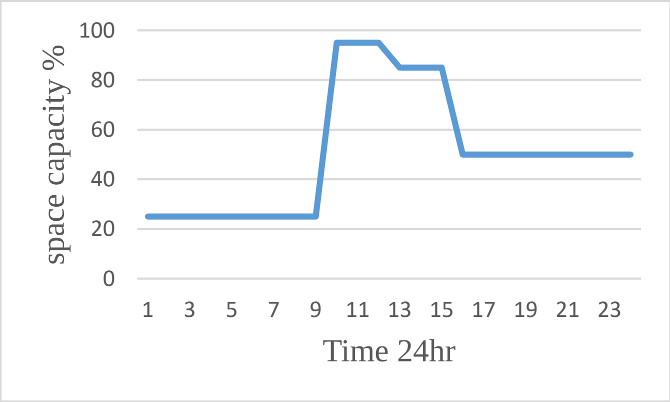


Figure 5.10: Occupancy Schedule 1-1

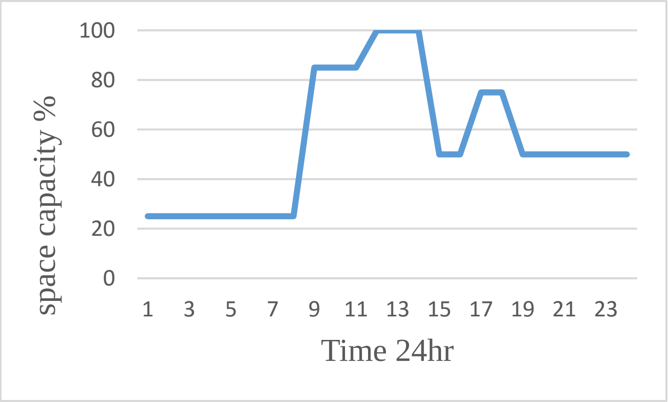


Figure 5.2: Occupancy Schedule 1-2

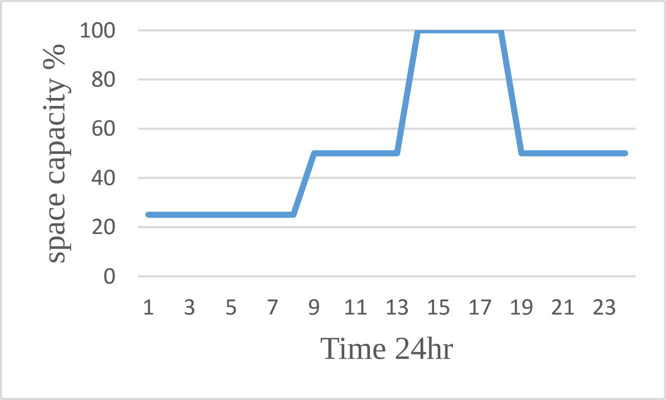


Figure 5.3: Occupancy Schedule 2-1

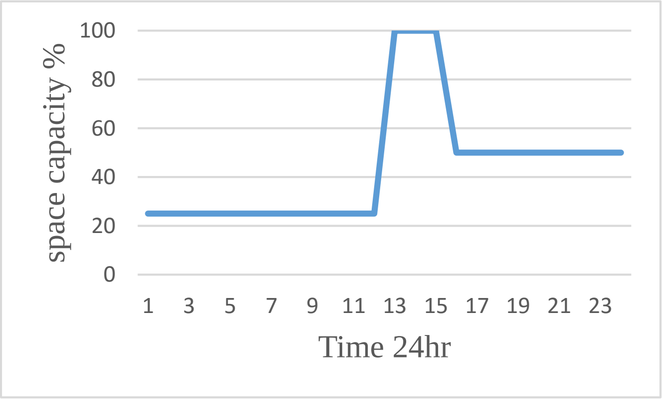


Figure 5.4: Occupancy Schedule 3-1

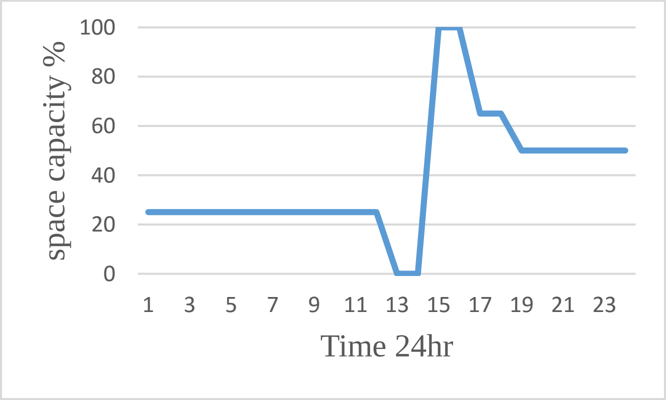


Figure 5.5: Occupancy Schedule 4-1

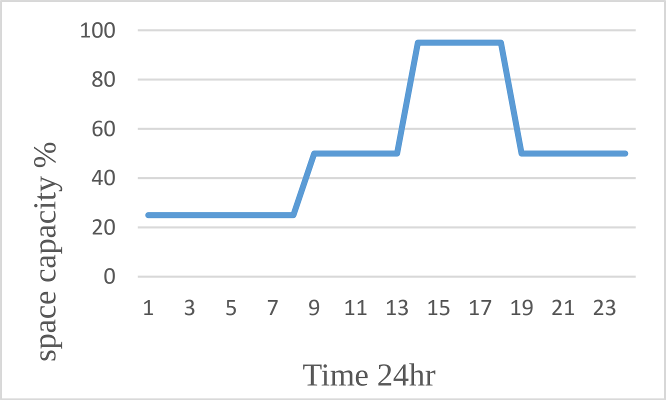


Figure 5.6: Occupation schedule 4-2

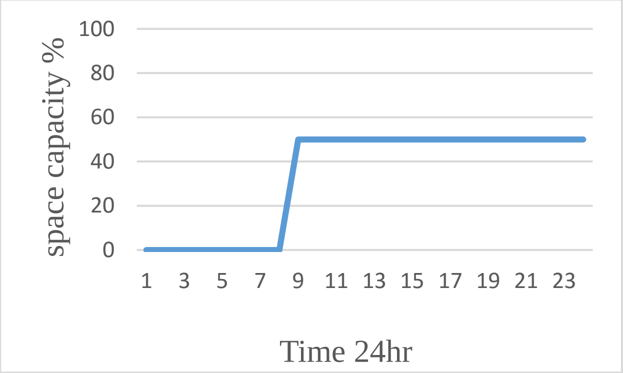


Figure 5.7: Occupancy Schedule 5-1

The as-built 3D BIM model was developed using laser-scan point clouds captured using a Trimble TX5 laser scanner. Sixteen total scans were required for the whole building. Autodesk Revit Scan-to-BIM plugin was used to model the building's structural components and its HVAC components from the 3D point cloud. Building energy-modeling attributes were added manually (Table 5.2), and the file was then converted to gbXML format to allow its import into DesignBuilder energy modeling software.

Table 5.2: Building components U-Values

Building envelope component	Heat transfer coefficient
Exterior walls	U-0.052
Roof	U-0.063
Floor/Slab	U-0.052
Windows/doors	U-value COG 0.35 U-factor unit 0.48

	SHGC 0.62
	Visibility Transmittance 0.74
Energy recovery	94% effectiveness

The BEMS in the building is connected to a DDC with over 250 sensors. BEMS is used to record weather data both inside and outside the building. For the purpose of this research, exterior weather recordings were used to create the weather file to be used in the energy model. The files were converted into an EnergyPlus^{TM} weather file (.epw) to enable direct import into DesignBuilder energy simulation software. Operation and maintenance data for the building was acquired from the CMMS system; this included serial numbers, CMMS IDs, warranty dates, and serving spaces, in addition to previous maintenance cost, type, task, description, and work numbers.

Research Methodology

The overarching goal of the study is to investigate how BIM can mediate between several FM systems to support effective and efficient performance of FM tasks. To achieve that we adopted a single case study research method with particular focus on 1) implementing BIM facilitate maintenance needs, 2) using BIM for frequent and comprehensive building energy management.

The adopted research methodology involved conducting a comprehensive literature review and occupancy surveys, developing BIM and energy model, developing and implementing concept framework, and data analysis. In addition to experimental energy simulations and comparisons, post-occupancy surveys helped finalize areas with maintenance and energy management techniques. Figure 5.8 illustrates the research methodology that was used to construct validity and reliability in the research.

Empirical investigations for modern applications within its real-life context falls under single case study research. The following elements should be taken into consideration when conducting such case study:

1- The study focus area
2- The study scheme
3- The analysis components
4- Framework development
5- Data analysis

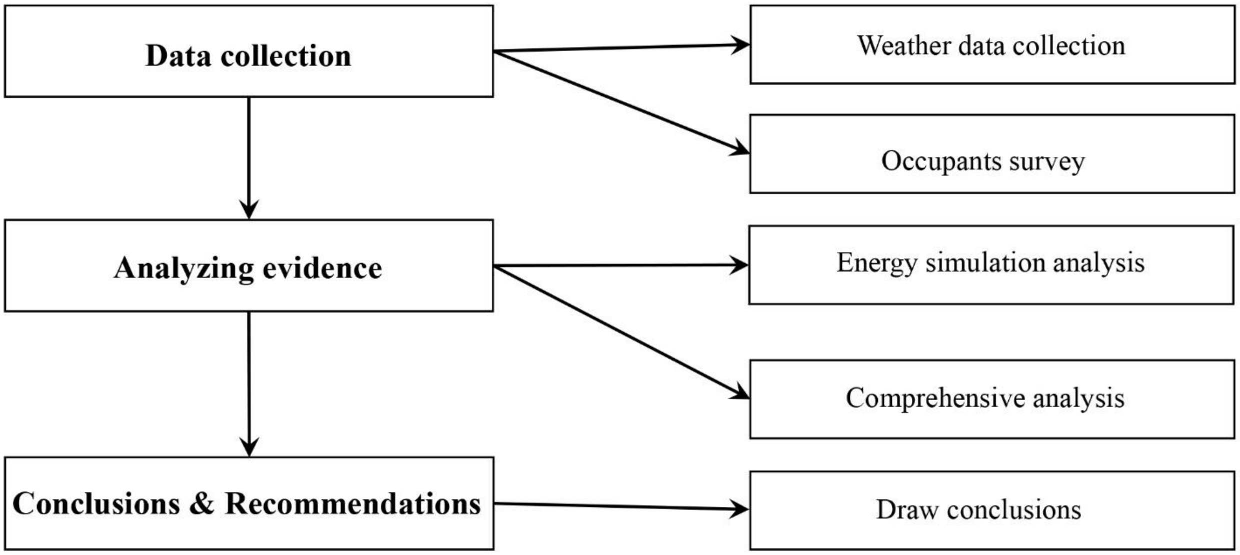


Figure 5.8: Research methodology

The study's focus area was energy management and maintenance of HVAC components from a facility manager's perspective. The analytic components of the study were BIM, BEMS, CMMS, BIM based energy modeling, and post occupancy evaluation (POE). The components were linked using a developed framework (presented in Chapter 3).

