Integrating Building Information Modeling (BIM) with Custom Software Development during the Design, Construction, and Operation Phases of the Facilities

By

Daniel Kazado

A thesis submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Civil Engineering
Faculty of Graduate Studies
University of Manitoba
Winnipeg, Manitoba

Abstract

Building Information Modeling (BIM) is a process that provides architecture, engineering, and construction (AEC) professionals the digital twin of physical and functional characteristics of the actual facility that paves the way for more efficiently design, construct and operate. The data volume achieved with the BIM process has the means to coalesce, become information, and opens the doors for the analyzing as never before for the built environment. Although creating a 3D visual representation of the facility is the manifestation of changing ways of working, BIM is the management and analysis of information through the life cycle of the facility.

The BIM process can be used to facilitate decisions at the early design stage that have a direct effect on the energy efficiency of buildings. The impact of the two main factors, shape and orientation of the buildings on energy consumption was analyzed and discussed to determine the optimal solution in cold climates. The results for the energy consumption have been presented with the combination of six building shapes with eight orientations, and the study showed the possibility to reduce the energy intensity by approximately 20%.

The fourth dimension of the BIM process is the intelligent linking of model elements with time and scheduling related information for monitoring progress of construction activities and improves project management. A datacenter building has been used as a case study to present the custom-developed add-in for the construction progress

visualization method. The method developed made it possible to monitor the progress of the individual model elements for the various states of progress.

Beyond the use of BIM during design and construction, there is much to gain in the long run throughout the facilities lifecycle, and the impact of the accumulated information with BIM transcends these phases. Three approaches for the integration of the sensor database with the BIM process have been demonstrated by using the fifth floor of EITC building as a case study to improve the efficiency of facility management (FM). The developed add-in has been created as a common data platform for the visualization of sensor technology and leads to more responsive facility management.

Acknowledgments

I would first like to thank my thesis advisor Dr. Miroslava Kavgic of the Civil Engineering at the University of Manitoba. The door to Dr. Miroslava Kavgic's office was always open whenever I ran into a trouble spot or had a question about my research or writing. She consistently allowed this paper to be my own work but steered me in the right direction whenever she thought I needed it.

I would also like to thank the experts who were involved in the advisory committee for this project: Dr. Rasit Eskicioglu and Dr. Mohamed Issa. Without their passionate participation and input, the project could not have been successfully conducted.

Finally, I must express my very profound gratitude to my spouse, my daughter, and to my son for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Daniel Kazado

Contributions of Authors

Kazado D, Kavgic M, Eskicioglu R (2019). Integrating Building Information Modeling (BIM) and sensor technology for Facility Management, Journal of Information Technology in Construction, Vol. 24, pg. 440-458, http://www.itcon.org/2019/23. (Published)

    a) Daniel Kazado: Developed the building model, the custom software, and wrote the paper.

    b) Miroslava Kavgic: Suggested and supervised this research and assisted with the writing and editing of the paper.

    c) Rasit Eskicioglu: Supervised for the data collection and assisted in the writing and editing of the paper.

Kazado D, Kavgic M, Ergen E (2019). Construction progress visualisation for varied stages of the individual elements with BIM: A case study, European Conference on Computing in Construction, pp. 110–116. doi:10.35490/EC3.2019.172. (Published)

    a) Daniel Kazado: Developed the case study building model, the custom add-in, and wrote the paper.

    b) Miroslava Kavgic: Suggested and supervised this research and assisted with the writing and editing of the paper.

c) Esin Ergen: Supervised for the data collection and assisted in the writing and editing of the paper.

Kazado D, Kavgic M, Issa M (2019). A study on the impact of shape and orientation on the energy consumption of buildings in cold climates using BIM.

(Under Review)

Contents

Back Matter

List of Tables

List of Figures

Abbreviation and Acronyms

Acronyms	Description
(BIM)	Building Information Modeling
(API)	Application Programming Interface
(AEC)	Architecture Engineering and Construction
(FM)	Facility Management
(GIS)	Geographic Information System
(ASHRAE)	American Society of Heating, Refrigerating and Air-Conditioning Engineers
(HVAC)	Heating, Ventilation, and Air Conditioning
(NBS)	National Building Specification
(ODBC)	Open Database Connectivity
(2D)	Two-Dimensional Drawing
(3D)	Three-Dimensional Model
(4D)	Intelligent Linking of 3D Elements with Time
(gbXML)	Green Buıldıng XML Schema
(SQL)	Standard Query Language
(SDK)	Software Development Kits
(EUI)	Energy Use Intensity
(COP)	Coefficient of Performance

(MEP)	Mechanical Electrical and Plumbing
(OLeDB)	Object Linking and Embedding Database
(LEED)	Leadership in Energy Environmental Design
(EITC)	Engineering and Information Technology Complex
(IT)	Information Technology
(DT)	Digital Technology
(IoT)	Internet of Things
(NWC)	Autodesk Navisworks Cache
(NWF)	Autodesk Navisworks File
(NWD)	Autodesk Navisworks Document

List of Symbols

Symbol	Description
CO_2	Carbon Dioxide
ºC	Centigrade Temperature Unit
°K	Kelvin Temperature Unit
ppm	Parts Per Million
Mbyte	Megabyte Digital Information
Gbyte	Gigabyte Digital Information

Papers' Copyrights

1 Introduction

The built environment is progressively becoming digitized, and smart city technologies are creating new avenues for more effective monitoring and optimization of buildings' performance (Pärn et al., 2017). Today high-performance buildings are equipped with sophisticated monitoring systems and sensors for collecting large amounts of data related to their indoor environmental quality and energy consumption that can be used to improve their overall performance. Nevertheless, many facility managers and decision-makers still use text or spreadsheets to visualize, interpret, and utilize the collected information. This spreadsheet approach makes it difficult to understand and track the building's performance in real-time as well as it is prone to errors.

On the other hand, understanding and using the real-time data is fundamental in commercial and institutional high-performance buildings equipped with complex and multiple systems that require dynamic operation to optimize their energy performance and provide adequate indoor environmental conditions for a large number of occupants. The awareness of the industry for the importance of using BIM in facility management (FM) is increasing (Becerik-Gerber et al. 2012). Therefore, a faster, more efficient and less error-prone method is needed for the real-time visualization and analysis of the collected data. The main objectives are to: (i) evaluate and report the value of using the proposed approaches for the integration of BIM and sensor data; (ii) enhance the availability of data for entire life-cycle of the facility; (iii) improve the efficiency and effectiveness of facility managers' decision-making and reduce the buildings energy consumption.

Assessing a project's geographical objectives is a major part of the preliminary design work and both the visual development and information development within the BIM process are required at the early design stage. BIM process has the functionalities to assist designers with evaluating design alternatives and decide for energy strategies at the conceptual design stage (Jalaei and Jrade 2014). Decisions given during the design phase of the project determines nearly 70% of the environmental impacts over the buildings' whole life-cycle(S. Liu et al., 2015). Furthermore, Aksoy and Inalli (2006) claims that building orientation is one of the most important effect on the energy demand of a building and suggest that the optimisation of both building orientation and shape can lead to heating energy savings of 36%. The software used in the BIM process allows designers to virtually evaluate the impacts of shape and orientation on building energy efficiency before construction (Abanda and Byers 2016). This study investigates the impact that building shape and building orientation have on energy consumption in cold climates. Additionally, evaluates how the BIM process can be used to facilitate the early design decisions for more energy-efficient buildings.

During the construction phase, the 4D BIM process is used as a powerful tool for construction planning, constructability analysis, and visualize construction plans and milestones (Park et al. 2017). However, in the current practice, 4D BIM has shortcomings in providing information about multiple stages of the individual model elements. The construction progress data can only be used for verifying the construction progress percentage or checking whether the element is installed, and they do not provide information about other stages of the elements (e.g., tested or inspected). Project management requires an extensive amount of information from a single model element to

achieve the information for decision making (Hallberg and Tarandi 2011). The main steps required for developing a 4D BIM process are: 3D model preparation, work schedule generation, and building the relationships between 3D model and schedule. Nevertheless, the creation of relationships between construction schedule and 3D BIM model require noteworthy improvement to facilitate the formation of 4D BIM process (Changyoon Kim et al., 2013). One of the main goals of this study is to define an element-based tracking method with a custom developed add-in, for the visualization of the actual progress of each element (i.e., the lowest level of detail in the model, for different custom status) and improve the relationship between model elements and actual site progress.

Currently, the data gathered from the sensors in the buildings are monitored by the facility operators or occupants on different platforms. Since the 80s, the building management system (BMS) infrastructure is one of the most widely used systems for the visualization and interpretation of collected data (Allen 1986). BMS is a computer-based monitoring and controlling system for the buildings' mechanical and electrical services such as ventilation, power system, fire safety system, heating, lighting, and security (Malatras et al., 2008). Reconsolidation of data from varied management systems (Yu et al, 2000), integration of internet of things (IoT) data with the built environment (Dave et al. 2018), and adoption of wireless sensors (Hammad et al. 2006; Krishnamurthy et al. 2008), are the main research fields that integrate information technologies with facility management. Furthermore, building information modeling (BIM) process is widely used in the construction industry during the building's design and construction phases (Sacks et al. 2018). BIM process is utilized for visualization, construction, coordination, material

takeoff, planning, and cost proposes of the project (Gerrish et al. 2017). However, a large amount of the data collected during the design and construction phases of the project that could be of significant value for the building's operation are not transferred to the facility management phase (Thabet and Lucas 2017). Therefore, a new approach that integrates BIM data with the building sensors could create a shared data environment for improving the building's energy and indoor environmental performance while reducing the operational costs.

In buildings, indoor air temperature and carbon dioxide (CO_2) concentrations of the spaces are the main sensor readings monitored by the building owners/managers. The former impacts thermal comfort and energy efficiency, whereas the latter affects the indoor air quality, occupants' health and productivity (Cao and Deng 2019). Therefore, the building operators need to analyze both historical and current sensor data readings of the spaces to track and improve the overall performance of buildings. This study aims to facilitate the decision-making process during operation by visualizing the sensor data through the integration of software used in the design and construction phases of the BIM process. This is achieved through the investigation of the potential benefits of different visualization approaches that include both inbuilt functions and developed add-in. This study presents and discusses three possible approaches for integration of the BIM model of the university building with the sensor technology to visualize and analyze two indoor environmental quality parameters (i.e. temperature and CO_2), namely: (i) Sensor-Revit integration; (ii) Sensor-Revit-Navisworks integration; and (iii) Sensor-Revit-Navisworks-API integration. The three approaches range in their complexity and capability from the

real-time 2D visualization of temperature and CO_2 to the real-time 3D display and analysis of the historical trends and data.

Presently, the research work focused on the development of add-ins for the integration of BIM process with sensor technology for the entire life cycle of the facility typically relies on Autodesk Revit software. However, Autodesk Navisworks software allows users to open and combine 3D models, navigate around them in real-time, review them, while it disables modification of the 3D models and thus prevents any accidental changes. Furthermore, Autodesk Navisworks software is notable for its support of a wide range of file formats (e.g., AutoCAD, IFC, SketchUp, Solidworks, Rhino, ArchiCAD, MicroStation), whereas all data collected during design and construction phases can be accessed through elements in the model. To the best of the author's knowledge, there is no research study focused on development of the add-ins in Autodesk Navisworks software to integrate sensor technology with the BIM model for visualization of the historical and actual data. Moreover, contrary to other similar work, this study contributes to open source software as it provides the full script at the Mendeley Data (Kazado 2018). Consequently, the users can edit and alter the source code according to their specific needs and convenience at any point in time.

.

1.1 Objectives

The main objective of this thesis has been to investigate the use of BIM processes during design, construction, and operation phases of the facilities to utilize BIM data accessible during building's lifecycle and reduce energy consumption. The multiple steps that have been carried out to meet this objective for each phase of the facilities are as follows:

1. Design Phase

    a. To develop the conceptual model of the main building shapes.

    b. To identify the building shape that improves the energy efficiency of a building most.

    c. To employ eight different rotation to each main building shapes for energy consumption.

    d. To compare the impact of shape and orientation on the energy use intensity.

    e. To examine the potential benefit of using BIM at the early design stage, on energy consumption.

2. Construction Phase

    a. To develop the BIM model for a data center building including MEP services for the case study.

    b. To test the status change of the individual model elements for six months including four different stages.

    c. To develop a custom add-in program that can load multiple parameters to the selected multiple elements.

d. To visualize project progress based on individual model elements.

3. Operation Phase

   a. To develop a BIM model for the EITC - E2 building for integrating with the sensor database.

   b. To employ three approaches for integrating the building sensor technology and the BIM process.

   c. To develop an open-source custom add-in program that integrates sensor technology and BIM process.

   d. To provide the information on the facility in the BIM environment, including the total assets.

   e. To compare the obtained results of the three different approaches to the EITC – E2 building.

1.2 Contribution to the field

The novelty and contributions of this study are as follow:

1. This is the first work to utilize widely known Autodesk Navisworks software for the development of an add-in program to enable real-time and historic data characterization and analysis.

2. This study provides the open-source code of the add-in for future research in this area and adds value to the previous studies, both scientifically and information sharing point of view.

3. The novelty of the BIM process and sensor technology integration consists of creating a unique application that is able to visualize the information in a common data environment and to lead to more responsive facility management.

4. The research demonstrates a new method for visualization of the status progress of the individual building elements within the BIM models.

5. The study provides information regarding the capabilities of the BIM process in the early design phase for the energy consumption of alternative designs.

6. The findings from this study can serve as a useful guide for the integration of the BIM process with the design, construction, and operation phase of the facilities.

1.3 Thesis structure

Chapter 2 provides an extensive overview of the use of BIM processes during the design, construction, and operation phases of the facilities and highlights the previous studies and their limitations.

Chapter 3 is a paper styled chapter for the design phase; that seeks to extend the existing knowledge and understanding for the capabilities of the BIM process in the early design phase for the energy consumption of the alternative designs

Chapter 4 is a paper styled chapter for the construction phase; that evaluates the potential use of a new approach for visualization of the multiple status progress of the individual building elements, which uses a custom-developed add-in.

Chapter 5 is a paper styled chapter for the operation phase; that aims to present three approaches for integration of the building sensor technology and the BIM process to enable visualization and analysis of real-time and historical readings. Furthermore, this chapter demonstrates how BIM-sensor integration can lead to more responsive building management and operation by making sensor data tangible and accessible for property managers, owners, and occupants.

Chapter 6 summarizes and reflects on the use of BIM processes during the design, construction, and operation phases of the facilities and makes recommendations for future work.

2 Literature review

This chapter presents a background of the use of BIM processes during the design, construction, and operation phases of the facilities. Moreover, this chapter provides a comprehensive review of the previous work and highlights the previous studies with their limitations.

Previous studies indicate that there have been increasing attempts to integrate sensor technology with BIM for improving the life-cycle efficiency of facilities, and the studies related with operation phase can be classified as (i) enhancing safety management in construction, (ii) improving energy performance of buildings, (iii) decision support to facility management, and (iv) add-ins to BIM software. In addition, the studies related to the construction phase and design phase are classified in construction progress visualization and early design decision sections.

2.1 Safety Management in Construction

The construction industry is known as one of the most dangerous industries due to higher accident rates compared to all industry sectors. Over the last ten years, BIM processes have been increasingly used for identifying potential safety hazards early in the design and planning phases (Melzner et al. 2013). The integration of sensor technology with BIM provides a new opportunity for visual monitoring of the sensor data and the implementation of the advanced safety measures. For example, Riaz et al. (2014) developed a prototype system named 'CoSMoS' (Confined Space Monitoring System)

that can be integrated with the BIM Revit model for alerting the health and safety manager when oxygen and temperature sensor values increase beyond specified limits.