Data Collection and Model Development

Weather data for King Pavilion building were collected for a period of two months during which the building was unoccupied for one month and occupied for the other. The data captured by BEMS sensors were used to register the actual exterior weather data at fifteen-minute intervals. Weather data collected included exterior dry bulb temperature, relative humidity, dew points, atmospheric pressure, wind speed, and wind direction. The other data collected by BEMS for a specific space included the percentage of valve slot opening, inside temperature, fresh air exchange rate, and CO_2 levels. Once collected, the actual weather data file was converted to .epw file format compatible with EnergyPlus^{TM} simulation software. The weather file is essential to conduct of accurate energy simulations.

An accurate as-built BIM for this building was developed. The modeling was conducted in two stages; geometry modeling and attribute data entry. Geometry modeling is important to locate the HVAC equipment, openings, rooms, etc., necessary to determine spatial relationships between different elements. Attribute data entry on the other hand provides the FM team with necessary information regarding the building equipment and elements, such data define the attributes of different elements, including vendors, thermal characteristics, location, thicknesses, dimensions, etc. the attribute data supplements data requirements needed for FM tasks, and energy modeling.

The as-built geometry information was captured using a laser-scan point cloud. Sixteen total scans were conducted to cover the whole building, with eight scans for each story. The 3D point clouds were converted to 3D structural and HVAC elements in BIM environment using Autodesk Revit Scan-to-BIM plugin. At the end of the modeling stage, the Revit file was exported to IFC (Industry Foundation Classes, a neutral file format). Handover documents provided the necessary data to be included in the BIM. Such data were added to the IFC file as IFC-PROPERTY-SETs, with each set containing multiple IFC-PROPERTY-SINGLE-VALUEs. Each IFC-PROPERTY-SET defines one characteristic of an element, e.g., wall type A has an IFC-PROPERTY-SET called thermal properties that includes multiple IFC-PROPERTY-SINGLE-VALUEs in which values for layers, thicknesses, and conductivity assembly are stored.

The as-built BIM was then loaded into EnergyPlus™ based DesignBuilder energy modeling software from Revit through a gbXML import process. After that, attributes and settings were checked for accuracy manually. The conductivity of the building envelope components was adjusted based on the verified data after the commissioning and testing of the building, i.e., they are not based on the design simulations. HVAC equipment attributes, schedules, and distributions were matched with the actual HVAC equipment operating in the building. Operational set points were retrieved from BEMS; Table 5.2 summarizes the attributes uploaded to the model.

In order to assess the performance of the building comprehensively, a survey was conducted to investigate the occupants' level of comfort. Sixty-seven occupants representing all 14 spaces in the building participated in the survey. The building was divided into smaller areas sharing similar mechanical and spatial characteristics (Figure 5.9). The building has 14 different HVAC outlets, i.e., heating radiators and TABs for ventilation and cooling, that provide heating and cooling for 14 different spaces in the building. Each space was further divided into three smaller zones depending on the location of other elements such as windows, ducts, and heating radiators, i.e., areas A, B, and C. Area A corresponds to the areas located next to windows and heating radiators. Area B covers areas located under TABs and ventilation ducts, and area C corresponds to areas adjacent to the corridor and some ventilation ducts. The survey was prepared to measure the occupants' thermal comfort levels and actions they take to improve them. The survey also included questions regarding the amount of time the occupants, i.e., students, spend in the building outside official classroom time. These extra durations were reflected in the energy model by the occupants' schedules.

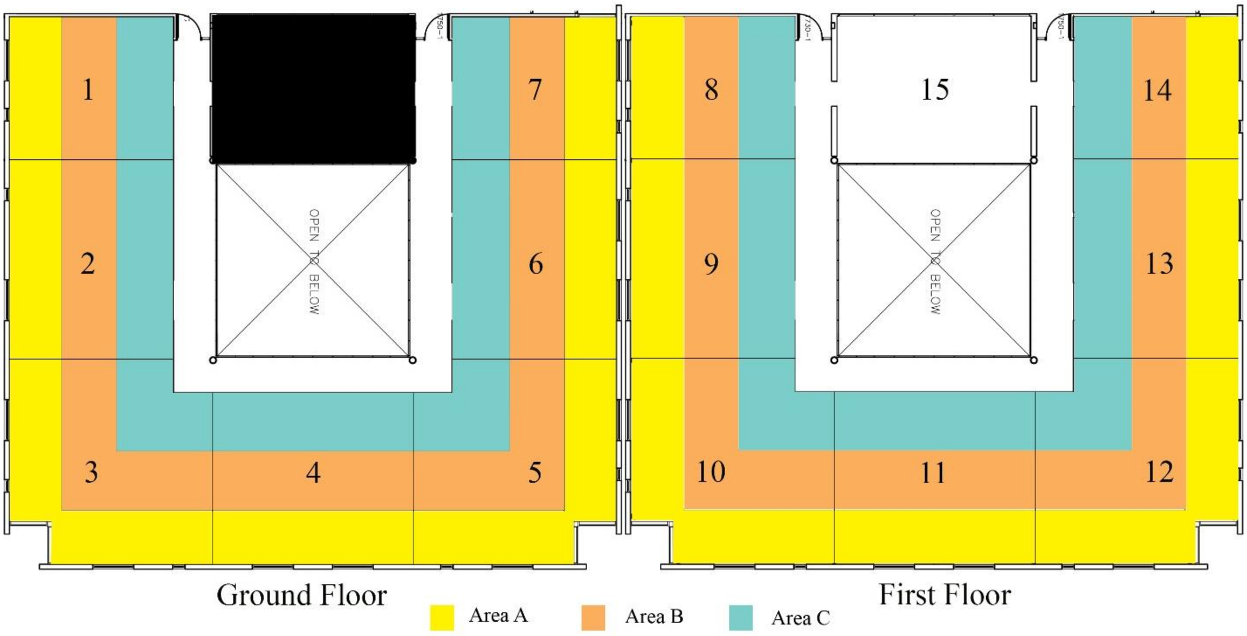


Figure 5.9: Building Spaces with different Thermal Characteristics

Experiments and Results

Results yielded by the IFC-BIM-FM framework, the energy simulations, and the survey results were combined to reach a more comprehensive and proactive FM approach integrated and presented in IFC-BIM. Results of IFC-BIM based FM framework implementation were presented in (Shalabi and Turkan 2016). This section summarizes the results of energy simulations and the survey conducted among the building's occupants.

Energy Simulations

The two energy simulations conducted to examine a two-month period, for occupied and unoccupied scenarios. The simulation conducted for the occupied scenario used an energy model that included the number of actual occupants and schedules for each specific space depending on class schedules and the survey results. Table 5.3 summarizes the occupant densities (person/sf) for different days during the week. This schedule has been augmented by the survey results to include occupant densities outside the official class periods. Occupant densities and schedules were uploaded to the DesignBuilder energy simulation program.

While the simulations for both scenarios covered the entire two-month period, actual monitoring and recording of the building heating valves were simultaneously performed, even though the building was actually unoccupied for the first month and occupied for the second month. This is important when analyzing the simulation results shown in the following sections.

Table 5.3: Schedule of occupants' densities (person/sf)

Space #	Mondays / Wednesdays / Fridays			Tuesdays / Thursdays			Weekends
	Max	Min	overnight	Max	Min	overnight	
1	0.0287	0.026	0.015	0.0301	0.0219	0.015	0.015
2	0.0215	0.0108	0.0108	0.0164	0.0123	0.0108	0.0108

3	0.0208	0.0104	0.0104	0.0125	0.0104	0.0104	0.0104
4	0.0175	0.0087	0.0087	0.0129	0.0092	0.0087	0.0087
5	0.0109	0.0109	0.0109	0.0219	0.0109	0.0109	0.0109
6	0.0108	0.0108	0.0108	0.0215	0.0108	0.0108	0.0108
7	0.0143	0.0143	0.0143	0.0287	0.0143	0.0143	0.0143
8	0.0246	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123
9	0.0184	0.0092	0.0092	0.0092	0.0092	0.0092	0.0092
10	0.0167	0.0089	0.0089	0.0177	0.0089	0.0089	0.0089
11	0.0147	0.0078	0.0078	0.0156	0.0078	0.0078	0.0078
12	0.0167	0.0089	0.0089	0.0177	0.0089	0.0089	0.0089
13	0.0164	0.0087	0.0087	0.0174	0.0087	0.0087	0.0087
14	0.0219	0.0116	0.0116	0.0232	0.0116	0.0116	0.0116

The simulation results for the unoccupied period showed that nine of the spaces compiled with the actual heating measurements. However, five spaces actual heating measurements did not conform to the simulation. This incompliance took four different shapes that were previously explained in Chapter 4. The four shapes include (1) unresponsive behavior where the actual heating pattern shows no response to the change in simulated heating demand, (2) excessive heating, where the actual heating response exceeds the simulated heating demand,

(3) insufficient response by providing less heat than the simulated demand, and (4) irregular response.

During the heating months, use of the building by occupants reduces the heating demand because their physical actions and appliances produced energy that helped provide heat to the space. When comparing simulated heating demand between occupied and unoccupied scenarios, for the same period, the results show that occupied scenario heating demand is less than that of the unoccupied one (Figure 5.10) in all spaces; this result validates the energy simulation results.

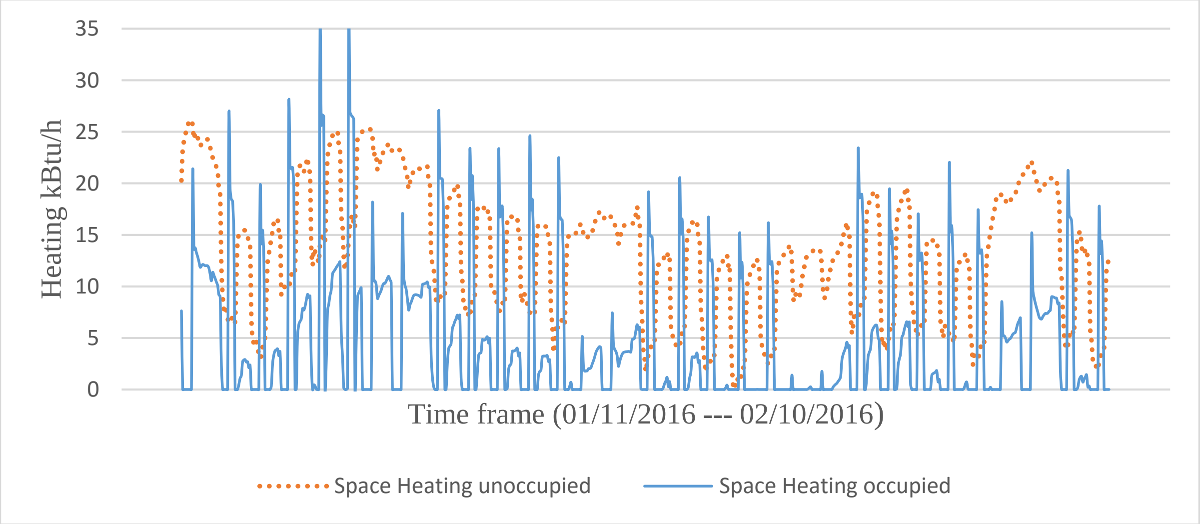


Figure 5.10: Occupied vs. unoccupied heating demand for Space #10

For the first testing period, the unoccupied heating demand matched the actual heating recorded by the building systems (Figure 5.11). The building heating system controlled by BEMS responded to the heating needs as predicted by the heating demand simulation. However, when the building was occupied, not all space-heating elements corresponded to the simulated heating demand. A summary of the unresponsive and irregular behaving spaces will be presented next.

Space #10 heating system responded to the simulated heating demand (Figure 5.11) when the building was not occupied, the regular behavior. However, when the building was occupied (Figure 5.12), the heating system exhibited a period of unresponsive behavior.

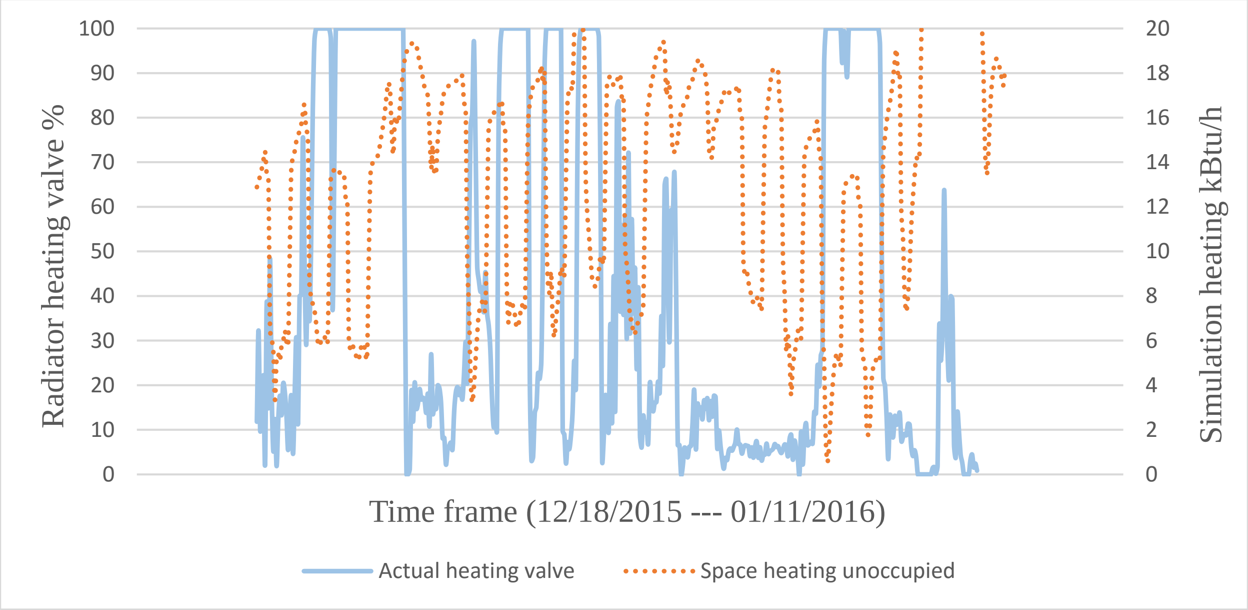


Figure 5.11: Unoccupied heating demand vs. actual heating for space #10

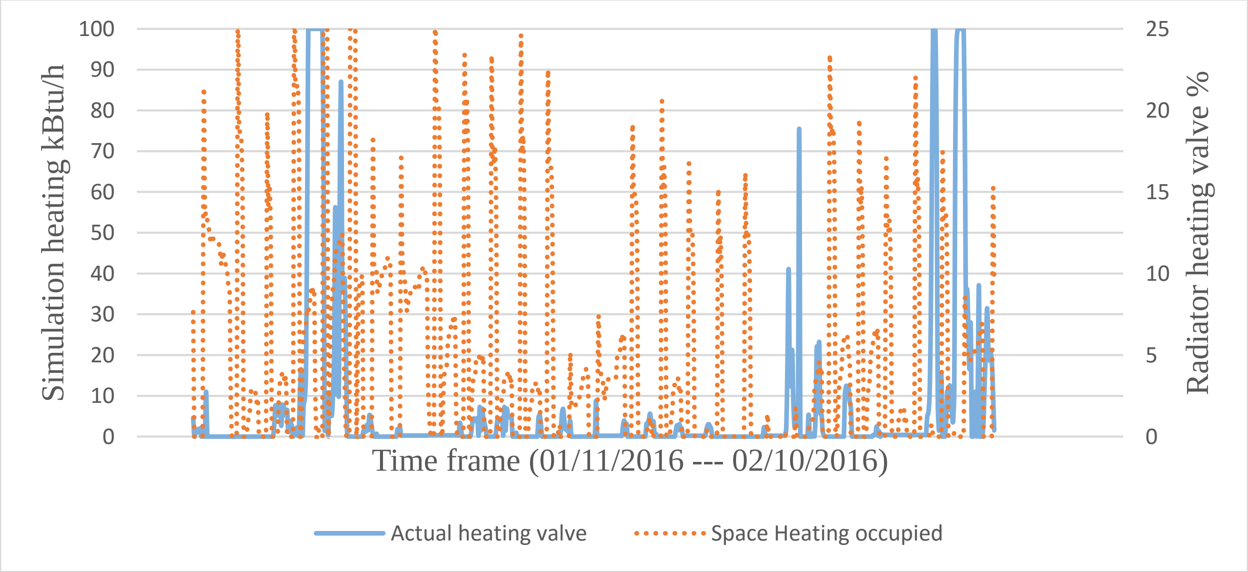


Figure 5.12: Occupied heating demand vs. actual heating for Space #10

In Space #4, the heating system responded to the simulated heating demand (Figure 5.13) when the building was unoccupied. However, the results show that system was overheating the space. In the occupied scenario, the heating system continued the same pattern of overheating the space (Figure 5.14). The overheating phenomenon was verified using the occupancy thermal comfort evaluation. The overheating behavior can be noticed when the heating valve opening value is 100% for several days and the simulated heating demand decreases.