Furthermore, another study compared the performances of various database models to find the optimal configuration for 'CoSMoS' (Riaz et al. 2017). Dong et al. (2018) introduced an approach for determining the misuse of personal protective equipment with integrating pressure sensing and positioning technology with BIM. Cheung et al. (2018) developed a system in the BIM model to visually alert the detection of abnormal conditions (hazardous gas level and environmental conditions) and start ventilators for removing the hazard. Additionally to the use of sensors for measuring environmental conditions, Lee et al. (2012) integrated sensor technology with BIM model to develop a hardware and software system to assist the operation of a tower crane during blind lifts, and thus increase productivity during the construction phase. Furthermore, Guven et al. (2012) integrated sensor technology with the BIM model to develop an approach for the safe evacuation of facilities in emergency situations.

2.2 Energy Performance of Buildings

The International Energy Agency reported that the built environment is responsible for approximately 30% of the total energy consumption, and nearly 40% of the total carbon emissions (International Energy Agency 2017b). There is an increasing body of literature focused on the integration of BIM and sensor technology to improve the energy performance of buildings. For example, Wu et al. (2015) developed a framework to improve the thermal performance and energy efficiency of data centers by integrating BIM and wireless sensor networks. Wang et al. (2013) defined a conceptual web

information service framework for the Smart Building idea by integrating live sensor data with the BIM model. Bottaccioli et al. (2017) presented a software infrastructure that integrates different sensor devices with BIM and geographic information systems (GIS) for analyzing and visualizing the energy behavior of the facilities. Lee et al. (2016) developed an energy management platform for improving the operation control of equipment in the energy operation center using BIM and building automation system integration. Another study reported that when applied to all buildings in Sejong city, approximately 12.1% energy savings can be achieved (over 40 million dollars can be saved per year) by using BIM-based energy efficiency technologies with integration to sensor technology (Lee et al., 2016). Mousa et al. (2016) developed an approach to decrease the carbon emissions of facilities during their lifecycle using the BIM process to represent the real-time carbon emissions. Marzouk and Abdelaty (2014b) proposed an application for monitoring of thermal comfort in subways utilizing sensor technology and the BIM model. The integration of sensor technology and BIM models was also used for comparison of the building energy simulation in the design phase with actual data collected in the operational phase of a test facility (Andriamamonjy et al. 2015). Moreover, Liu and Deng (2017) developed a method for the design of sustainable construction, which integrates the BIM model and sensor technology.

2.3 Facility Management Decision Supporting Applications

During the entire life cycle of a building, the facility management (FM) phase accounts for the most substantial portion of time and cost (Guillen et al. 2016). Representation of data in a visual platform using BIM and GIS technologies can allow facility managers a

better understanding of various building-related issues (Araszkiewicz 2017). For instance, Cahill et al. (2012) examined the role of BIM in optimized building operation using existing building performance data gathered via wired and wireless sensors. Lee et al. (2013) studied an integrated approach for status monitoring and operations of urban facility management with 3D visualization of the sensor information. Marzouk and Abdelaty (2014a) developed a framework for monitoring temperature and particulate matter in subway stations to provide operators with improved visual information using BIM and sensor technology. Hu et al. (2018) proposed an intelligent operation and maintenance software for the integration of the mechanical, electrical, and plumbing (MEP) systems as-built model with the monitored sensor data. Zhang and Bai (2015) utilized BIM environment and radio frequency identification based sensor technology to develop an approach for structural condition monitoring designed for post-hazard inspections.

2.4 Add-ins to BIM Software

Chen et al. (2018) studied the integration of BIM and IoT technologies for fire visualization in the BIM model using Autodesk Revit software. Pärn and Edwards (2017) argued that an API plug-in developed in the BIM authoring tool Autodesk Revit could be used for BIM-FM integration with live feed sensor data from the building management system. Autodesk research group presented a BIM-based building dashboard to provide visualization of BIM with sensors (Attar et al. 2010). Alves et al. (2017) developed a solution for embedding information from BIM models while performing real-time queries over sensor data. Kazado et al. (2019) proposed a method for monitoring and

visualization of construction progress based on model elements with a new add-in developed using BIM design review software. Cheng et al. (2017) investigated an integrated system of sensors with BIM for fire prevention and disaster relief using applications developed in Revit software. Plug-in development in Revit was also used for improving the accuracy and quality of the final decision in the early design stage of the renovation projects (Kamari et al. 2018). Several other studies relied on the application programming interface (API) software plug-in to integrate sensor technology with the BIM model using Autodesk Revit software (Arslan et al., 2014; Chen et al., 2014; Kensek, 2014; Liu *et al.*, 2015; Zhang et al., 2015).

2.5 Construction Progress Visualization

Updating the project schedules requires actual progress data collection from the site (Abdelsayed and Navon 1999). For example, the comparison between the actual and planned progress shows the project deviations, whereas the automated progress monitoring enables an equal measure of the project performance, and each activity actual dates can be defined more precisely (Turkan et al., 2012). One of the most critical tasks of construction management is to track the progress and take corrective actions required on time. Software packages such as Microsoft Project and Oracle Primavera are widely used in the construction industry for this purpose. Planning software is based on activities defined in different work breakdown structures with planned and actual dates for each activity. In addition to the dates, many other parameters can be loaded to the activities, such as resources or quantities for reporting purposes. It is possible to receive a planned versus actual data from the software and report activities that are in the critical path of the

project. All these reports created by using the software are limited with the activities defined that do not include a visual representation of the project.

Updating the schedules with actual progress at the site and creating reports requires the necessary skills in using the related software. Moreover, progress is monitored based on activities. Consequently, it is not possible to monitor each stage in the project or each status of the activities in a large-scale project due to the excessive number of activities. However, in some cases, it is necessary to monitor the critical building elements at this level of detail to make proactive decisions. Reinhardt et al. (2004) developed an approach to collect data for the project management tasks by employing navigational models as well as identified that the interaction between data at different levels of detail is one of the needs for progress monitoring.

4D scheduling is another method that combines the schedule with the BIM model elements to visually represent the progress at the construction site. Visualization of the progress increases the decision-making capabilities of project managers through the latest data collected from the progress performance (Golparvar-Fard et al., 2009). Furthermore, 4D scheduling has been utilized for the planning and constructability review as well as for the improvement of the coordination and collaboration between the project's stakeholders (Mahalingam et al., 2010). Software packages, such as Autodesk Navisworks Manage, Synchro Pro Software, and Vico Office, have functionalities for linking the model elements automatically with the work schedule through a standard parameter. Although 4D simulations are commonly used in the construction industry for the last decade and provide valuable information to decision-makers, a limitation is that they are based on schedules, which have a limited number of manageable activities. Since

the number of activities is limited, the granularity of the progress data is low. As a result, the representation of all statuses and stages of a large-scale project is often not possible due to a large increase in the number of activities in the schedule.

The majority of studies that updated the BIM model based on the progress of building elements performed this update automatically by matching the activity ID and the 3D element ID. Kim et al. (2013) proposed a methodology for automatic updating of the 4D model by using image processing to monitor construction progress. Tuttas et al. (2014) presented two approaches for automatic monitoring of the construction site, firstly generation of as-built data, and secondly comparison between planned and the as-built data. Getuli et al. (2016) described a workflow using apps and mobile devices for information exchange in construction. However, this approach only allowed visualization of the installation activities and required properly structured schedule information. In contrast, we present an approach for progress monitoring of the various status of building elements without the need for integration with the schedule information.

Several strategies for automatic collection of the construction progress data using advanced technologies have been explored by the researchers(Golparvar-fard et al., 2015; Shih and Wang, 2004; Son and Kim, 2010; Turkan et al. 2012). These studies used remote-sensing technologies (e.g., laser scanning) and demonstrated that visual information from the site could be collected as a point cloud data and compared directly with a building information model of the project. For example, Park et al. (2017) developed a real-time web and database-supported visualization method for presenting the latest information in 4D BIM models. Also, Chen and Luo (2014) proposed to

integrate the construction quality management system and 4D BIM application for improving the current processes.

However, the previously developed methods for automatic collection of the construction progress data can only be used for verifying the construction progress percentage or checking whether the element is installed, and they do not provide information about other stages of the elements (e.g., tested or inspected). Moreover, the tracking methods of the construction progress that are used in the industry - even with emerging technologies- are based on the activities defined in the work schedules of the project, which includes planned or installed status only.

2.6 Early Design Decision

The International Energy Agency has reported that the built environment is responsible for approximately 30% of the total energy consumption and nearly 40% of the total carbon emissions of a building (International Energy Agency 2017a). With the increase of global warming risk, the construction industry has started to define alternative solutions for more energy-efficient buildings (Bynum et al., 2012). Even though the design stage itself does not induce significant environmental effects, it determines almost 70% of the environmental effects over the entire lifetime of a building (Rebitzer 2002). The decisions at the initial design stage have an essential effect on the energy efficiency and life cycle costs of buildings.

Building information modeling (BIM) is a process of developing a virtual equivalent of the actual building that supports data exchange, management, and communication during

the entire building's life cycle. In recent years, the BIM process has become an approach for designing energy-efficient buildings and simulating building performance in the virtual environment supported the design of the sustainable building. The BIM model of a building saves all of the information, including geometry, spatial relationship, geographic information, quantity data, cost information, and properties of building elements (Azhar 2011). BIM models have been used to compare the building energy simulation in the design phase with actual data collected in the operational phase of a test facility (Andriamamonjy et al. 2015). In addition, Liu and Deng (Z. Liu and Deng 2017) have developed a method for designing sustainable construction, which integrates the BIM model and sensor technology. Moreover, Jalaei and Jrade (Jalaei and Jrade 2015) have developed a methodology for integrating BIM with the Leadership in Energy Environmental Design (LEED) certification to eliminate the documentation process. Therefore, the BIM process provides functionalities for simulating the energy performance of buildings at early design stages and enables the designers to select the optimal energy-saving solution.

The International Energy Agency reported that the energy performance of a building envelope and its components such as external walls, floors, roofs, windows, and doors are critical in determining the energy required for heating and cooling the buildings (International Energy Agency 2013). Improving insulation and using more efficient building materials can decrease the energy consumption of buildings (Tiberiu Catalina et al., 2008). Several researchers have investigated the relationship between the shape of a building and its energy consumption (AlAnzi et al., 2009), (T Catalina et al., 2011), (Parasonis et al., 2012). The external surface of the building has a direct effect on the

18

energy used for heating in cold climates, and a larger external surface requires more energy for heating; consequently, a minimum external surface is optimum. The heating systems of mechanical services and lighting systems of electrical services are significant factors that increase the energy consumption of buildings, both of which are associated with the building's orientation (Mardookhy et al. 2014). Furthermore, Abanda and Byers (2016) have investigated the impact of orientation on energy consumption using the BIM process, and Andersson et al. (1985) have studied the variation of building loads in response to the orientation of the buildings. Thus, the shape and orientation of buildings are main parameters that can be selected at the early design stage and impact the life cycle cost of buildings.

3 A Study on the Effect of Shape and Building Orientation on Energy Consumption in Cold Climates Using BIM

Abstract

Building information modeling (BIM) is a process of developing a virtual equivalent of an actual building that can be used in different stages of the building design to test, analyze, and optimize various energy efficiency strategies and solutions. The shape and orientation are the two main parameters in the early design stage that have a direct impact on the building's energy consumption. The energy-efficient design is essential for extreme climates such as Winnipeg, Canada where temperatures fluctuate from +35°C in summer to -40°C in winter. This study aims to investigate the effect of the shape and orientation on the energy consumption of a building exposed to a cold climate and evaluates how BIM can be used to facilitate this process. The following steps were undertaken to achieve this goal. First, six primary building shapes were modeled using Autodesk Revit, a widely utilized BIM tool. Second, the energy consumption of each building shape was calculated using the energy simulation software Green Building Studio. Third, different building orientations were tested and analyzed for every building shape. Finally, the impact of the combination of the two factors, shape and orientation, on annual energy consumption was analyzed and discussed along with the suitability of BIM to determine the optimal shape and building orientation in the early design stage. The results showed that the surface-area-to-volume ratio and orientation significantly impact the overall building's performance. Because the impact of these factors varies between different end uses, they should be optimized for a specific building type and used in the

early design stage. For instance, shapes with a small exposed surface-area-to-volume reduce energy intensity by approximately 20% compared to shapes with larger surface-area-to-volume ratios. However, because of the reduced daylight, the former increase electricity consumption by approximately 11% compared to those with large surface-area-to-volume ratios.

3.1 Methodology

The concept building shapes have a simple morphology, which is affected by the nature of a project. The selection of the building shape in the early design stage has a direct impact on the life cycle energy performance of the building. Figure 1shows the six main shapes of buildings (Geletka V. 2012) that were selected in this study to compare the energy consumption. A generic model of each building shape was created using Autodesk Revit (2019) software, one of the most commonly used BIM authoring tools according to surveys conducted by the National Building Specification for the last three consecutive years (NBS 2016), (NBS 2017b), (NBS 2018). Additionally, the same software supplier provides other tools fully compatible with their BIM authoring software for energy simulation. The building models were created using Revit massing tools and converted to three-story buildings. Each floor was 3 m high, and building components such as walls, windows, floors, and roofs were modeled. All of the models were created at a specific geographic location at Winnipeg, as shown in Figure 2, which is particularly important since over the year Winnipeg experiences extreme temperature fluctuations that range between +35°C in summer to -40°C in winter. All the building shapes were modeled for the same total building area (1,200 m^2) and the same gross volume (3,600