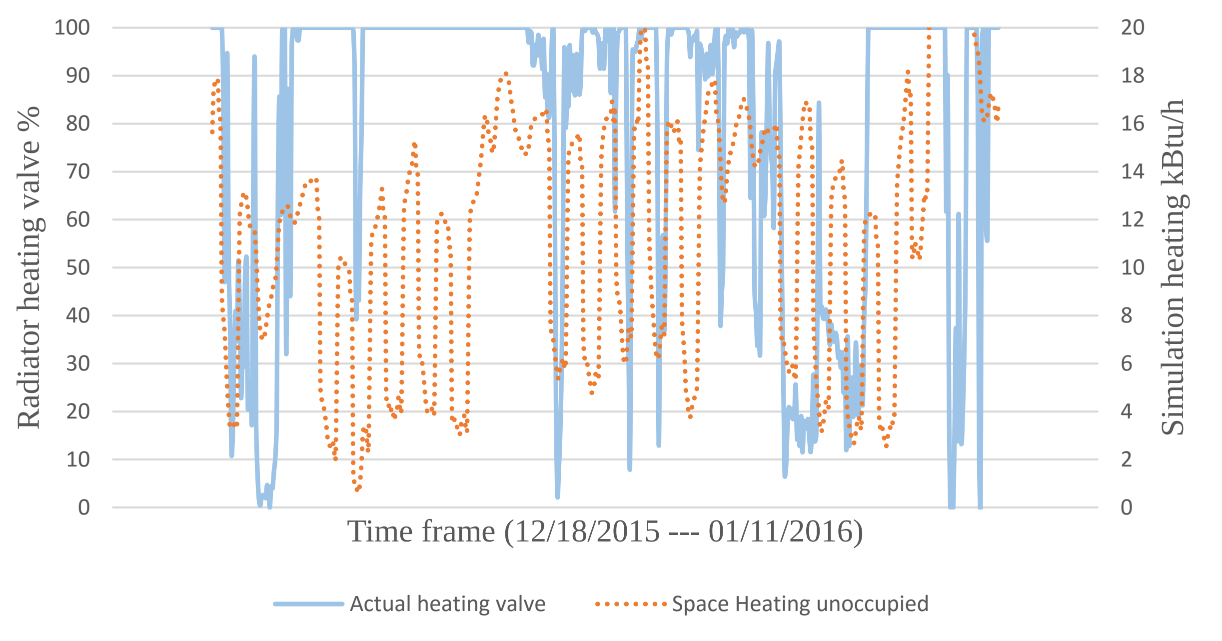


Figure 5.13: Unoccupied heating demand vs. actual heating for Space #4

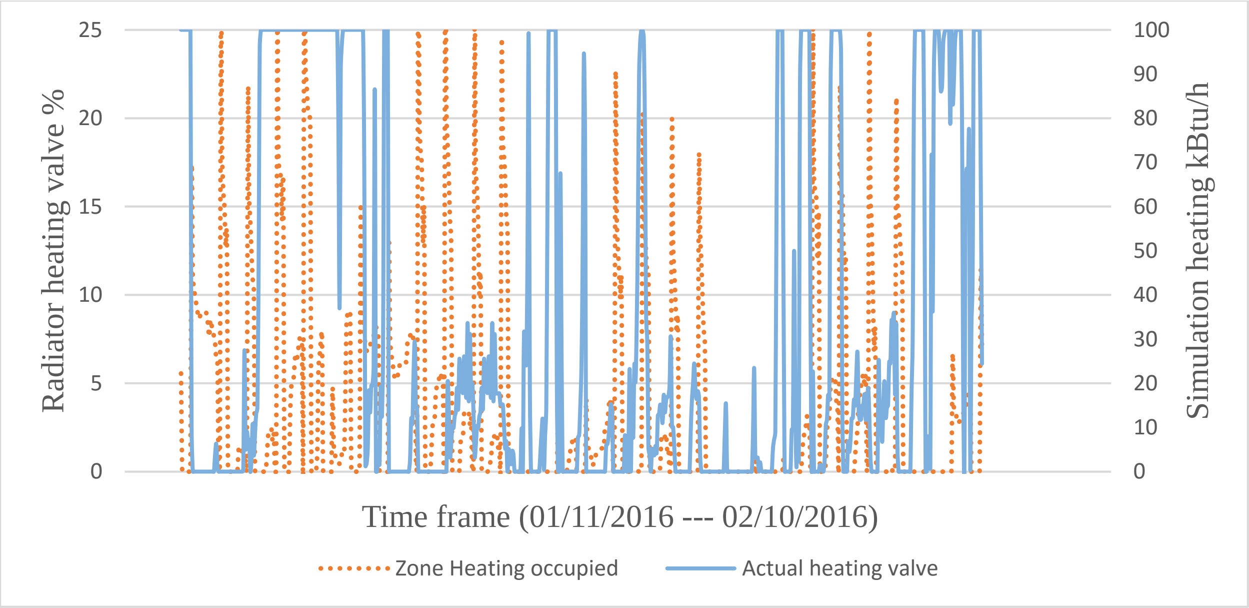


Figure 5.14: Occupied heating demand vs. actual heating for Space #4

On the contrary, Space #5 was not responding correctly to the simulated heating demand in the unoccupied scenario (Figure 5.15). The results show that the heating system was not heating the space sufficiently. This lack of heating behavior continues in the occupied scenario (Figure 5.16). This behavior was verified by the occupants' thermal comfort evaluation. Here, the insufficient behavior can be noticed when the valve opening cannot exceed a specific percentage e.g. in space #5 the heating valve did not open more than 30%.

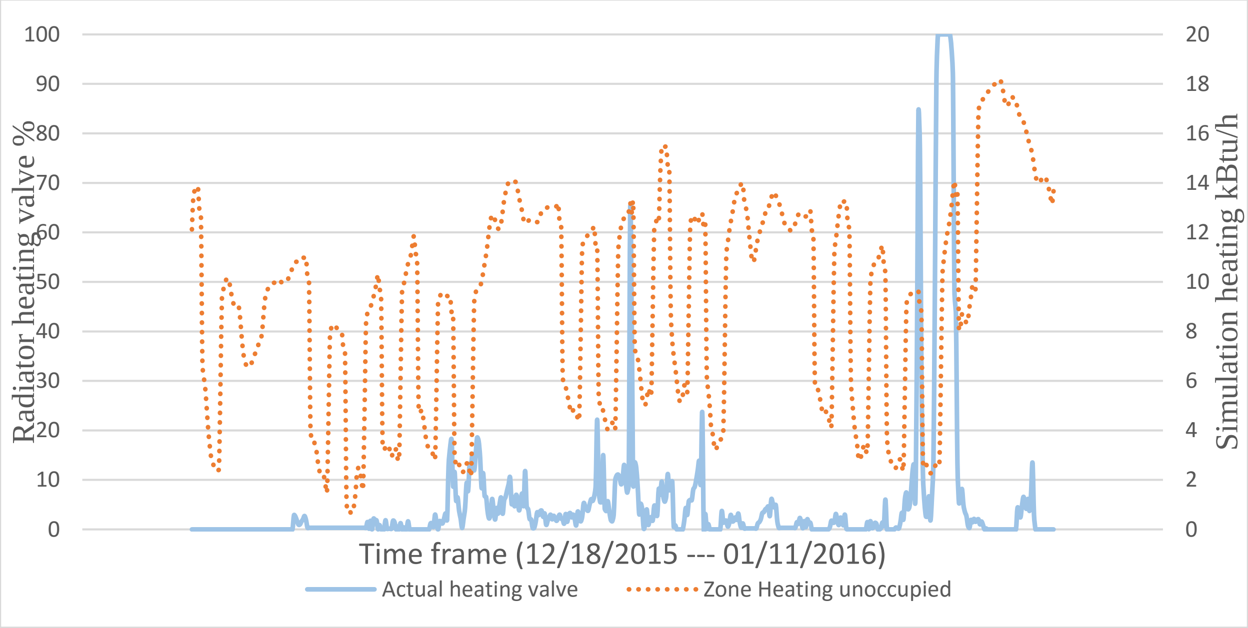


Figure 5.15: Unoccupied heating demand vs. actual heating for Space #5

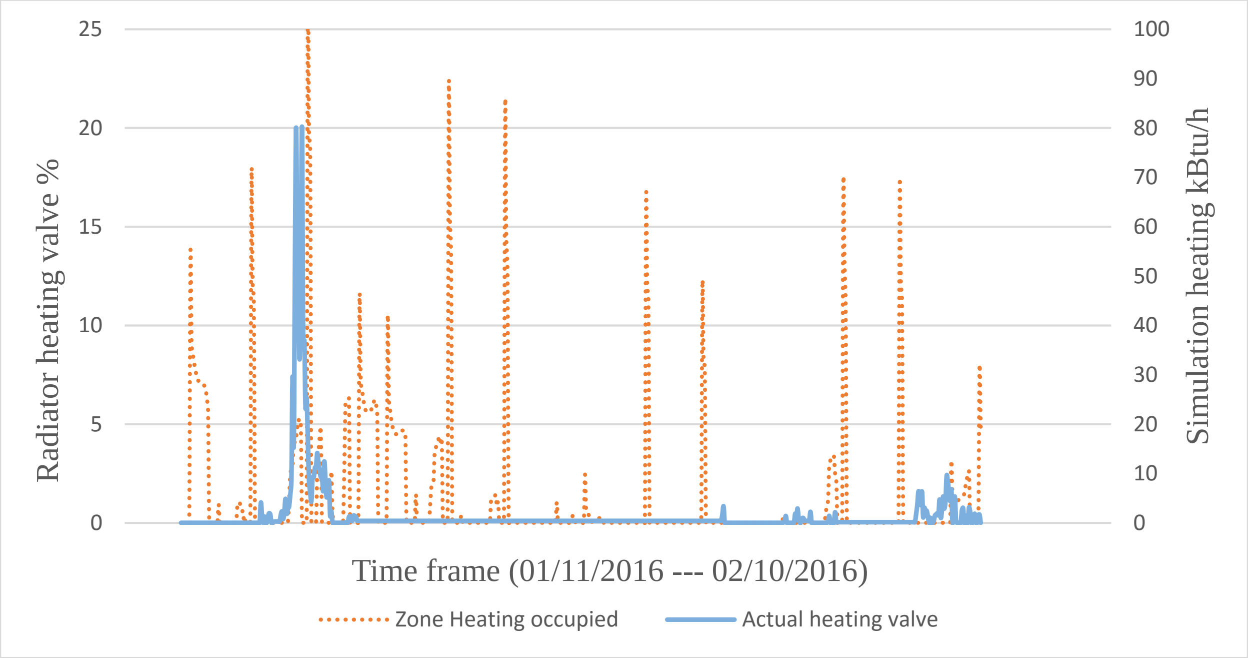


Figure 5.16: Occupied heating demand vs. actual heating for Space #5

To explain the various unresponsive behaviors in various spaces, further investigations and records of other systems are required to define the problems and flows in the heating system.

Survey Results

A survey to measure occupants' thermal comfort, their behavior, and actions to achieve their thermal comfort was conducted. A sample of sixty-seven occupants participated in the survey, representing all spaces in the building (i.e. 1-14). The survey included questions in two main categories; those regarding the spatial space and those of occupants' personal preferences regarding thermal comfort and the amount of time they use that space. Spatial information included space number, area within the space, e.g., A, B, C, heating and cooling fixtures around their workspace. Personal preference included thermal comfort in the space (e.g. warm, comfortable, and cold), hours spent during the day, hours spent during the night, and actions conducted to reach thermal comfort.

The participants were 52% female, 42% male. Participant distribution in areas A, B, and C was 40%, 33%, and 27% respectively. While the participants occupied various spaces and areas in the building, 54% were not thermally comfortable (Figure 5.17). Depending on their location, the occupants felt either too cold or too warm. Area B reported the highest level of thermal comfort; 60% of the participants were thermally comfortable compared to only 40% of participants reporting the same in areas A and C.

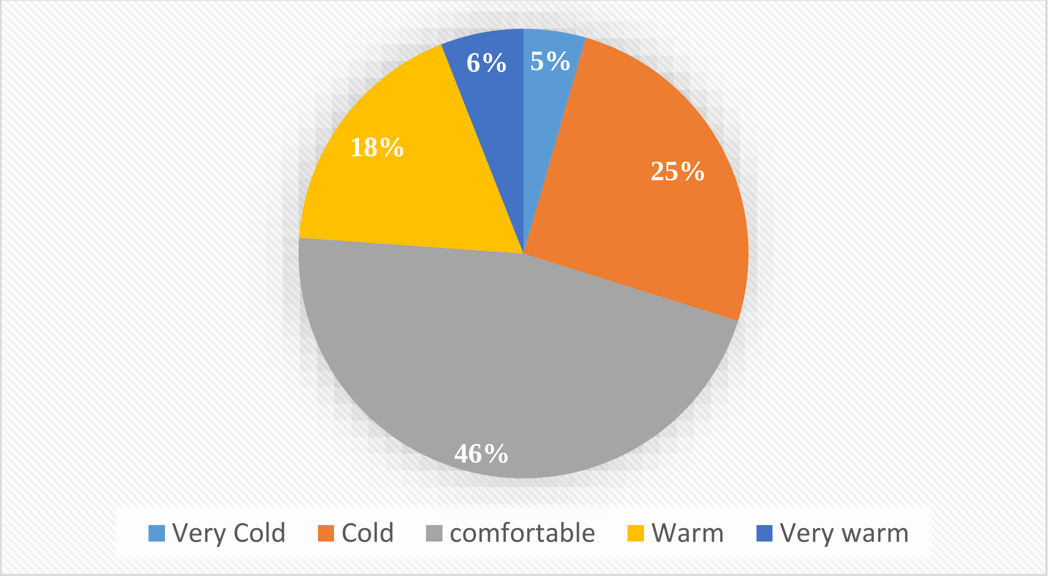


Figure 5.17: Occupants' thermal comfort level

Spaces with the smallest levels of thermal comfort were those with larger windows (i.e., 3, 4, 5, 10, and 12). Depending on their location within the space, participants reported being either too warm or too cold. In those spaces, participants managed their thermal comfort by adjusting their clothes and locations relative to the windows. Sixty-three percent of participants controlled their thermal comfort by adjusting their clothes when feeling hot and 84% used this technique when feeling cold (Figure 5.18).

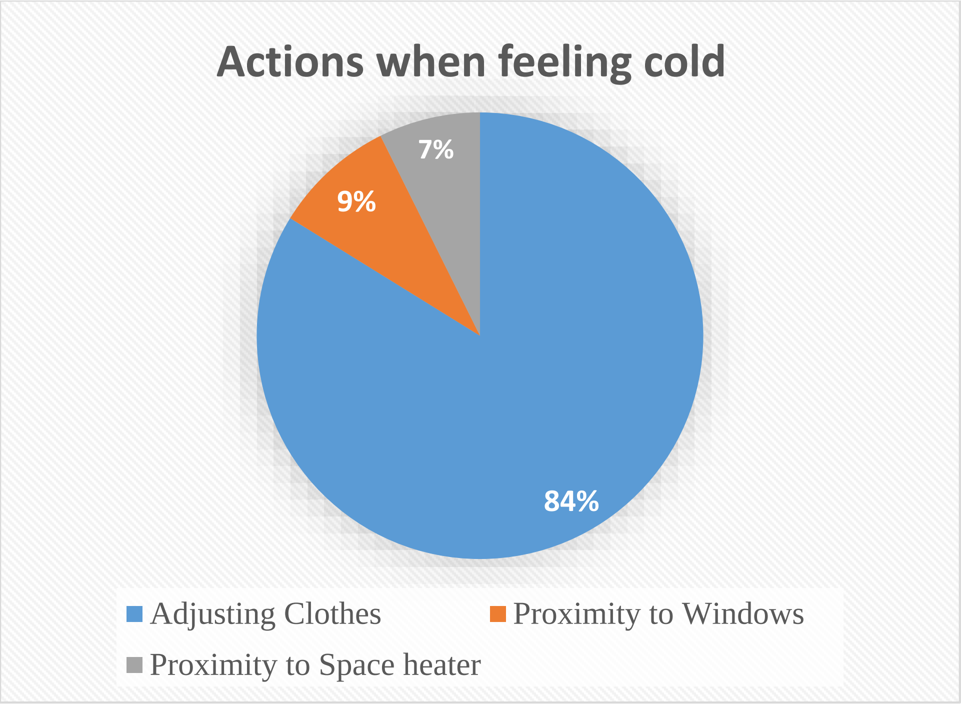


Figure 5.18: Occupant behavior to achieve thermal comfort in winter

The survey included a question to figure out whether the occupants open the windows to achieve thermal comfort. However, the results suggest that the majority of occupants do not operate any windows in the building to achieve thermal comfort. Consequently, the effect of occupant behavior on BEMS errors was minimized.

Comprehensive Analysis and Discussion

Facility managers depend on multiple systems to operate, maintain, and optimize performance of a building. One important measure of building performance is its energy consumption. However, detecting spaces with poor energy performance within a large building is cumbersome and requires comprehensive analyses. Poor energy performance is triggered by multiple interconnected variables. This section will implement a previously developed IFC-BIM based framework on the King Pavilion building to combine results from the energy simulation analysis with information obtained from different components including BIM, BEMS, CMMS, energy modeling, and Post-Occupancy Evaluation (POE) represented in the survey. The analysis will expand on three levels that will be performed in sequence.

At the first level, the building was unoccupied, and any dysfunctional heating or cooling components were detected and related to the actual HVAC component behavior rather than the simulated demand. This behavior can be unresponsive, excessive, insufficient, and irregular. The first level was thoroughly investigated and its results interpreted in Chapter 4.

At the second level, the building was occupied and fully functional. Nine spaces that did not show dysfunctional behavior at the previous level were examined. Space #10, that did exhibit any dysfunction when the building was unoccupied (Figure 5.11), changed its behavior when it was occupied, showing a period of unresponsive behavior. This shows that there was a problem with heating that space. However, a more comprehensive investigation is required to identify the problem, leading to the third level of the analysis.

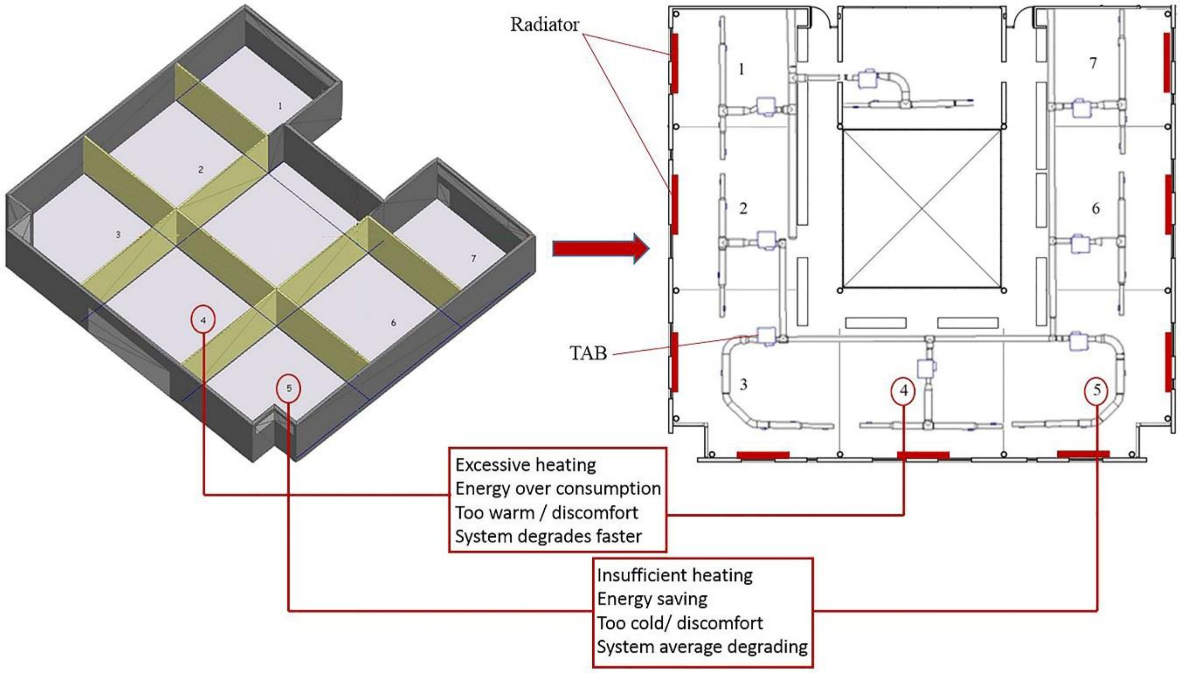
In the third level, previous maintenance history, post occupancy evaluation, and simulation results are presented using BIM to detect problems with either the HVAC system or the energy management approach. Investigating each space in isolation from other spaces will produce an incoherent status of the building's HVAC problems. While the previous levels helped localize any dysfunctions within the building, the third level investigates other systems to prioritize and explain dysfunctions. Table 5.4 summarizes dysfunctional spaces and information collected from other analysis components. Connecting multiple data streams into BIM provides a space-specific source of information. This would give facility manager a comprehensive perspective regarding the building spaces and their condition. When investigating the information provided by other systems regarding space #10, no mechanical problems were reported. Consequently, a facility manager could conclude that occupant behavior is responsible for providing insufficient heat.