m^3). The building shapes in the model had the same window-to-wall ratio of 30%. Figure 3 shows the final views of the shapes modeled in Revit software. Each floor contains a total of five room elements: four office spaces and one circulation area. The space elements were modeled based on the room elements in the model required for an energy analysis. The space elements for offices were specified to be heated and cooled to meet the requirements of 25 m^3/h outdoor air per person and the occupancy of 20 m^2 per person. The HVAC system for the buildings was specified as central variable air volume chillers with 5.96 Coefficient of Performance (COP) for cooling and the boilers with 85% efficiency for heating. In addition, the thermal properties of each building component were identical for each building shape. Winnipeg is located at the 7A climate zone in Canada, and the overall thermal transmittance values for the components were: walls 0.21 W/ (m^2 °K), roofs and floors 0.16 W/ (m^2 °K), doors 2.20 W/ (m^2 °K), dual-glazed windows 2.00 W/ (m^2 °K), and floors in contact with the ground 0.75 W/ (m^2 °K).
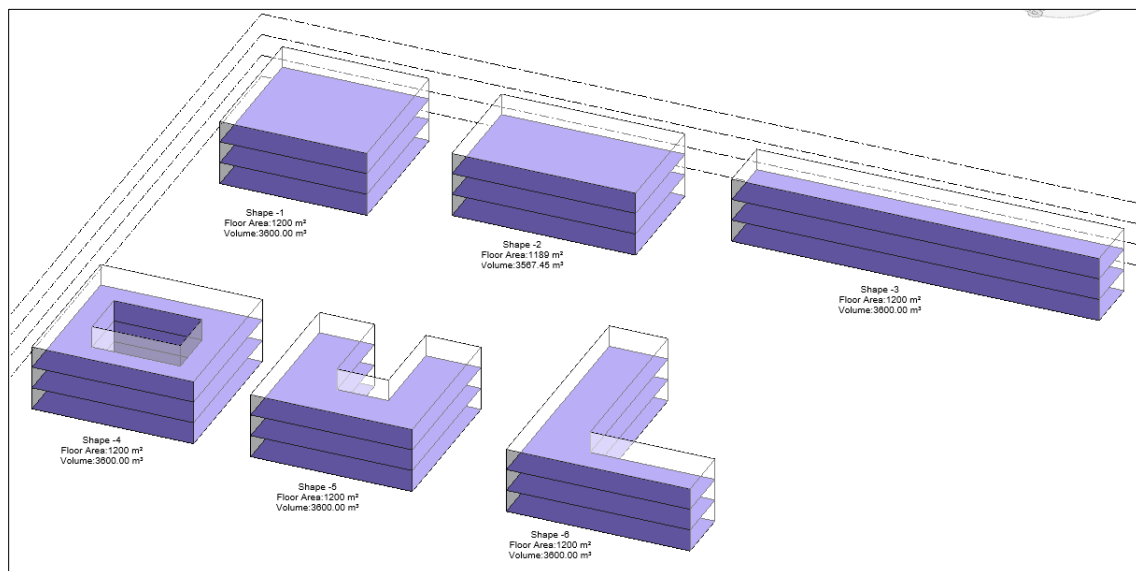
Figure 1 - Main building shapes selected to compare the energy consumption
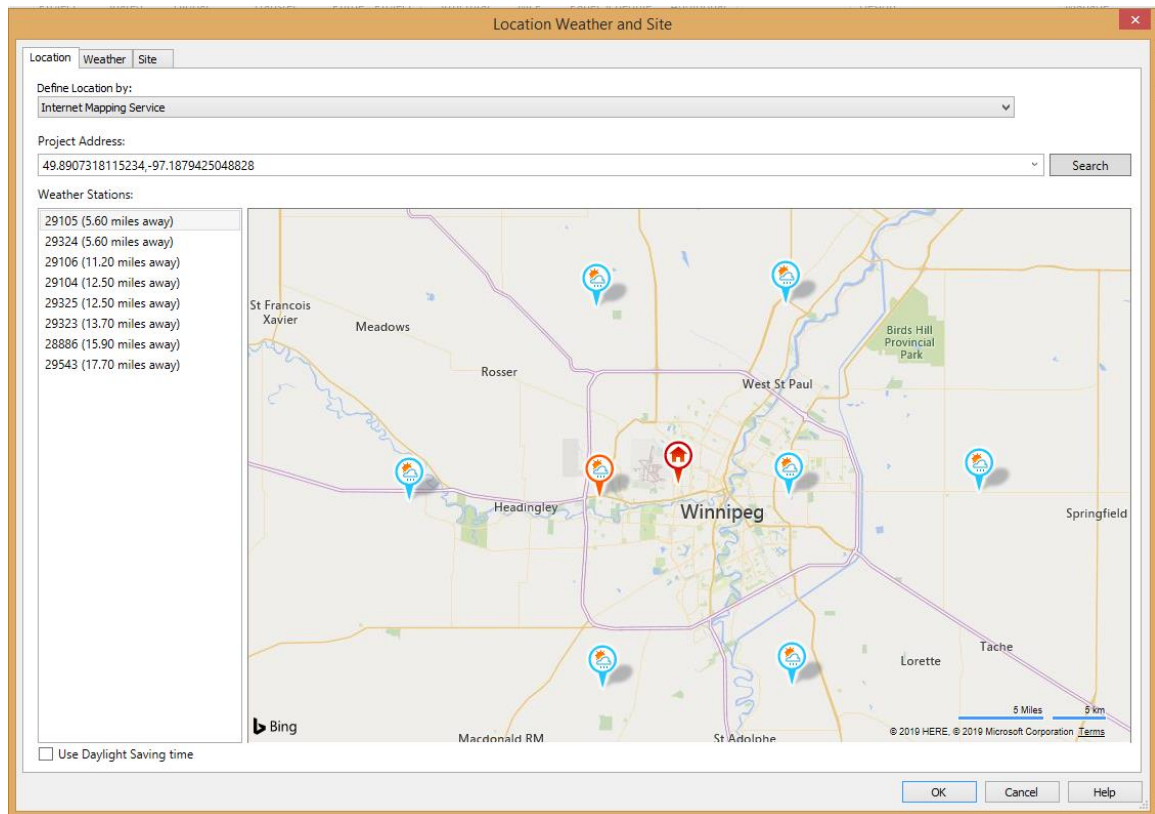
Figure 2 - Location selected in Revit software
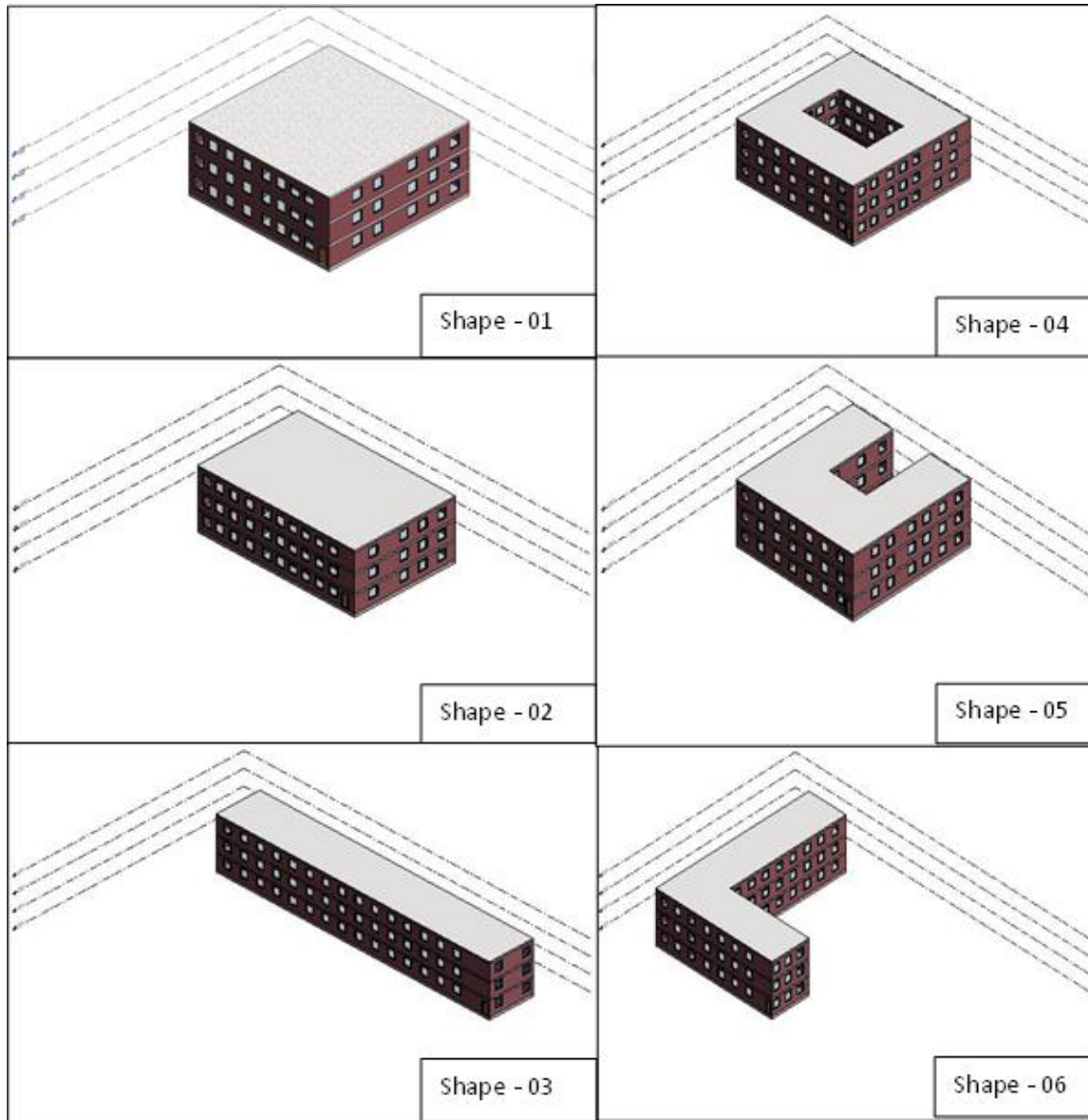
Figure 3 - Building shapes modelled in Revit software

The building models created were then exported from Revit to Green Building Studio, one of the leading energy simulation software. The main reason for choosing Green Building Studio was because both the Revit and Green Building Studio software can smoothly share data through a gbXML format. The total life cycle energy consumption in thirty years for electricity and fuel of each building shape was calculated with the Green

Building Studio software. In addition, the energy use intensity (EUI), annual electric consumption, and annual fuel consumption of the buildings was calculated in the cloud using the energy simulation software. The results of the energy simulations were presented as the base run results in the software. Figure 4 shows the sample base run results for Shape-01.

1 Base Run	
Energy, Carbon and Cost Summary	
Annual Energy Cost	$9,764
Lifecycle Cost	$132,984
Annual CO₂ Emissions	
Electric	0.0 Mg
Onsite Fuel	23.4 Mg
Large SUV Equivalent	2.3 SUVs / Year
Annual Energy	
Energy Use Intensity (EUI)	852 MJ / m² / year
Electric	147,741 kWh
Fuel	470,187 MJ
Annual Peak Demand	47.4 kW
Lifecycle Energy	
Electric	4,432,242 kW
Fuel	14,105,598 MJ

Figure 4 - Base run results for Shape-01

To investigate the impact of building orientation on energy consumption, design alternatives for orientations were created. The design alternatives were created using the Green Building Studio software functionality with a rotation of 45° for seven orientations (45°, 90°, 135°, 180°, 225°, 270°, and 315°). The data created by the initial base run for each building shape was used for alternative orientations, and no changes were made in

Green Building Studio. For each building shape, the model created in Revit without any rotation was the base run, and the EUI, annual electric consumption, and annual fuel consumption was recorded for every change of 45°.

Finally, the results for the effect of building shape and orientation on the EUI, annual electric consumption, and annual fuel consumption were analyzed and presented. Furthermore, the study investigated the value of utilizing BIM in the pre-conceptualization stages of the design to determine the best shape and orientation of the building. The capability of using BIM to optimize the energy consumption for alternative design solutions and the accuracy of the results were investigated.

3.2 Results

The study results were presented, analyzed, and discussed to understand the relationship between building shape, building orientation, and energy consumption. First, the EUI, annual electric consumption, and annual fuel consumption of each building shape was presented, and the optimized shape of a building was analyzed. Figure 5 illustrates the EUI in MJ/m^2/year for each building shape at the base run. Shape-01 had the lowest EUI among the building shapes. Figure 6 and Figure 7 provide further insights into the annual electricity consumption and annual fuel consumption of each shape at the base run. However, Shape-03 had the lowest annual electric energy consumption, and Shape-02 had the lowest annual fuel energy consumption. Figure 8 demonstrates the comparison between the annual electric energy use and annual fuel energy use for each shape at the base run. The annual electric consumption values were converted to MJ for comparison. While the annual electric consumption was higher than the annual fuel consumption for