Table 5.4: Dysfunctional spaces with collected information

Space	BEMS	Problem	Detection level	Survey	Potential problem
1	Controller alarm	Insufficient heating	1	A little cold	Valve / controller / set point
3	None	None	N/A	Comfortable	The system operates normally
4	None	Over heating	2	Very warm	Valve operates normally Sensor might be blocked
5	Valve alarm	Insufficient heating	2	Cold	Controller / temperature set point Temperature sensor
7	None	Not working	1	Cold	The valve isn’t operating
10	None	Insufficient heat for limited period	2	Cold	Valve operates normally. Temperature sensor Outside heating source

In the King Pavilion building, the majority of spaces were operating normally, although nine spaces reported dysfunctions when compared to the heating demand simulated by the energy simulation software. Space #7 reported no response to the heating demand and the radiator valve remained closed, affecting the thermal comfort in that space; all users of that space reported that it was cold. While providing spaces with insufficient heating (e.g. space #1) reduces energy consumption, occupant thermal comfort level in that space is negatively affected. The radiator valve in Space #1 was unable to achieve more than a 40% opening, perhaps indicating that the valve or its controller might be broken.

A broader perspective of the building's behavior can be gained by studying spaces #4 and #5 (Figure 5.19). While Space #4 shows excessive heating behavior, space #5 shows insufficient heating behavior. Presence of both problems in the BIM environment shows the interconnectivity of both dysfunctions. BEMS reported that space #5 was facing a dysfunction in its radiator valve. On the other hand, the radiator in space #4 was excessively heating the space to compensate for insufficient heating in space #5. This situation consequently creates thermal discomfort in both spaces and increases occupant complaints to the facility management team. The POE results show that about 60% of space #4 occupants, especially occupants of area (A), reported feeling uncomfortably warm. Conversely, 65% of space #5 occupants reported feeling cold except for occupants of area (A) who were closer to the heating radiator.

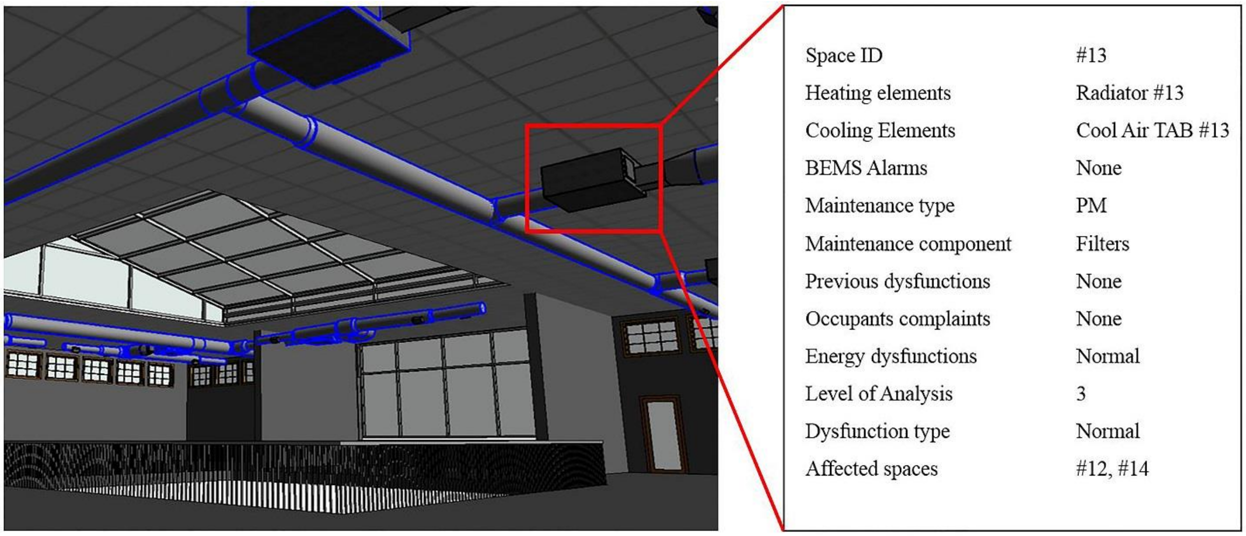


Excessive heating
Energy over consumption
Too warm / discomfort
System degrades faster

Insufficient heating
Energy saving
Too cold/ discomfort
System average degrading

Figure 5.19: Comprehensive presentation of spaces #4 and #5

It can be cumbersome for facility managers to detect and solve heating and cooling problems within a facility, especially when spaces are interconnected and affected by several factors. However, having all the information ready in an object-oriented manner and presented in BIM (Figure 5.20) improves its quality and reduces the time needed to detect and solve the problem. This helps facility managers gain needed information about a building space and its equipment necessary to respond to various dysfunctions in a timely manner.



Space ID	#13
Heating elements	Radiator #13
Cooling Elements	Cool Air TAB #13
BEMS Alarms	None
Maintenance type	PM
Maintenance component	Filters
Previous dysfunctions	None
Occupants complaints	None
Energy dysfunctions	Normal
Level of Analysis	3
Dysfunction type	Normal
Affected spaces	#12, #14

Figure 5.20: BIM framework interface

Conclusions

Two of the elements contributing to the energy performance gap are systems malfunctions and equipment deterioration. Current FM practice lacks the tools and methods to locate spaces within a building that have deteriorating energy performance and systems malfunctions, an obvious deficiency for planning maintenance activities.

This paper explored the applicability and extent to which BIM-energy simulation and monitoring framework could be used to support and effectively conduct FM tasks. The paper focused on an educational building at Iowa State university campus used as a collection of studio spaces. The experiments were conducted in two phases: occupied and unoccupied. The framework compared the actual energy performance monitored in the building spaces and the predicted performance simulated by energy simulation software. It used a monitoring and assessment approach in which the building was divided into smaller spaces to represent each heating or cooling element within each HVAC thermal zone.

The results of the case study show that Energy simulation results and IFC-BIM support existing FM function. In addition, it improves the existing practices by detecting energy abnormalities that occur due to systems malfunctions. The framework succeeded in detecting three types of malfunctions. The first type was a BEMS malfunction in which the system logic needed calibration to respond to heating demand. The second type was a hardware malfunction in which a controller or a sensor was not functioning properly. The third type of system malfunction was human behavior that caused discrepancies and affected the functionality of the building systems.

This paper concludes that BIM provides a viable option for FM teams for managing building maintenance activities. Comparing the actual heating patterns with predicted heating demand on a microscale level can lead to the detection of systems malfunctions that cause thermal discomfort or energy waste. The framework also succeeded in isolating specific spaces with dysfunctions causing a performance gap that required hardware maintenance, system calibration, or adopting energy management techniques. When applied correctly, this system can improve the FM practice by providing a comprehensive resource for information that aggregates isolated information from other systems and presents it in a single environment. Future work should build on this work by creating a decision-making model that specifies more reasons for the performance gap in a particular building. Moreover, an energy-cost/ maintenance-cost index should be developed to help facility managers set priorities for their maintenance plans.

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CHAPTER 6. CONCLUSIONS

Facility managers use multiple FM information systems to operate and guarantee a facility’s functionality. However, current FM information systems suffer from poor visualization and lack of interoperability capabilities that might allow for seamless operation and data transfer during the FM phase. Moreover, current energy management practices lack automated data sharing, require manual data entry, and do not support continuous data flow throughout a facility’s life cycle. Furthermore, facility managers face challenges in identifying problematic spaces in a facility, isolating different types of problems, and prioritizing their impact of those problems. Nevertheless, facility managers are aware of the importance of improving FM practice by finding efficient ways to manage and reduce energy consumption in their facilities.

BIM implementation for facility energy-management practices has recently gained increased attention both in academia and in industry. In addition, BIM is sought to improve current FM practices because it has capabilities to coordinate different FM systems and energy management systems. It also provides a comprehensive perspective of building spaces, equipment, and information to a facility manager. Furthermore, BIM-enabled energy management allows extracting and analyzing data to improve decision-making processes, increase efficiency in work order executions, and eliminate redundancy in data entry.

In this dissertation, a framework that implements BIM for facility and energy management tasks was developed. This framework has been presented and validated in the dissertation across four research papers and more specific details of the thesis is provided below:

1- It links BIM with BEMS to help overcome the interoperability issue

2- It represents an automated process that responds to alarms received from BEMS or BAS systems by retrieving previous maintenance data required for corrective maintenance from CMMS databases.
3- It implements BIM to coordinate energy simulation results with actual HVAC pattern, and historical BEMS and maintenance information.
4- It was validated with real-life data in order to see whether energy simulation and monitoring support FM tasks.

This dissertation contributes to existing knowledge in several ways through: (1) developing a schema that enables integrating data required for corrective maintenance in a 3D IFC-BIM environment, (2) developing a process for linking alarm reports of equipment failures and the related maintenance information from a CMMS system using IFC-BIM. (3) providing a methodology for achieving quick comparisons between actual HVAC behavior and simulation results that use actual input data, (4) identifying spaces with undesired energy performance and collecting high-quality data for required maintenance. (5) Identifying the impact of human behavior on the framework.

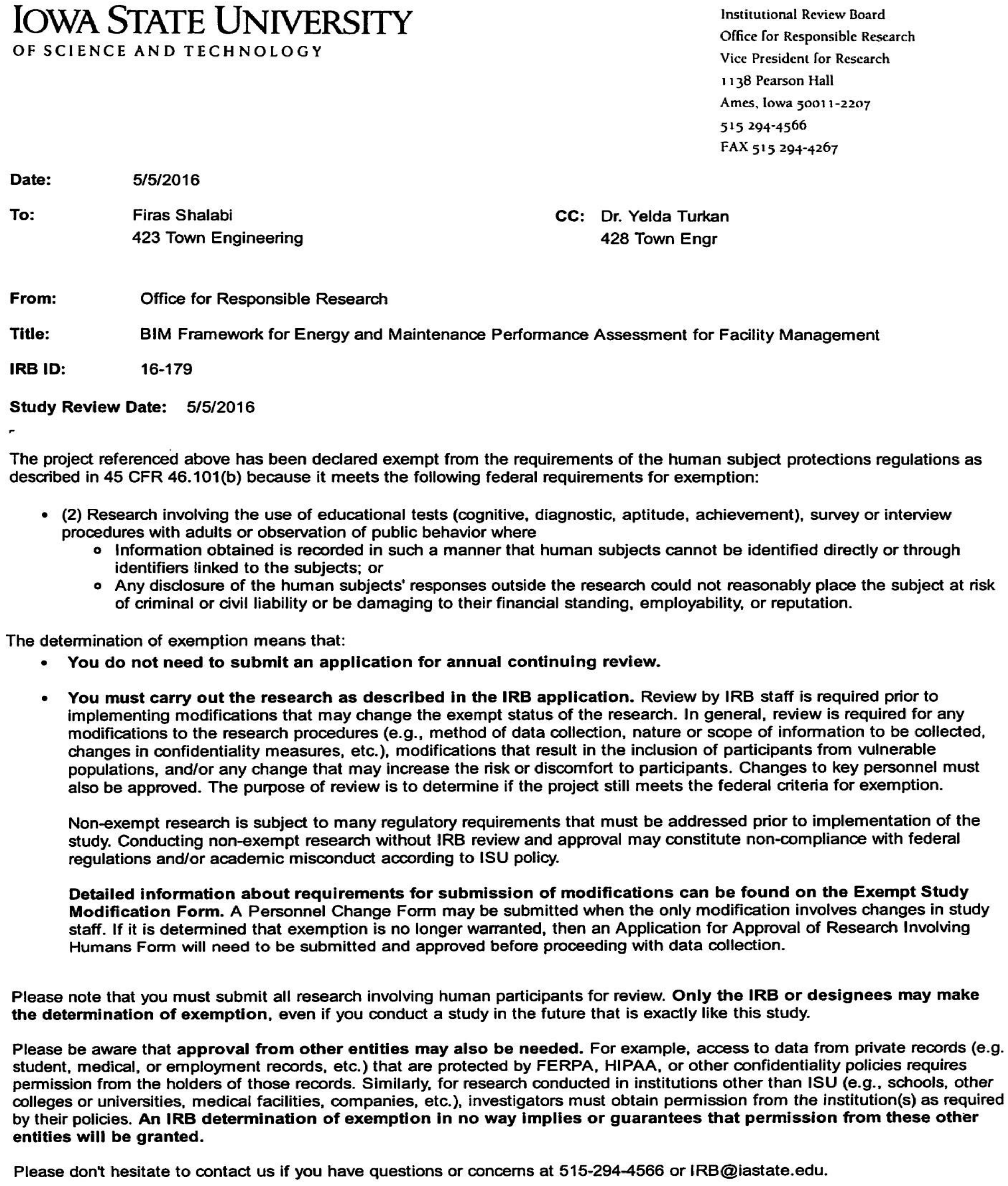
The papers forming the dissertation concluded that the developed processes and framework were capable of collecting any type of FM information needed to support facility managers' maintenance needs. Moreover, they helped facility managers in collecting related data and information for corrective maintenance activities and to help in predicting need for maintenance actions. One other important conclusion is that BIM need not be all-inclusive, meaning that data can be aggregated from different systems and temporarily merged into IFC-BIM on an as-needed basis. The dissertation also concludes that BIM allows information to be accessed and edited by responsible FM personnel who have the access and right to edit and/or collect necessary information for maintenance actions.

Furthermore, the energy performance of a facility when compared to as-built-based simulated energy performance can specify spaces with maintenance needs. Comparing the intended energy performance with the actual performance of the building's HVAC equipment highlights faults and problems. In addition, the actual performance compared to the intended energy performance can be related to one of four cases: unresponsive, excessive, insufficient, or irregular. This concludes that BIM supports existing FM functions and provides an environment where facility managers can administer, coordinate, and present facility information. BIM when combined with energy analysis improves existing practices by detecting energy management faults that occur because of system malfunctions.

The proposed framework can detect three types of malfunctions: (1) Energy management system malfunctions where system logic needs calibration to respond to heating demand. (2) Hardware malfunctions of a controller, sensor, or an operating valve. (3) Human behavior that can be solved by adopting a different management approach. Finally, microscale monitoring of building energy performance would enable detection of systems malfunctions, thermal discomfort and improve predictive maintenance plan.

Future work should focus on determining the different needs of various FM crews to provide them with specific data they need. Another logical next step in this area is the development of a decision-making model providing more specific reasons and justifications for the performance gap. Moreover, after identifying specific causes for poor energy performance, an energy-cost/ maintenance-cost index could be developed to help facility managers set priorities in their predictive maintenance plans. Finally, future research can focus on developing bi-directional data transfers from IFC-BIM to FM systems and vice versa.

APPENDIX A. INSTITUTIONAL REVIEW BOARD APPROVAL



IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
1138 Pearson Hall
Ames, Iowa 50011-2207
515 294-4566
FAX 515 294-4267

Date: 5/5/2016

To: Firas Shalabi
423 Town Engineering

CC: Dr. Yelda Turkan
428 Town Engr

From: Office for Responsible Research

Title: BIM Framework for Energy and Maintenance Performance Assessment for Facility Management

IRB ID: 16-179

Study Review Date: 5/5/2016

The project referenced above has been declared exempt from the requirements of the human subject protections regulations as described in 45 CFR 46.101(b) because it meets the following federal requirements for exemption:

- (2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey or interview procedures with adults or observation of public behavior where
    - Information obtained is recorded in such a manner that human subjects cannot be identified directly or through identifiers linked to the subjects; or
    - Any disclosure of the human subjects' responses outside the research could not reasonably place the subject at risk of criminal or civil liability or be damaging to their financial standing, employability, or reputation.

The determination of exemption means that:

- **You do not need to submit an application for annual continuing review.**
- **You must carry out the research as described in the IRB application.** Review by IRB staff is required prior to implementing modifications that may change the exempt status of the research. In general, review is required for any modifications to the research procedures (e.g., method of data collection, nature or scope of information to be collected, changes in confidentiality measures, etc.), modifications that result in the inclusion of participants from vulnerable populations, and/or any change that may increase the risk or discomfort to participants. Changes to key personnel must also be approved. The purpose of review is to determine if the project still meets the federal criteria for exemption.

  Non-exempt research is subject to many regulatory requirements that must be addressed prior to implementation of the study. Conducting non-exempt research without IRB review and approval may constitute non-compliance with federal regulations and/or academic misconduct according to ISU policy.

  Detailed information about requirements for submission of modifications can be found on the Exempt Study Modification Form. A Personnel Change Form may be submitted when the only modification involves changes in study staff. If it is determined that exemption is no longer warranted, then an Application for Approval of Research Involving Humans Form will need to be submitted and approved before proceeding with data collection.

Please note that you must submit all research involving human participants for review. **Only the IRB or designees may make the determination of exemption**, even if you conduct a study in the future that is exactly like this study.

Please be aware that **approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **An IRB determination of exemption in no way implies or guarantees that permission from these other entities will be granted.**

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

APPENDIX B. SURVEY

Users' Actions Effects on Energy Consumption

Department of Civil, Construction and Environmental Engineering

Questionnaire

Part 1: Introduction

For a research in Construction Management, Firas Shalabi under the supervision of Dr. Yelda Turkan, is studying the thermal comfort of King Pavilion users, there actions to achieve thermal comfort and their use of operable windows in the building. The goal is to identify different users' actions on energy consumption.

You are invited to participate in the study by giving us your feedback for one time as a user of the building. There are no foreseeable risks for your participation.

Although you will not benefit directly from participating in this study, you will make a major contribution in understanding the relationship between different behaviors and energy consumption.

By proceeding to the next section, you agree with the abovementioned and your age is above 18 years old.

Part 2: Participant

Male Female

I work in studio space number: _______ (see attached plan)

I usually set in area: 1 2 3 (plan attached)

Where I set there is:

1) Radiator
2) Window
3) Under a duct
4) Nothing

Part 3: Space and Actions

What devices do you use select (all that apply)?

a) Laptop
b) Desk lamp
c) Coffee maker
d) Fan
e) Other:________

How long do you use your computer while in the studio?