Shape-01 and Shape-02, the fuel consumption was higher for the other four building shapes. Although the lowest EUI was calculated for Shape-01, Shape-03, which had the highest access to daylight, had the lowest electricity consumption. Shape-01 and Shape 02 had similar a EUI, annual electric energy, and annual fuel consumption compared to the other building shapes.
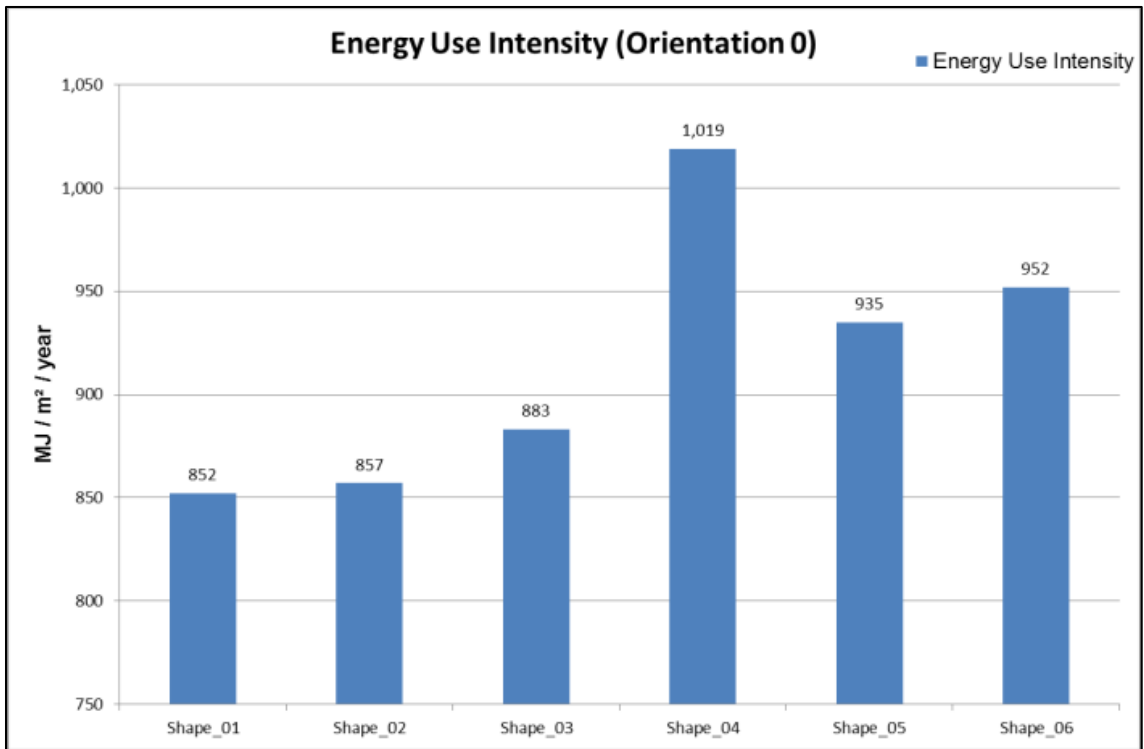
Figure 5 - EUI for each shape at the base run
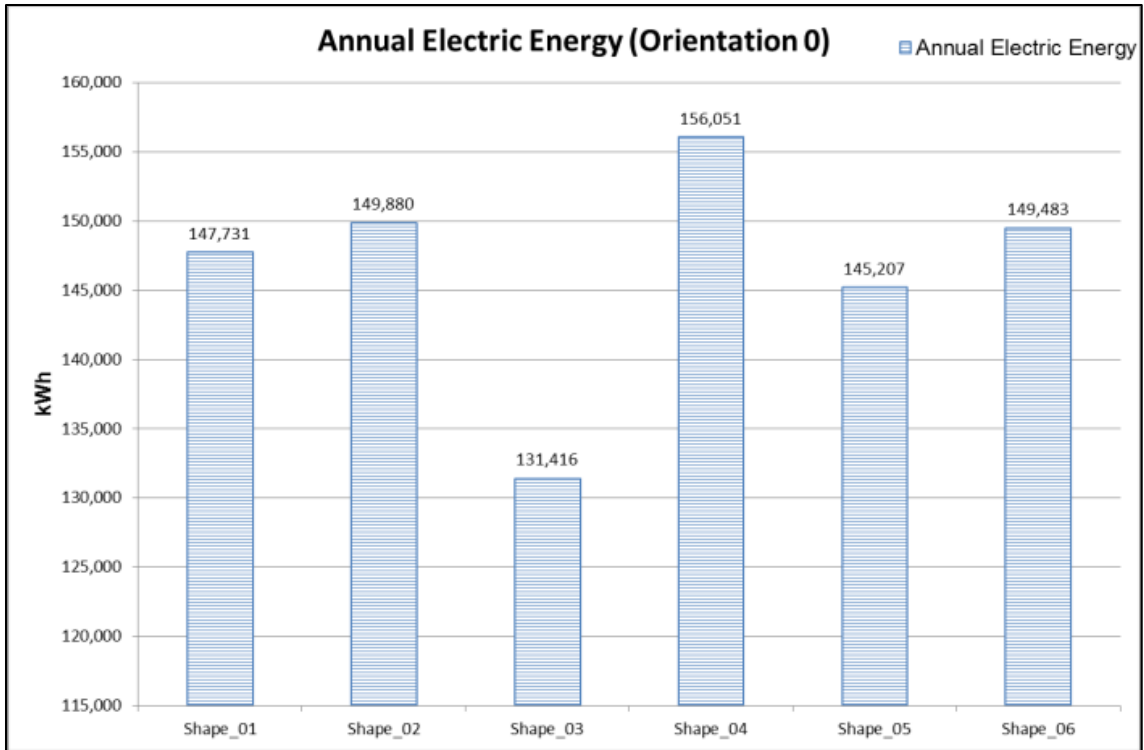
Figure 6 - Annual electricity consumption for each shape at the base run
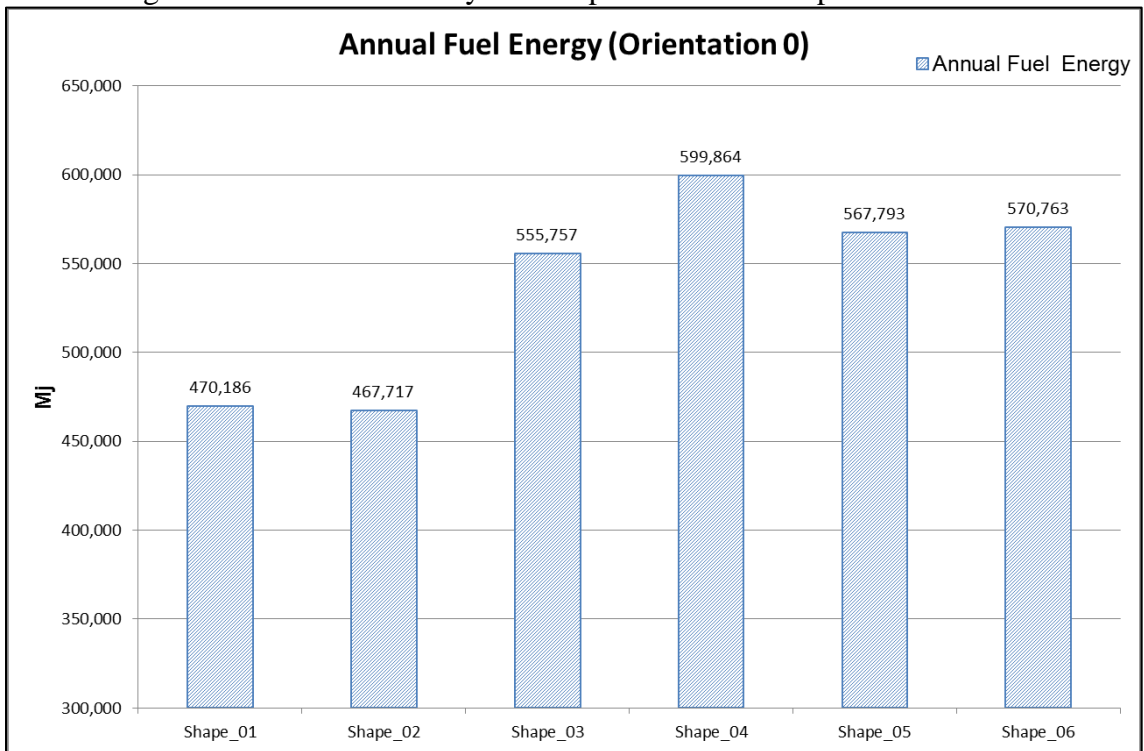
Figure 7 - Annual fuel consumption for each shape at the base run
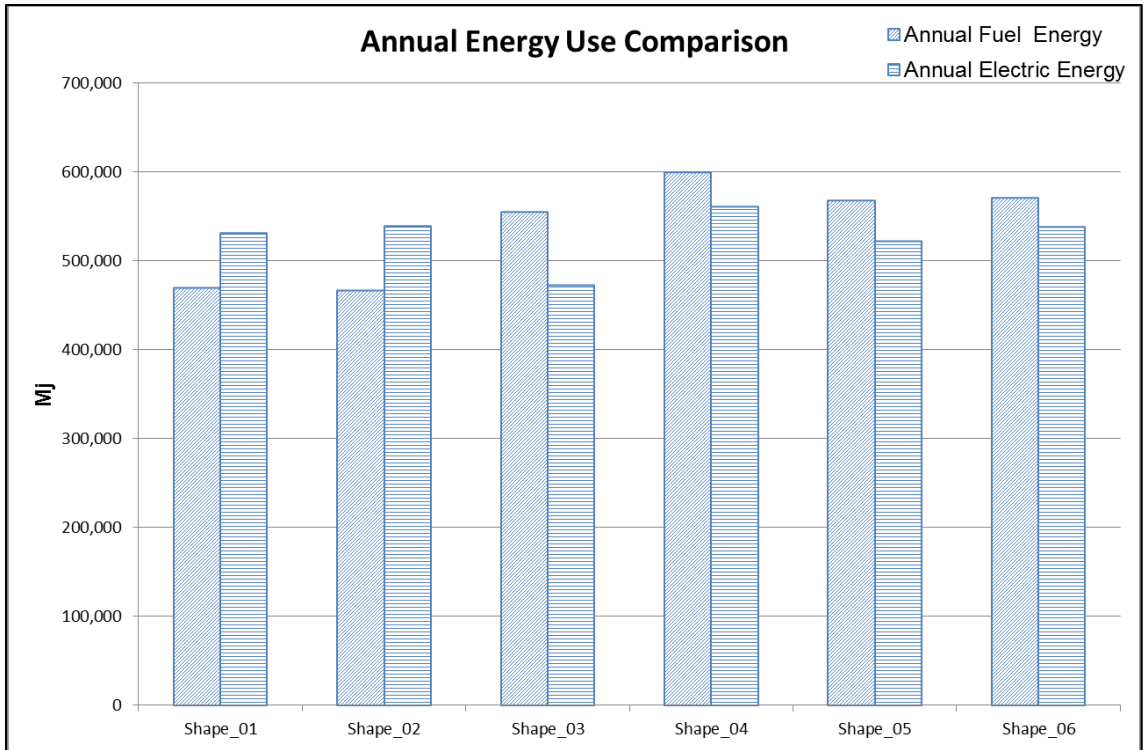
Figure 8 – Comparison of annual electric and fuel use for each shape at the base run

The effect of building orientation for each building shape was introduced, and the effect of building orientation on the optimized building shape was further explored. In addition, the typical results output for each alternative were presented for the EUI, annual electric energy, and annual fuel consumption. Figure 9 shows the EUI for each building shape at alternative orientations. Building orientation_0 represents the base run. There was consistency in ranking between all these findings for alternative orientations and the results of the base run EUI values. The collocation of each building shape EUI for the base run was the same for the alternative building orientations. While all the building shapes' EUI was within a tighter range (850 MJ/m^2/year to 950 MJ/m^2/year), only the EUI of Shape-04 for all orientation alternatives was over 1,000 MJ/m^2/year. Although the EUI of Shape-01, Shape-02, and Shape-03 increased for the building orientations 135°

and 180°, the EUI of the Shape-05 and Shape-06 decreased for the same orientations. In addition, the EUI of Shape-06 was 7.81% higher than the EUI of the Shape-03 for the base run and only 0.88% higher for the building orientation of 135°. The mean EUI calculated from the 48 values for the alternative orientations of the all the building shapes was 918 MJ/m^2/year. While the three building shapes Shape-01, Shape-02, and Shape-03 EUI values for all orientations were lower than the mean value, the other three building shapes Shape-04, Shape-05, and Shape-06 EUI values were higher than the mean value for all alternative building orientations. The lowest EUI was calculated for Shape-01 at the base run and the 45° orientation. On the other hand, Shape-04 had the highest EUI for the base run, 270°, and 315° orientations. The maximum EUI calculated was approximately 20% higher than the minimum, and this significant difference directly impacts the life cycle cost of the buildings.
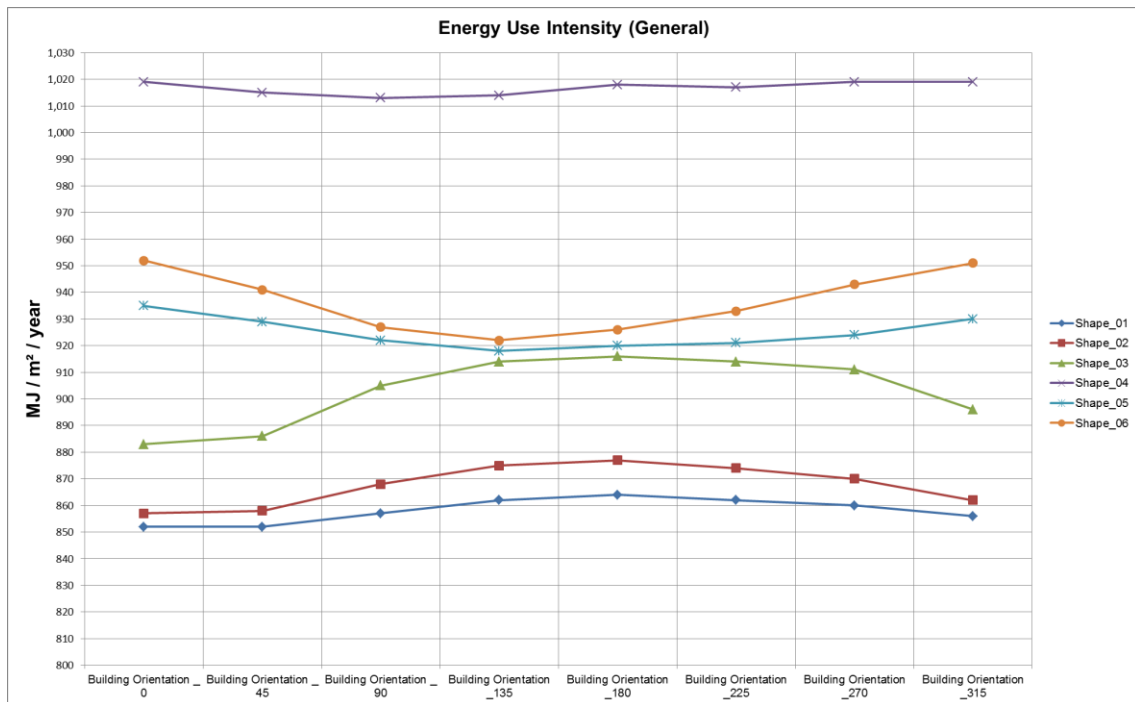
Figure 9 - EUI for each shape and orientation

To better illustrate the difference in the energy consumption variations between the alternative building orientations, Figure 10 compares the annual electric consumption and annual fuel consumption for each building shape. Shape-02, Shape-03, Shape-05, and Shape-06 illustrate same curve change for the electric and fuel consumptions of the alternative building orientations. The curve changes at Shape-01 and Shape-04 are significantly different for the electric and fuel consumptions. Shape-05 and Shape-06 had the lowest electric and fuel consumptions at the 135° orientation. The maximum electric energy use was at the 135° orientation, and the maximum fuel energy use was at 180° for Shape-01.

Table 1 summarizes the average values for the building orientations of the six alternative building shapes. The lowest EUI, annual electric energy use, and annual fuel energy use was calculated for the 45° building orientation. The 270° building orientation had the maximum EUI and annual fuel energy use, whereas the maximum annual electric energy use was at the 315° building orientation. The averages calculated from the 48 values for the EUI, annual electric energy, and annual fuel energy are 918 MJ/m^2/year, 146,701 kWh, and 540, 442 Mj, respectively. The average values of the 135° building orientation had the proximate values with the average of all three energy consumption criteria.

Table 1 - Average values for building orientations of all shapes

Building Orientation	EUI (Mj/m²/year)	Annual Electric Energy (kWh)	Annual Fuel Energy (Mj)
Building Orientation _ 0	916	146,628	538,680
Building Orientation _ 45	914	146,408	536,375
Building Orientation _ 90	915	146,471	538,317
Building Orientation _135	918	146,633	540,383
Building Orientation _180	920	146,800	542,813
Building Orientation _225	920	146,852	542,789
Building Orientation _270	921	146,898	543,305
Building Orientation _315	919	146,917	540,874

	Lowest value
	Highest value
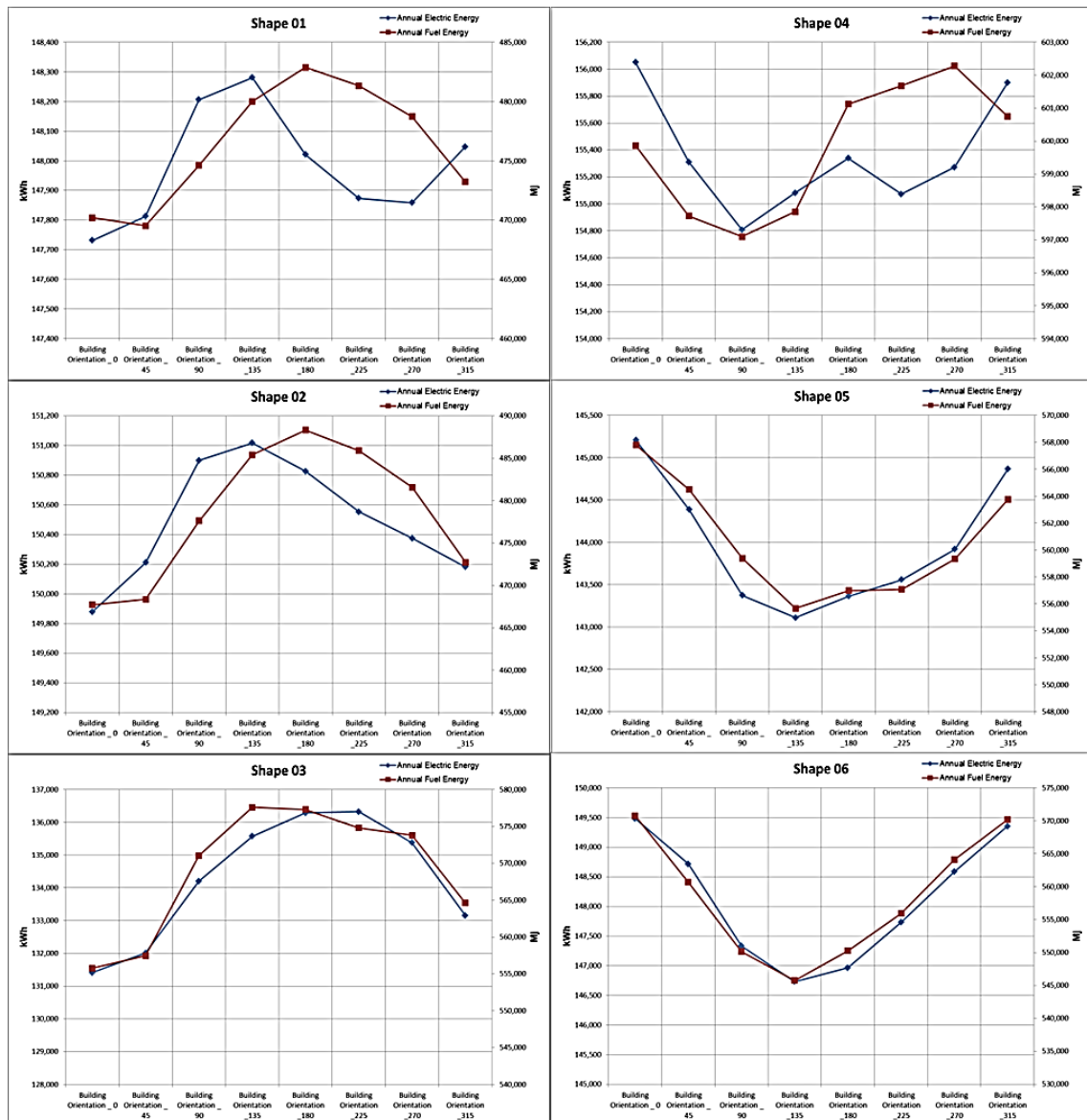
Figure 10 - Annual electric and fuel consumption for each shape and alternative orientation

Finally, the possibility and capability of using BIM and energy analysis software at the concept design stage to optimize the energy consumption was investigated. The BIM process provides opportunities to explore alternative solutions and analyze related buildings' energy consumption before undertaking the building development at the early

design stage. Energy analysis software with the BIM process gives designers and clients a general view of their projects and increases the probability of more energy-efficient designs. In addition, energy analysis software generates results faster compared to the traditional methods and could save substantial time and resources. However, despite these capabilities of using BIM and energy analysis software at the concept design stage, some limitations remain. First, the energy simulation software uses predefined HVAC templates and estimates a fixed level of occupancy. Modern buildings have complex HVAC systems that cannot be defined in the software, and the energy analysis software is not flexible in the modeling of HVAC systems. Occupants' behavior impacts the level of energy required, and the actual occupancy level may differ in each year of operation. Second, the building model must be developed up to a required standard in Revit prior to exporting to Green Building Studio. The software uses generic predefined values for the building elements that are not defined in the model, and the alternative template building elements are limited. Therefore, the energy simulation results are valuable for comparing the alternative solutions, but errors due to predefined element parameters are unpredictable. Third, the energy analysis results were calculated for annual or monthly energy consumption, and a detailed analysis for daily or hourly energy consumptions cannot be performed. Finally, the BIM authoring and energy analysis software of the same vendor has a smooth data sharing process, but the interoperability among various BIM applications presents a gap.

3.3 Discussion

It is possible to foresee the potential performance characteristics of building developments at the early design stage and plan more energy-efficient buildings. The BIM process and energy analysis software offer an opportunity to explore the energy consumption of alternative designs starting from the concept design stage. This study demonstrated that building shape and orientation impact a building's energy use and that the impact can be substantial. Autodesk Revit and Green Building Studio were used to model the buildings and perform an energy analysis based on alternative shapes and orientations. The building shape that improved the energy efficiency of a building was presented along with a comparison of the six building shapes' EUI, annual electric consumption, and annual fuel consumption. Similarly, the energy consumption for a building orientated on site was presented and the results were analyzed. The potential benefits and limitations of using the BIM process and energy analysis software at the early design stage were investigated.

4 Construction Progress Visualization for Varied Stages of the Individual Elements with BIM: A Case Study

Abstract

Building information modeling (BIM)is an intelligent 3D design and modeling process that gives architects, engineers, construction, and facility managers the ability and tools to plan, design, construct and manage buildings more effectively and efficiently. Currently, the construction progress is monitored by comparing the baseline project schedules, which include the planned dates and resources, with the actual dates in the updated schedules. 4D scheduling is used in the construction industry for linking individual model elements with the schedule activities to visualize the progress of construction activities. However, the limitation of this approach is a need for the creation of a dedicated activity for monitoring each model element, which can result in an excessive number of activities. This paper presents a construction progress visualization method, which uses a custom-developed add-in to present the status of building elements (e.g., planned, installed) without linking them with the schedule. The new tool enables a visual presentation of the progress of each element within the BIM model during different stages of the construction process to increase the decision-making capabilities. A case study is used to demonstrate the capabilities of the developed BIM add-in tool for construction progress visualization.

4.1 Description of Case Study Building

The case study is a data center building that is under construction in Turkey and aimed to be completed in 2019. The facility is constructed on 75,486 m² and includes 52,000 m² of data center space, 3,000 m² of conference space, 10,500 m² of underground carparks, and 34,000 m² of landscaping. Four floors of the data center building are selected as the case study to demonstrate the application of the developed add-in.

The main reason for selecting a data center building as a case study is its' unique requirement for monitoring of the construction progress. The data centers are value-added services that offer resources for processing and storing data on a large scale for organizations of any size. They have complex mechanical and electrical systems to operate 24 hours and seven days a week and are equipped with fire protection systems. Moreover, the data centers' electrical and mechanical services are tested by the international standards, whereas installation sequences need to follow the completion of commissioning. Also, the site inspections following the testing are the predecessor for the following installations and need to be monitored and recorded. While the visual representation of the completed installation, testing, and inspections present very valuable information for the data center construction, it also improves the construction planning.

4.2 Methodology

Autodesk Revit (Autodesk Inc. 2018b) was used as BIM authoring software since it is one of the most commonly used BIM authoring tools, according to the surveys conducted by the National Building Specification (NBS) for last three consecutive years (NBS 2016,

2017a, 2018). Additionally, the same software supplier provides other tools fully compatible with their BIM authoring software. The main goal of our approach is to develop a custom add-in for an element-based status tracking method that allows for updating multiple statuses at once. The used Autodesk Navisworks Manage 2018 comes with application programming interface (API) and software development kit (SDK). The add-in is developed in MS Visual Studio 2015 for Autodesk Navisworks Manage 2018. Moreover, Autodesk Navisworks Manage is used for visualizing, clash detection and 4D work schedule integration.

Each model element has specific parameters loaded from BIM authoring software, and their values are represented in the Properties tab after selecting the individual elements. These properties are grouped in different tabs based on the BIM authoring software used. It is possible to include progress data of each building element (e.g., statuses) by adding custom parameters and values. However, it is not possible to select multiple elements and add custom parameters to these elements at the same time. Consequently, since there are high numbers of elements in the project, updating the statuses of elements is a tedious process when performed by hand.

```
'COMAPI .net connect
        Dim nwState As Autodesk.Navisworks.Api.Interop.ComApi.InwOpState10
        nwState = Autodesk.Navisworks.Api.ComApi.ComApiBridge.State

        'create new Property Category Vector
        Dim newPvec As Autodesk.Navisworks.Api.Interop.ComApi.InwOaPropertyVec
        newPvec = nwState.ObjectFactory(Autodesk.Navisworks.Api.Interop.ComApi.nwEObjectType.eObjectType_nwOaPropertyVec)

        'propertycategory vector
        For Each row As DataRow In dtProperty.Rows
            'create new property
            Dim newP As Autodesk.Navisworks.Api.Interop.ComApi.InwOaProperty
            newP = nwState.ObjectFactory(Autodesk.Navisworks.Api.Interop.ComApi.nwEObjectType.eObjectType_nwOaProperty)

            'set name, username and value of the new property
            newP.name = row.Item("Property_Name")
            newP.UserName = row.Item("Property_Name")
            newP.value = row.Item("Property_Value")
            'add the new property to the new Property Category
            newPvec.Properties().Add(newP)

        Next
```

Figure 11 - Code for connection between .net and .comapi

The add-in is created using windows for the application template of MS Visual Studio with .net framework 4.5.2. Firstly, in the software, a connection is created between .net and .comapi for writing new parameters and their values to the elements (Figure 19). Next, the defined property category data is added to each selected model element and control operation is defined to prevent any duplicated information (Figure 20).

```vbnet
Dim oItem As Autodesk.Navisworks.Api.ModelItem
        Dim oDOC As Autodesk.Navisworks.Api.Document
        oDOC = Autodesk.Navisworks.Api.Application.ActiveDocument

        'add property category to each item selected
        For Each oItem In oDOC.CurrentSelection.SelectedItems
            'select path of the item
            Dim oItemPath As Autodesk.Navisworks.Api.Interop.ComApi.InwOaPath
            oItemPath = Autodesk.Navisworks.Api.ComApi.ComApiBridge.ToInwOaPath(oItem)
            'select Property Category from path
            Dim PropCat As Autodesk.Navisworks.Api.Interop.ComApi.InwGUIPropertyNode2
            PropCat = nwState.GetGUIPropertyNode(oItemPath, True)

            If CheckBox1.Checked = True Then
                Dim PropCatAtt As Autodesk.Navisworks.Api.Interop.ComApi.InwGUIAttribute2
                Dim checkAtt As Boolean = False
                For Each PropCatAtt In PropCat.GUIAttributes()
                    If PropCatAtt.ClassUserName = TextBox1.Text() Then
                        checkAtt = True
                        MsgBox("You Selected Existing Tab " & TextBox1.Text() & " to remain." & vbCrLf & "Please give a
unique TAB NAME to prevent duplicate data." & vbCrLf & vbCrLf & "Sample:  " & TextBox1.Text() & "_1",
MsgBoxStyle.OkOnly, "BIMCAVE")
                        TextBox1.Text = TextBox1.Text() & "_1"
                        Exit Sub
                    End If
                Next
                'if the PropertyCategory does not exist add it
                If Not checkAtt Then
                    PropCat.SetUserDefined(0, TextBox1.Text, TextBox1.Text, newPvec)
                End If
            End If

            If CheckBox2.Checked = True Then
                Dim PropCatAtt As Autodesk.Navisworks.Api.Interop.ComApi.InwGUIAttribute2
                Dim Index As Integer = 1
                For Each PropCatAtt In PropCat.GUIAttributes()
                    If Not PropCatAtt.UserDefined Then Continue For
                    If Not PropCatAtt.ClassUserName = TextBox1.Text() Then
                        Index += 1
                        Continue For
                    End If
                    PropCat.RemoveUserDefined(Index)
                    Exit For
                Next
                PropCat.SetUserDefined(0, TextBox1.Text, TextBox1.Text, newPvec)

            End If

        Next
        MsgBox("PROPERTIES LOADED UNDER NEW TAB :" & vbCrLf & TextBox1.Text, MsgBoxStyle.OkOnly, "BIMCAVE")
```

Figure 12 - Code for adding the property category data

The user can select multiple elements at the same time based on the status of each element (i.e., planned, installed, tested, and inspected). Elements can be selected manually from the model or by using find items in-built functionality of the Navisworks. Element selections can be saved for future references and used through search or selection sets. While the selection sets are used to store the selected elements, they do not refresh the selection. Instead, the search sets refresh the selected elements based on the defined criteria in each run. On the other hand, the individual element selection enabled to change the status of each element based on the progress at the site.

A custom tab name, parameter name, and parameter value can be defined using the Add-in for the selected elements. The workflow for loading custom parameters is aimed to be simple and user-friendly with three basic steps: (1) selecting elements, (2) specifying the parameter values, and (3) loading to the elements, as the user form illustrated in Figure 13. It is also possible by the software in-built functionalities to filter elements based on the custom parameters loaded as well as change the visual properties, such as making transparent or change color temporary. Appearance profiler built-in functionality of the Autodesk Navisworks software is used for changing the elements' visual properties based on the defined values of their parameter. In the case study, the following set up was used: transparent for the planned elements, green for the installed elements, blue for the tested elements, and red for the inspected elements.
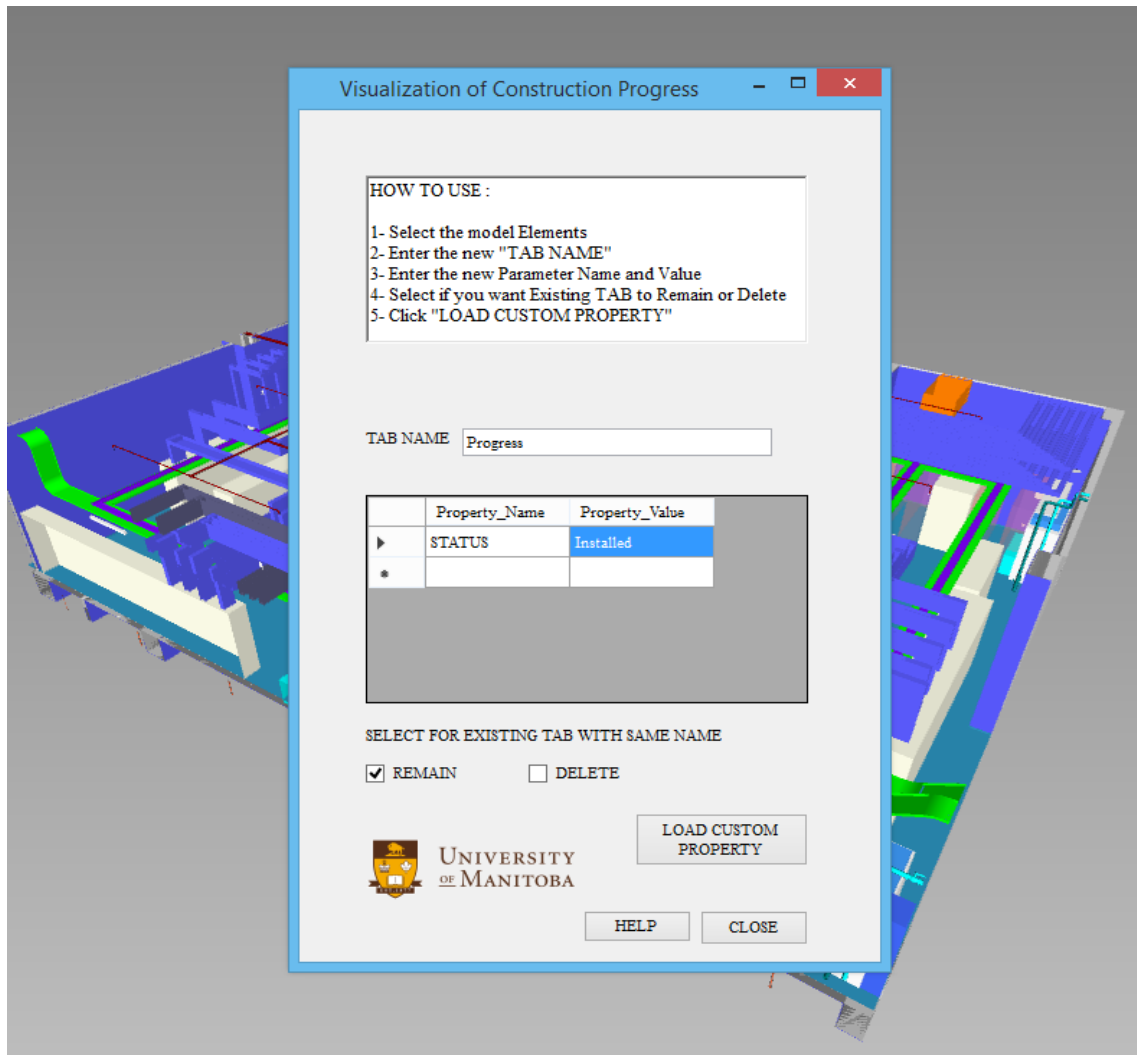
Figure 13 - Add-in user form view

Structural and architectural model elements are selected manually from the model, and progress status of the elements was entered into the model. Search sets used for loading the actual status to the elements are created for electrical and mechanical elements based on their installation, testing and inspection sequences. A sample room with a total area of 538 m2 was selected for visualizing the results of our approach using the developed add-in and in-built functionalities of Navisworks. In addition to structural and architectural elements, the sample room has 2,080 elements, including cable trays, bus bar system,

electrical equipment, sprinkler and ductwork for the ventilation, as presented in Table 2. The status of each element is loaded using the add-in for compliance with construction progress for six consecutive months.

Table 2 - Element type and quantities

Element Type	Element Quantity
Air Terminals	1
Cable Tray Fittings	234
Cable Trays	310
Ceilings	91
Data Devices	3
Doors	1
Duct Accessories	25
Duct Fittings	19
Ducts	72
Electrical Equipment	96
Electrical Fixtures	19
Fire Alarm Devices	105
Floors	8
Lighting Devices	3
Lighting Fixtures	69
Mechanical Equipment	5
Pipe Accessories	11
Pipe Fittings	212
Pipe Insulations	8
Pipes	156
Rooms	13
Security Devices	6
Sprinklers	49
Structural Columns	14
Structural Framing	67
Walls	483
Total	2080

4.3 Results

The work schedule used for this project has 1,855 activities, including contractual, design, and construction activities. The construction phase only includes the installation activities, whereas the hand-written daily reports monitor the status of tested or inspected elements. It is a common practice to define the installation activities of the work schedules based on floor, system or zone. Consequently, the monitoring for individual elements is not possible with the existing work schedule breakdown. Besides, the project has 131,952 model elements that need to be monitored. As a result, a large number of building elements prevent the creation of the individual activities for each element, and the installation progress monitoring is limited with the activities defined in the work schedule. Table 3 presents a summary of the status change of the model elements for six months. Furthermore, Figure 22 presents the visualization of the monthly status change of model elements. The model elements that are monitored using this approach can also be more specific. For example, the hanger and support of the piping systems can also be monitored. This level of detailed information provides the decision-makers with a higher level of understanding of the progress at the site.