a) 0 - 2 hours
b) 2 - 5 hours
c) 5 - 7 hours
d) 7+ hours

Hours spent in the space between 6am to 6pm (estimate): __________

Hours spent in the space between 6pm to 6am (estimate): __________

This space tends to feel

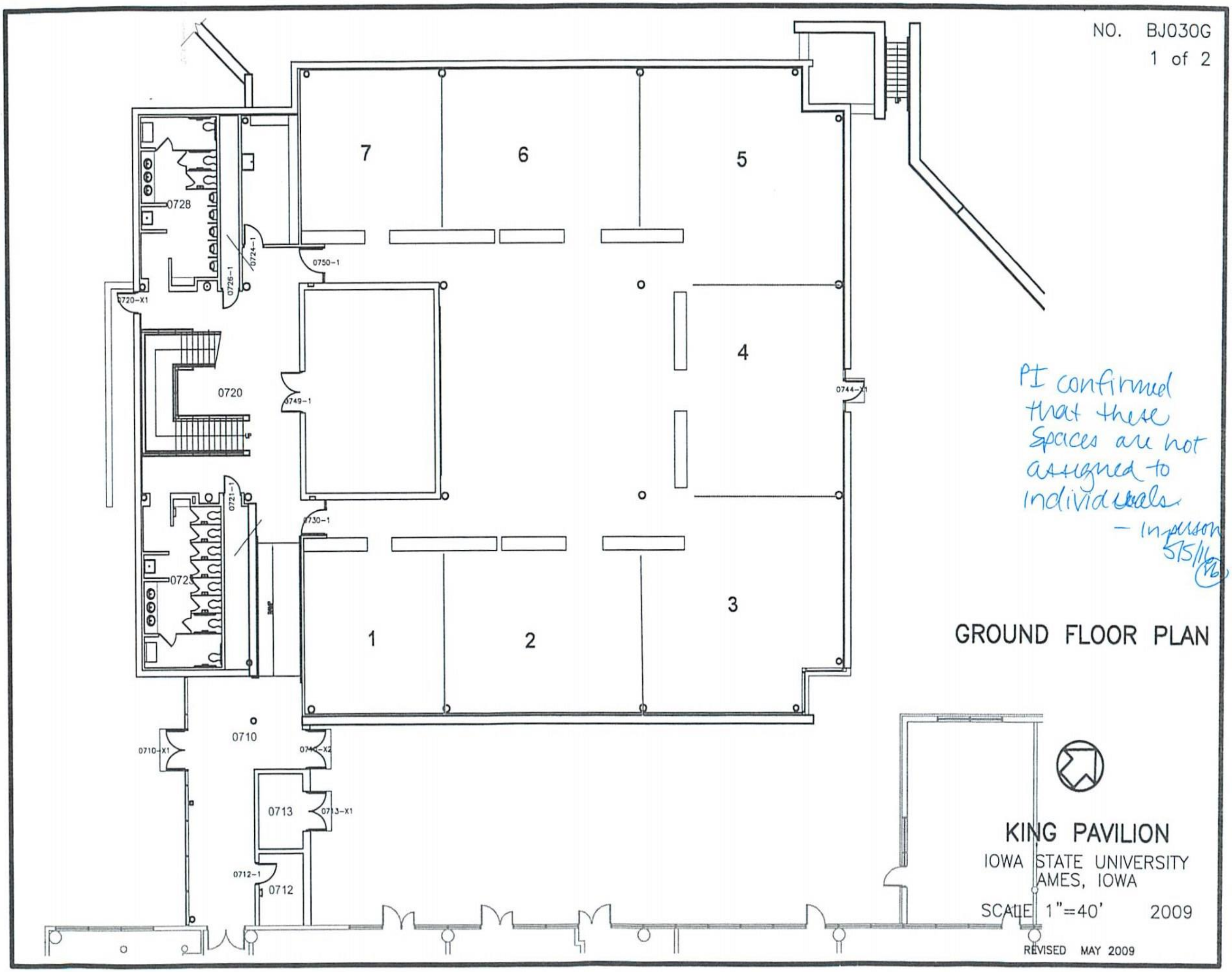
a) Very cold
b) A little bit cold
c) Comfortable
d) A little bit warm
e) Very warm

When I am warm, I tend to:

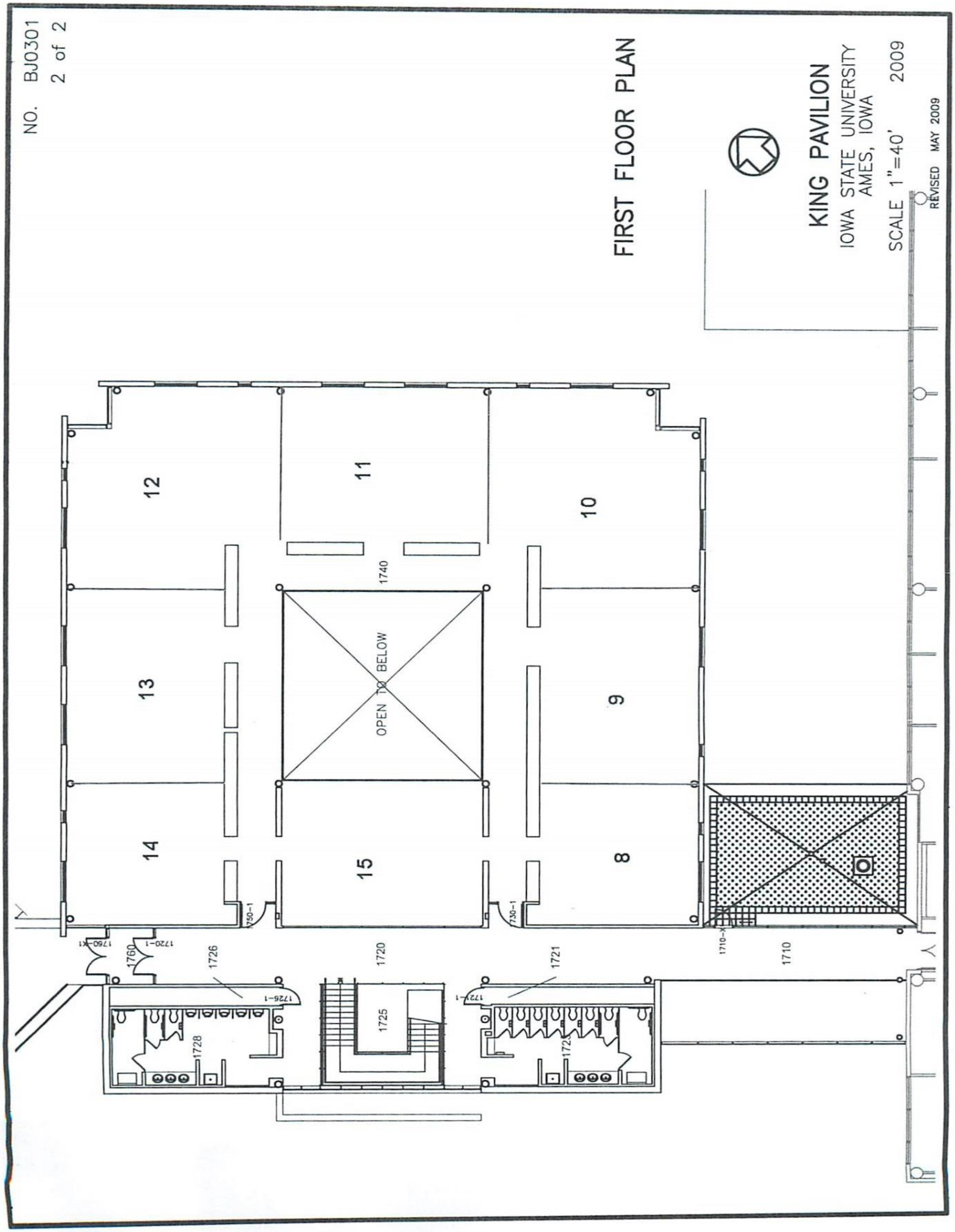
a) Take clothes off
b) Open a window
c) Do both
d) Other (please specify):_______

When I feel cold, I tend to:

a) Put extra layer of clothes
b) sit away from a window
c) turn on a space heater
d) All the above
e) other_____



PI confirmed that these spaces are not assigned to individuals.
– in person 5/5/16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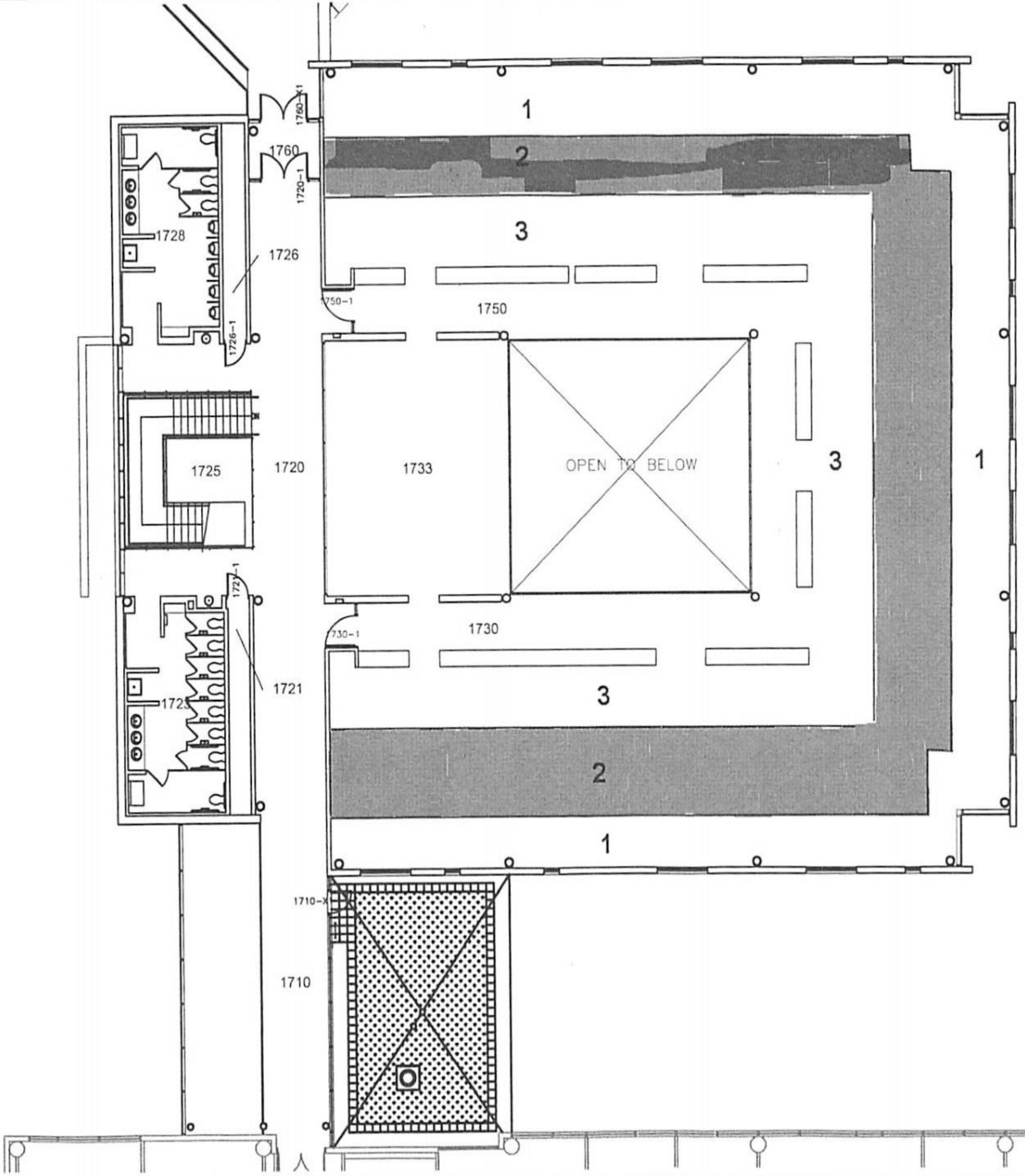

FIRST FLOOR PLAN

KING PAVILION
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