Table 3 - Status of model elements for six months

Model Elements	Months					
	1	2	3	4	5	6
Structural System	Installed	Installed	Installed	Installed	Installed	Installed
Cable Trays	Planned	Installed	Tested	Inspected	Inspected	Inspected
1,000A Busbar	Planned	Planned	Installed	Installed	Tested	Inspected
3,000A Busbar	Planned	Planned	Installed	Installed	Tested	Inspected
4,000A Busbar	Planned	Planned	Planned	Installed	Installed	Inspected
5,000A Busbar	Planned	Planned	Planned	Installed	Installed	Inspected
Sprinkler system	Planned	Planned	Planned	Planned	Installed	Tested
HVAC system	Planned	Planned	Planned	Planned	Planned	Tested
Main Equipment	Planned	Planned	Planned	Planned	Planned	Installed

During the construction phase, the progress data is collected using 2D drawings, daily reports, site photographs (e.g., laser scanning). In the 4D process, all this data for individual elements collected from the site is not effectively used. The progress is only represented if it is related to a dedicated activity in the schedule. Therefore, the data

available for individual elements are not used for visualizing the construction progress. Instead, only the progress based on the activity definitions can be visualized. The results of the proposed approach show that it is possible to visualize the construction progress data based on each element.

The visualization of the case study results shows different status of the elements in a 3D environment. The two main advantages of the developed approach are: (1) it allows the selection of individual model elements and loading data to these elements, and (2) it supports the selection of the model's elements from different systems and monitoring progress status of each element. In our case study, we defined two additional status 'tested' and 'inspected.' On the other hand, the use of the 4D scheduling method would require the creation of the additional 263,904 activities next to the existing installation activities.

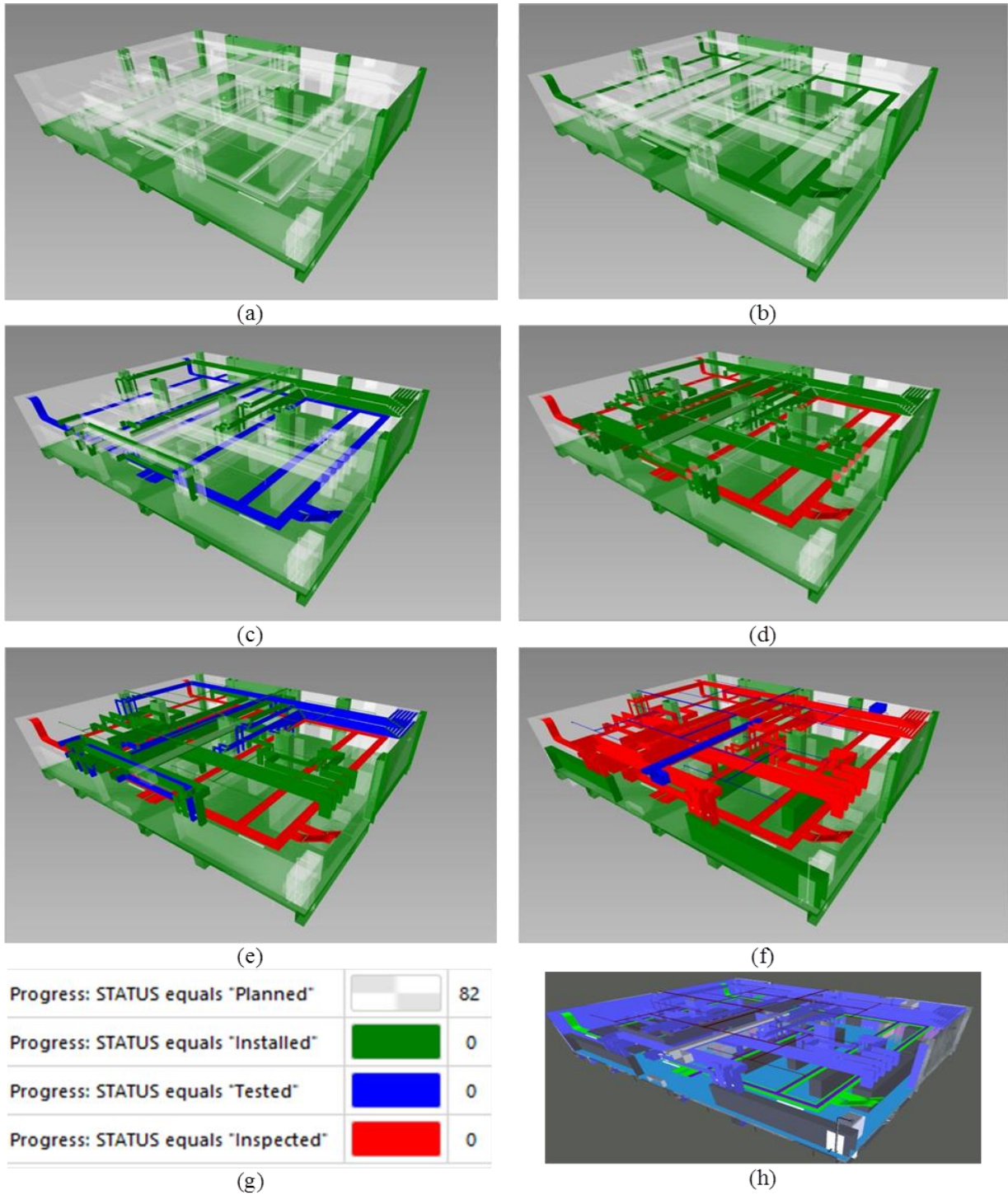| Progress: STATUS equals "Planned" | ⬜ | 82 |
Progress: STATUS equals "Installed"	🟩	0
Progress: STATUS equals "Tested"	🟦	0
Progress: STATUS equals "Inspected"	🟥	0

Figure 14 - Visualization of 6 months progress: (a) first month progress; (b) second month progress; (c) third month progress; (d) fourth month progress; (e) fifth month progress; (f) sixth month progress; (g) color coding for status; (h) 3D model of the case study room

4.4 Discussion

In the common practice, visualization of the 4D process is limited with the activities defined within the construction schedules, and it is not possible to define the activity of each element status. This paper proposes a new add-in method for visualization of the status progress of the building elements (e.g., inspected, tested) within the BIM models. The add-in is developed in Navisworks, and it enables project monitoring based on the individual elements. The effectiveness of the developed method is tested using the complex data-center building as a case study. A sample room with a large number of elements is selected to present the monthly construction progress visualization over the six months. The results show that it is possible to successfully monitor construction progress based on the individual elements in the model. This approach increases the planning ability of decision-makers and allows easier foreseeing of the potential problems.

One of the limitations of our approach is the requirement of Navisworks software. However, Navisworks is a widely used tool in the construction industry, and it comes with other Autodesk products. Another limitation of the proposed approach is that the construction progress is monitored based on the elements that do not have any relation with the construction schedules (e.g., actual dates). While the primary goal of this paper is to propose the new method for visualization of the construction progress based on the model elements, separate parameters within the developed add-in can be used to load actual dates for the elements.

The future work will include the expansion of the proposed method to allow instant data integration with handheld devices, which can be used for updating the element parameter values. Furthermore, further integration will be developed - using the unique ID of model elements and work breakdown structure codes of schedules- between construction schedule software and proposed method for updating the actual schedule data from the add-in. Future work will include adding additional parameters such as the actual dates, related entity names, and reference document links to the individual elements. This approach will enhance the visualizations of the construction progress and create a valuable database for the project handover and facility management.

5 Integrating Building Information Modeling (BIM) and Sensor Technology for Facility Management

Abstract

Today high-performance buildings are equipped with sophisticated monitoring systems and sensors for collecting large amounts of data related to the buildings' indoor environmental quality and energy consumption. To visualize, interpret, and utilize the collected data, facility managers and decision-makers typically use text or spreadsheets, which make it difficult to understand and track the real-time building's performance. Building information modeling (BIM) is a process of developing a virtual equivalent of the actual building that supports data exchange, management, and communication during the whole building's life cycle. However, the BIM model cannot show real-time information related to the performance of the building in the operational stage. This paper presents three approaches for integration of the building sensor technology and the BIM process to enable visualization and analysis of real-time and historical readings: (i) Sensor-Revit integration; (ii) Sensor-Revit-Navisworks integration; and (iii) Sensor-Revit-Navisworks-API integration. The comparison between the potential value-adding functions of each approach and the associated limitations is discussed.

Furthermore, this is the first work to utilize widely known and popular Autodesk Navisworks software for the development of a user-friendly add-in program to enable real-time and historic data characterization and analysis. The overarching aim of this paper is to improve the efficiency of facility management (FM) and utilize BIM data

accessible during building's lifecycle. The university engineering building equipped with a monitoring system for tracking and collecting various building-related parameters is used for demonstration of the developed software technologies. This study demonstrates how BIM-sensor integration can lead to more responsive building management and operation by making sensor data tangible and accessible for property managers, owners, and occupants.

5.1 Research Method

This paper presents and discusses three approaches for integrating, visualizing, and analyzing sensor technology data with the 3D model created within the BIM process: (i) Sensor-Revit integration; (ii) Sensor-Revit-Navisworks integration; and (iii) Sensor-Revit-Navisworks-API integration. Figure 15 shows the flowchart of the adopted research methodology and development of the three approaches. At the beginning of the research study, the two-dimensional (2D) as-built construction drawings and data collected on-site (e.g., sensors location, room numbers, and variations from as-built drawings) enabled development of the three-dimensional (3D) model of the existing university building.
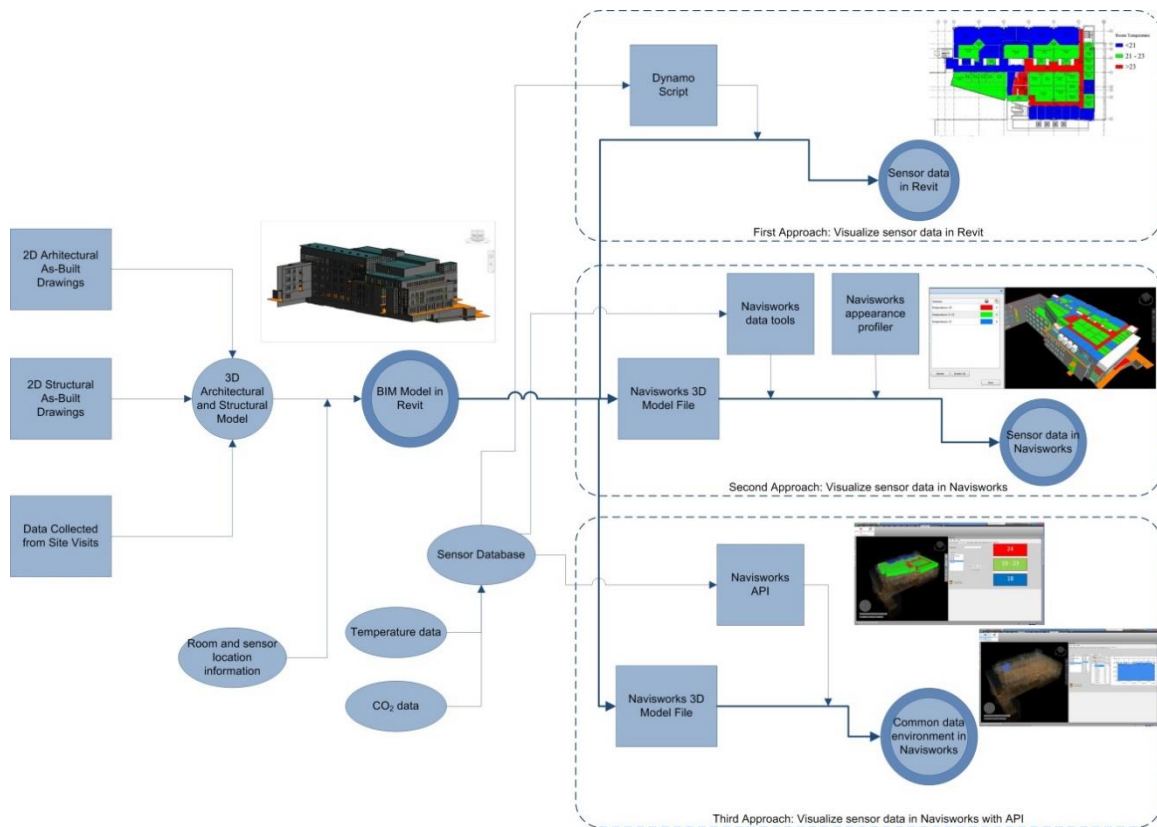
Figure 15 - Research methodology process map

There are different 3D modeling tools available today for creating a visual representation of the facilities. However, not all of them include information required for the development of the BIM process. In this research, Autodesk Revit software (Autodesk Inc. 2018b) was selected for the modeling of the case study building for two main reasons. First, Revit is well established and widely used BIM tool (Gerges et al. 2017). Second, Autodesk provides other tools that are fully compatible with Revit and can be used for the development of different add-ins. Figure 16 presents 3D Revit model of the university building. It is of essential importance to have a unique parameter available while connecting two different databases and in this study the room numbers are used for mapping the data from the sensors with the 3D model. The rooms are modeled based on

the drawings and existing building information, whereas each room was assigned with a room number based on the numbers used in facility management. The same room number data loaded to the sensors is used as the unique tag for integrating the data.

After that, three different approaches for creating a common data platform are developed. Visualization and a better understanding of the sensor data require color-coding. In the first approach, the readings from the room temperature and CO_2 sensors were integrated using Dynamo (Autodesk Inc. 2018c) software to the room elements within the Revit's model through the built-in functions of the software to enable real-time visualization of the data. In the second approach, the Revit model was imported into Autodesk Navisworks, which is one of the commonly used software for visualization of the extensive and detailed BIM data (Johansson et al., 2015). Additionally, the readings from the temperature and CO_2 sensors were integrated as parameter data in the room elements of the 3D Revit model using the "DataTools" function. Next, the "Appearance Profiler" function was used to develop colour-coding and represent the real-time profiles of the temperature and CO_2 in the three-dimensional environment. The final approach uses Visual Studio.Net platform and software development kits (SDK) for the construction of a new add-in that is compatible with a BIM software solution, Autodesk Navisworks (Kazado 2018). The new add-in provides real-time 3D representation of the temperature and CO_2 data of the selected room along with the historical trends and profiles for in-depth analysis and further interpretation.
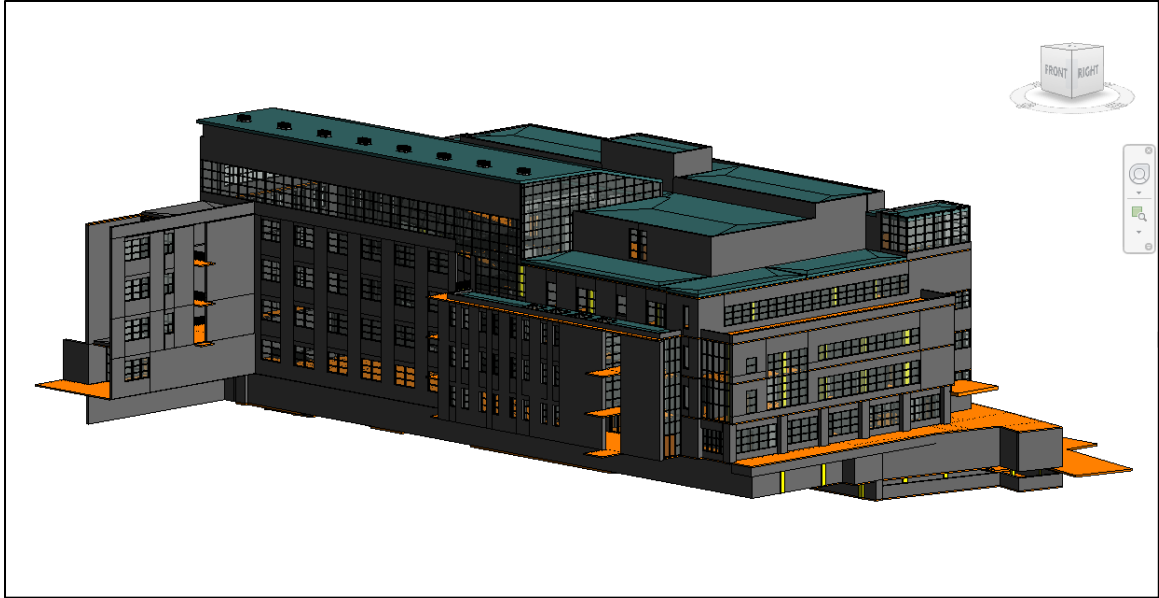
Figure 16 - General view of the 3D model in Revit

5.2 Description of the Building Used in the Case Studies

Engineering and Information Technology Complex (EITC) is located at the Fort Garry campus of the University of Manitoba, Winnipeg, Canada. As presented in Figure 17, the orientation of the EITC is 26° to the west of true north, and the engineering complex is composed of three buildings constructed in different periods, namely: EITC E1, EITC E2, and EITC E3. The first building E1 was constructed in 1931, and the southwest section E3 was constructed in 1967. The case study, E2 building, is the latest addition constructed in 2005. The total area of the building of 12.000 square meters spreads over five floors and comprises the northeast section of the engineering complex, thus linking the E1 and E3 building sections (see Figure 17). The E2 building accommodates various space types, including graduate areas, laboratories, fabrication spaces, and offices.

Figure 17 - The case study building

The E2 building was chosen for three main reasons. First, the building has advanced sensors that collect temperature and CO_2 parameters every 15 minutes for each space, and the collected data is stored in the university server. Consequently, both the real-time and the historic temperature and CO_2 readings of each room are available for display and analysis (see Figure 18). Second, the E2 building accommodates spaces that require maintenance of different indoor conditions due to the differences in their location (e.g., perimeter vs. core), orientation (e.g., south vs. north), usage (e.g., labs vs. classrooms) and occupancy rate (e.g., classrooms vs. offices), which can represent a significant challenge for the facility management. For example, the analysis of the temperature data

in the room E2-468 shows that nearly 10% of the time the room air temperature was below the set-point temperature range during the occupied hours and approximately 7% of the time it was above the set-point temperature range during the unoccupied hours (see Figure 19). Moreover, as presented in Figure 18 on several occasions the CO_2 levels were above the 700 parts per million (ppm) above outdoor air as recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1-2016 (ANSI/ASHRAE Standard 62.1-2016 2016).

Consequently, the E2 building offers significant potential for improvement of its energy performance and indoor environmental quality. Last but not least, the E2 building is equipped with modern heating, ventilation, and air-conditioning (HVAC) systems, which allow fine-tuning and control of the indoor environmental conditions. The fifth floor of the E2 building was selected for the demonstration of the developed software technologies. The selected floor contains a multitude of different rooms with a diverse array of purposes and varying functionalities that are representative of the majority of the spaces in the building as presented in Table 4. Additionally, the trended sensor data for each room of the floor was accessible at the time of this study, which enabled the visualization of the entire floor for the analysis. The open-source software is also able to accommodate and support the further development of custom visualizations that may be targeted for buildings, spaces, zones or individual mechanical systems serving areas following the needs of decision-makers.

Table 4 - Fifth floor room schedule

| Room Number	Room Name	Room Number	Room Name
E2 - 528	Heterogeneous Lab	E2 - 551	Cryptography Lab
E2 - 530	Comp. Discrete Math Lab	E2 - 553	Mobility
E2 - 532	Graphics Lab	E2 - 561	Comp. Finance Lab.
E2 - 534	Unassigned Docs Lab	E2 - 593	Large Machine Room
E2 - 568	Unassigned Docs Lab	E2 - 595	Large Workshop
E2 - 556A	Machine Room	E2 - 565	Unassigned Docs Lab
E2 - 510A	Machine Room	E2 - 583	Academic Office
E2 - 582	Academic Office	E2 - 585	Academic Office
E2 - 580	Academic Office	E2 - 586	Academic Office
E2 - 588	Academic Office	E2 - 584	Academic Office
E2 - 590	Tech Office	E2 - 578	Academic Office
E2 - 592	Tech Office	E2 - 576	Academic Office
E2 - 594	Tech Office	E2 - 574	Academic Office
E2 - 596	Tech Office	E2 - 572	Academic Office
E2 - 598	Tech Office	E2 - 571A	Vestibule
E2 - 599	Meeting Room	E2 - 571B	Vestibule
E2 - 510	Advanced Network Lab	E2 - 505	Grad Student Lounge
E2 - 520	Digital Documents Lab	E2 - 544cor	Corridor
E2 - 526	Unassigned Docs Lab	E2 - 549	Male Washroom
E2 - 556	Parallel & Distributed Systems Lab	E2 - 547	Female Washroom
E2 - 560	Unassigned Docs Lab	E2 - 573cor	Corridor
E2 - 564	Print Room	E2 - 579cor	Corridor
E2 - 554	Voice/Data	E2 - 557	Corridor
E2 - 524	Electrical	E2 - 558	Room
E2 - 508	HSKG	E2 - 527cor	Corridor
E2 - 509	PHD Office	E2 - 535cor	Corridor
E2 - 511	PHD Office	E2 - 531cor	Corridor
E2 - 513	PHD Office	E2 - 541cor	Corridor
E2 - 515	PHD Office	E2 - 525cor	Corridor
E2 - 545	PHD Office	E2 - 504	Robotics Lab
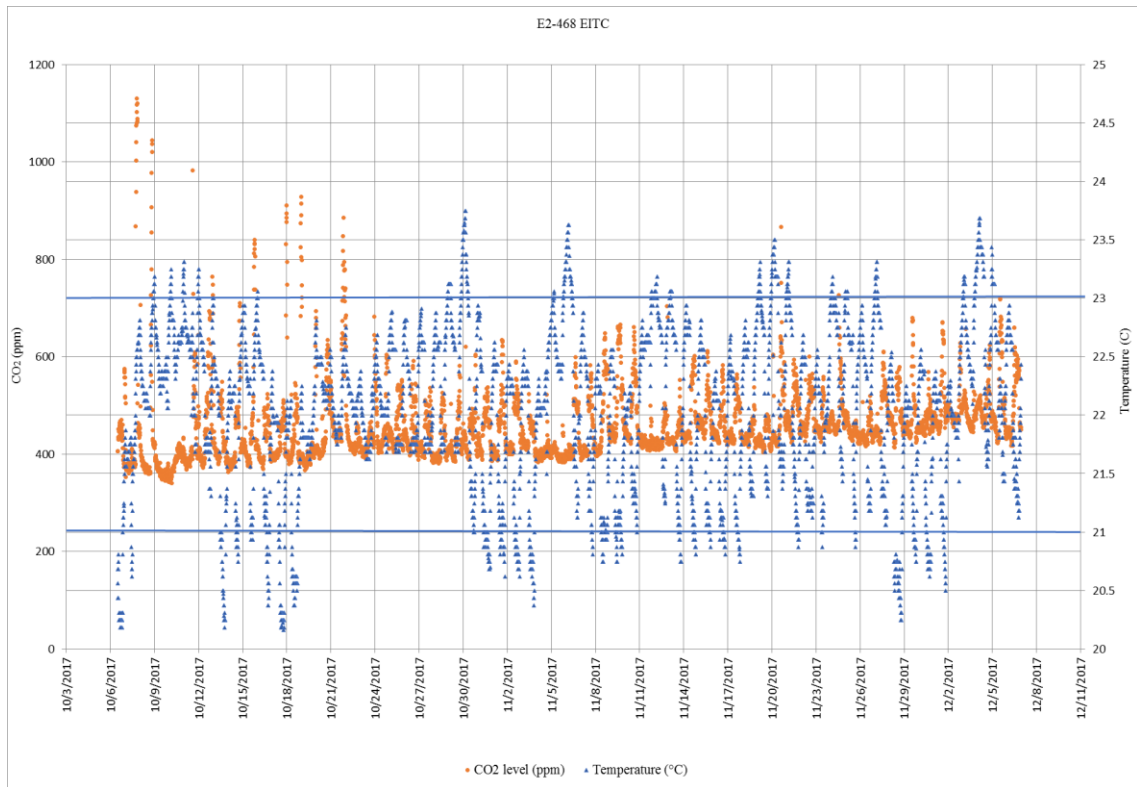
Figure 18 - Room E2-468 temperature and CO_2 data for two months
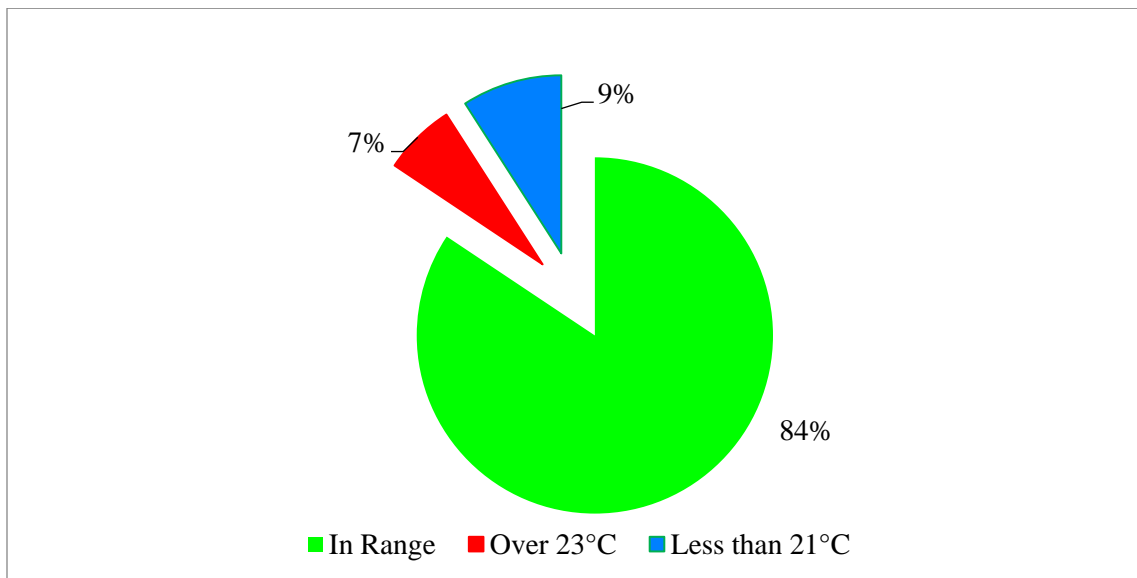

Figure 19 - Room E2-468 temperature data analysis for two months

5.3 Sensor – Revit Integration

In the first approach, the 3D Revit model is used to visualize temperature and CO_2 parameters collected by the building sensors. The 3D room element is created in the building model for the room boundary of each space with room number attribute, and this unique attribute is used for linking the model data with the sensors database. Two new attributes are generated in Revit software for temperature and CO_2 without value, and these attributes are loaded to room elements in the model.

Two Dynamo visual scripting interfaces are used as the link for importing the temperature, and CO_2 attributes value to the Revit model. In the first Dynamo script, Revit model room element attributes such as unique room number, temperature, CO_2, and element ID are exported and a database template is created in Microsoft Excel. Next, temperature and CO_2 values are inserted to the attributes in the template, and the room number attribute is used for the unique key for mapping. In the second Dynamo script, temperature and CO_2 parameters with values are imported to Revit software, and room elements are made visible in 2D view for visualizing the temperature and CO_2 parameter values.

"Color fill" functionality of Revit software is applied to describe the color schemes for model elements using their parameter values. The fifth floor was used to demonstrate a developed application for visualizing the temperature and CO_2 parameter values that were previously loaded to the room elements. As presented in Figure 20, different colors are utilized for defining specific temperature ranges (e.g., below 21ºC, between 21ºC and 23ºC, and above 23ºC). Furthermore, as illustrated in Figure 21, a similar approach is

applied for the color-coding of the CO_2 levels (e.g., below 400ppm, between 400 and 600ppm, and over 600ppm).

Figure 20 - Visualize temperature sensor data in Revit

Figure 21 - Visualize CO_2 sensor data in Revit

Integration of the Revit model and sensor data through Dynamo is an easy and straightforward approach that can provide building managers with the real-time information about the indoor air temperature level and CO_2 concentration within the space of interest. However, there are several limitations related to this approach. First, data can be only visualized within the two-dimensional environment, which makes it difficult to perceive the areas surrounding the space of interest. Second, this type of integration does not allow visualization of the historical data, which hinders understanding of the parameters' trends and development of the mitigation strategies. Third, since Revit is editing software, the direct integration of the Revit model allows changes to the models' design, and as a result, there is a high probability that the user unintentionally deletes or alters some elements within the model. Fourth, similar to other BIM-based authoring tools, Revit lacks full access and seamless integration with other BIM software vendors such as ArchiCAD (GRAPHISOFT 2018), Nemetschek Allplan (Nemetschek 2018), AECOsim (BENTLEY SYSTEMS 2018), and Rhino (McNeel North America 2018). Final, Revit operates slowly with large files (e.g., for 16Gbyte of RAM the file size shall be below 500Mbyte), which is an essential constraint in visualizing extensive facilities such as university campuses with multiple buildings (Hewlett-Packard Development Company 2014).

5.4 Sensor – Revit – Navisworks Integration

The second method included the integration of the sensors data and the Revit model using the functions of Autodesk Navisworks Manage software such as visualization, database connectivity, and appearance profiler. Three antecedent steps had to be undertaken within

Revit software in order to implement this method. First, two new shared parameters were created for temperature and CO_2 levels. Second, these parameters were loaded to all room elements in the Revit model. Final, Revit models were exported and saved as the cache files (NWC file). These NWC files were appended to the software and were saved as a read-only document file (NWD file).

"DataTools," which is the function of Autodesk Navisworks software, is used to create and manage links between model file and the sensor database with temperature and CO_2 data for each room. The utilization of the "DataTools" function is a recommended method for adding external bulk data (Wetzel and Thabet 2018). Open database connectivity (ODBC) driver was used within the "DataTools" function to access the sensor database. Standard query language (SQL) string is created for the integration of the model room elements in the software and the sensor database. Figure 22 illustrates an example implementation of the query with the SQL statement.
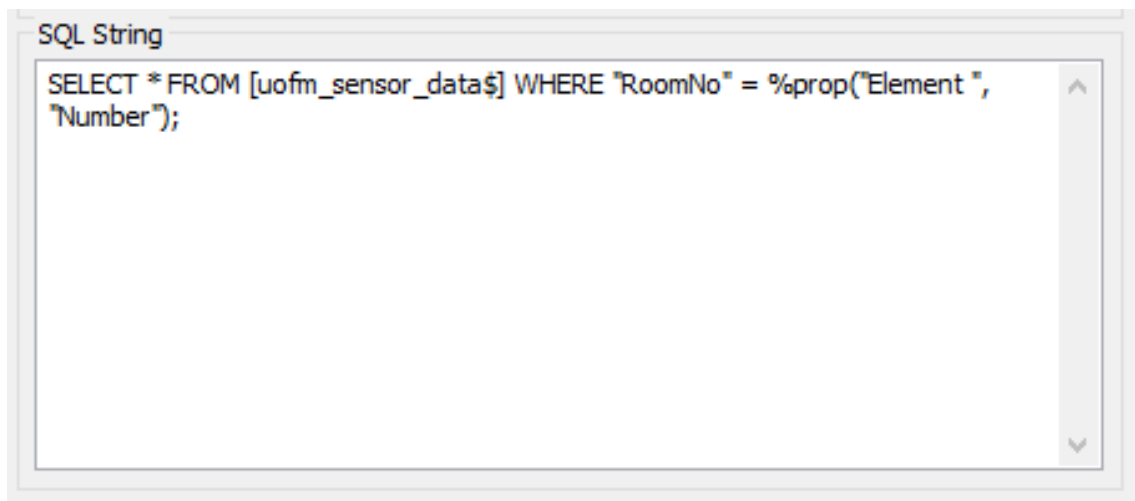


```
SQL String
SELECT * FROM [uofm_sensor_data$] WHERE "RoomNo" = %prop("Element ",
"Number");
```

Figure 22 - SQL-string for "DataTools" function

The "Appearance Profiler," which is the function of Navisworks, was used for defining the custom appearance profiles based on the elements' property values as well as for the color-coding of the objects. The fifth level of the case study building is used for the visualization of the applied color-coding of the sensor data ranges. As illustrated in Figure 23, different color schemes are assigned to the ranges of temperature parameter values: less than 21ºC, between 21ºC and 23ºC, and over 23ºC. Additionally, as shown in Figure 24, different color coding schemes are used to visualize CO_2 concentrations grouped in three categories: under 400ppm, between 400-600ppm, and over 600ppm.
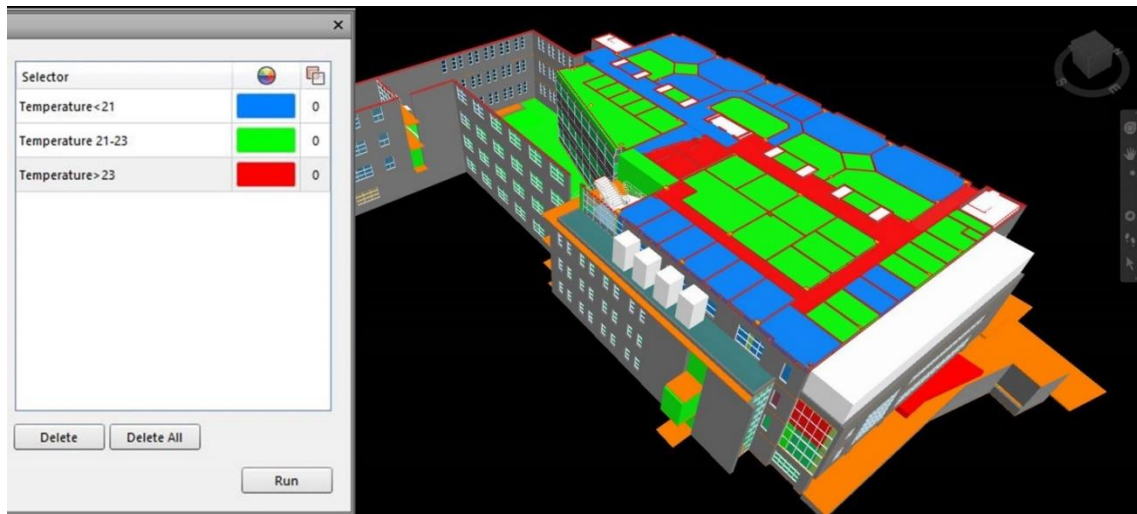
Figure 23 - Visualize temperature sensor data in Navisworks
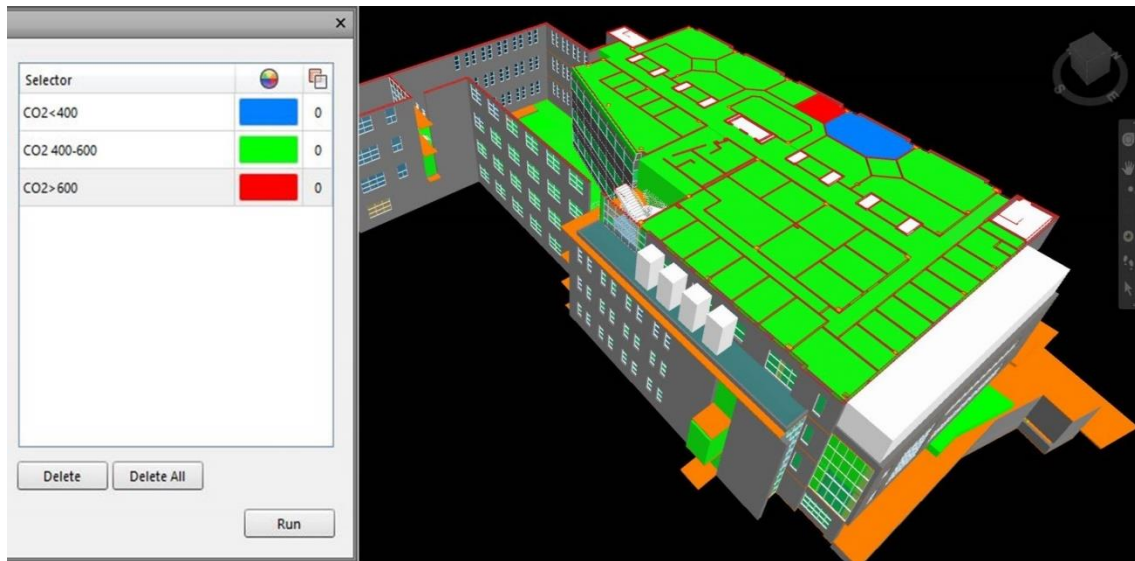
Figure 24 - Visualize CO_2 sensor data in Navisworks

Integration of the Revit model and sensor data through the functions of Autodesk Navisworks Manage allowed real-time 3D visualization of the parameters that cannot be edited by building managers and can be used to rapidly identify problematic areas and instantaneous reactions.

Furthermore, this approach does not have limitations related to the model size and can be used to visualize large models of complex individual buildings or groups of buildings. Moreover, the models created by other BIM software vendors such as ArchiCAD, GRAPHISOFT, Nemetschek Allplan, AECOsim, and Rhino can be visualized in the software. Nevertheless, the main limitation of this approach is the lack of historical data which similarly to the previous approach limits understanding about the long-term behavior of the indoor environment and therefore prevents the development of adequate mitigation measures and strategies.

5.5 Sensor – Revit – Navisworks - API Integration

The third approach involved development of the new add-in for Navisworks with four additional functions designed for facility management, including: (a) general information about model; (b) search assets of the facility in 3D environment; (c) visualization of the temperature and CO_2 data of the selected level; and (d) graphical representation of the historical sensor data of a selected room for a specified time period. The add-in is developed in Microsoft Visual Studio 2015 software for Autodesk Navisworks Manage 2018 (Autodesk Inc. 2018a) using .net application programming interface (.net API). Furthermore, object linking and embedding database (OLeDB) connection that allows importing of the data from a variety of sources in a uniform manner is used for reading the sensor data from the database. It should also be noted that this approach can be used to connect any other database that contains sensor readings. A small section for the database connection of the developed add-in script is presented in Figure 25, whereas the full script can be downloaded from the Mendeley Data (Kazado 2018).

```vb
        Dim oDoc As Document
        oDoc =
Autodesk.Navisworks.Api.Application.ActiveDocument
        Dim PropertyValue As String = "Rooms"
        Dim propertyValue1 As String =
ListBox8.SelectedItem.ToString()
        Dim s2 As New Search()
        s2.PruneBelowMatch = False
        s2.SearchConditions.Clear()
        s2.Selection.SelectAll()
s2.SearchConditions.Add(SearchCondition.HasPropert
yByDisplayName("Element", "Category") _
.EqualValue(VariantData.FromDisplayString(Property
Value)))
s2.SearchConditions.Add(SearchCondition.HasPropert
yByDisplayName("Item", "Layer") _
.EqualValue(VariantData.FromDisplayString(property
Value1)))
        Dim MySearchResult1 As New
ModelItemCollection()
        MySearchResult1.Clear()
        MySearchResult1.CopyFrom(s2.FindAll(oDoc,
True))

        'Connect Database
        Dim MyConnection As
System.Data.OleDb.OleDbConnection
        Dim DtSet As System.Data.DataSet
        Dim MyCommand As
System.Data.OleDb.OleDbDataAdapter
        MyConnection = New
System.Data.OleDb.OleDbConnection _
        ("provider=Microsoft.ACE.OLEDB.12.0;Data
Source= C:\Users\Daniel\Desktop\Stanley Pauley
Engineering Bldg\__Sensor API\Data.xlsx; Extended
Properties=Excel 12.0;")
        MyCommand = New
System.Data.OleDb.OleDbDataAdapter _
            ("select * from [Sheet1$]",
MyConnection)
        MyCommand.TableMappings.Add("Table",
"TestTable")
        DtSet = New System.Data.DataSet
        MyCommand.Fill(DtSet)


        'Read data from database and color
        Dim oItem As ModelItem
        Dim RoomNo As String
        Dim DateData1 As DateTime =
DateTimePicker3.Value
        Dim DateData As String =
String.Format("'{0}'", DateData1)
        Dim Temperature As String
        Dim items As New ModelItemCollection
        Dim row As DataRow = DtSet.Tables(0).Rows(70)
        oDoc.CurrentSelection.Clear()
        Dim newcolorBLUE As
Autodesk.Navisworks.Api.Color = Color.FromByteRGB(0,
0, 255)
        Dim newcolorGREEN As
Autodesk.Navisworks.Api.Color = Color.FromByteRGB(0,
255, 0)
        Dim newcolorRED As
Autodesk.Navisworks.Api.Color =
Color.FromByteRGB(255, 0, 0)
        Dim search As New Search()
        For Each oItem In MySearchResult1
            RoomNo =
oItem.PropertyCategories.FindPropertyByDisplayName("E
lement", "Number").Value.ToDisplayString
            Temperature = row.Item(RoomNo).ToString()
            search.Selection.SelectAll()
search.SearchConditions.Add(SearchCondition.HasProper
tyByDisplayName("Element",
"Number").DisplayStringContains(RoomNo))
            items = search.FindAll(oDoc, False)
            oDoc.CurrentSelection.CopyFrom(items)
oDoc.Models.OverrideTemporaryTransparency(items,
TextBox6.Text)
            If Temperature < "21" Then
oDoc.Models.OverridePermanentColor(items,
newcolorBLUE)
            ElseIf Temperature > "23" Then
oDoc.Models.OverridePermanentColor(items,
newcolorRED)
            Else
oDoc.Models.OverridePermanentColor(items,
newcolorGREEN)
            End If
            items.Clear()
            oDoc.CurrentSelection.Clear()
            search.Clear()
        Next
```

Figure 25 - Representation of the database connection

Additional information about the facility may greatly benefit the operators. For example,

general information about the building, such as the building's name, the total number of

assets, the total number of rooms, and the 2D view of the selected level can be useful for

building managers, and in particular for new staff. Therefore, separate tabs are created in

the add-in to present brief information about the selected building and floor level. Figure

26 illustrates this capability of the developed add-in. Furthermore, one of the main

challenges in the facility management process is to find a specific asset from the

thousands of assets that exist in a complex building. Therefore, the search asset tab is developed in the add-in to allow finding and visualizing of the specific asset in the 3D environment as well as to provide information about the total quantity of the existing assets. The search of the asset can be performed based on the three hierarchical properties of a model element, such as category (e.g., doors), type (e.g., M-Single-Flush), and assets properties (e.g., 1100x2134mm). Figure 27 shows an example of the applied approach.
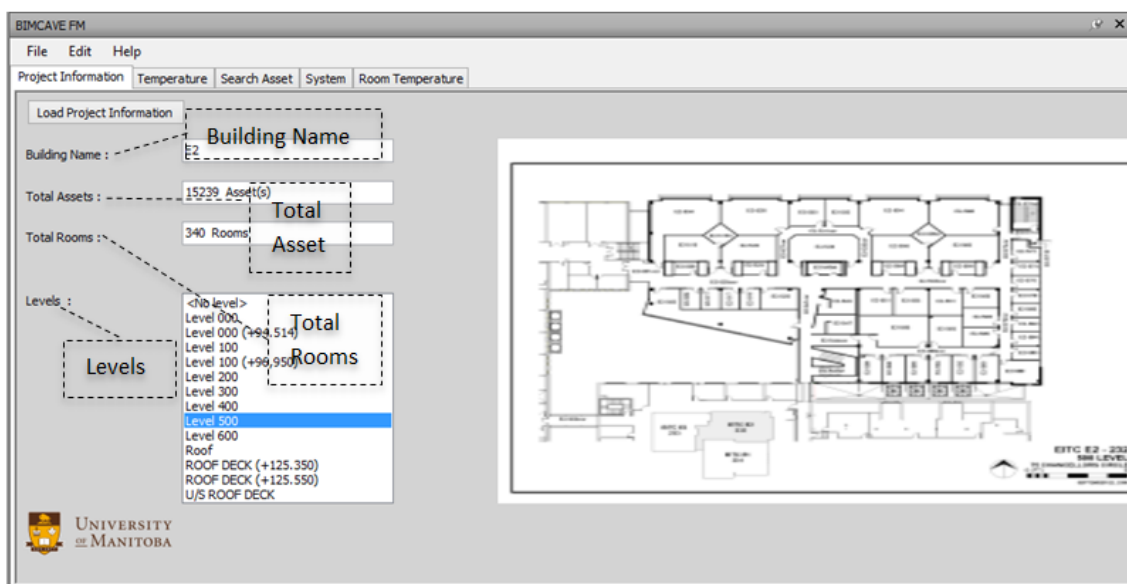

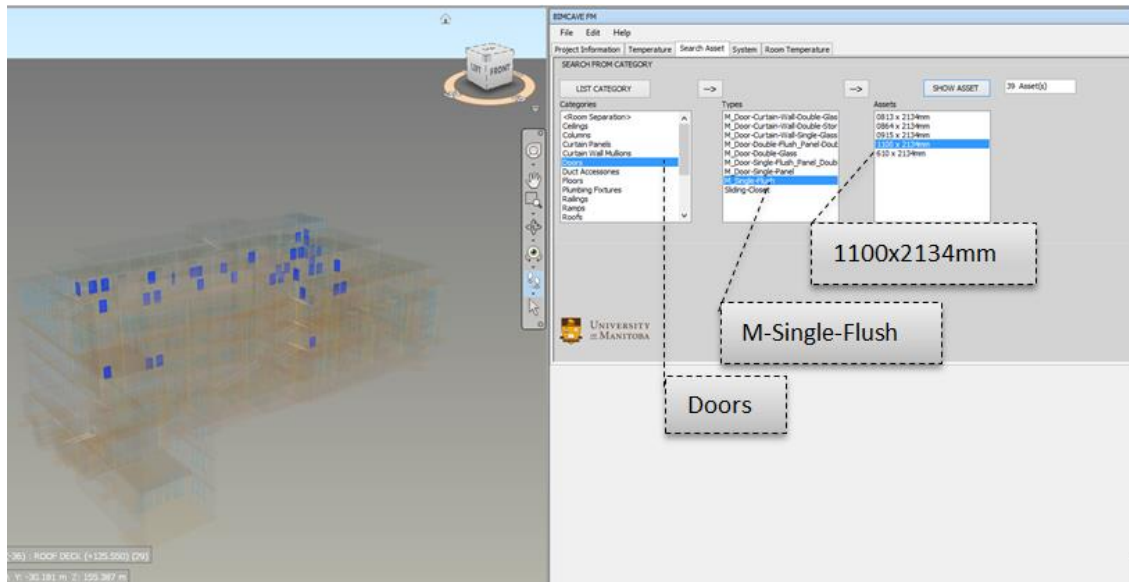Figure 26 - Project information sample

Figure 27 - Search asset function result for selected door type

The 15 minutes interval temperature and CO_2 readings are first collected through existing sensors from each room within the building. Thereafter, the readings are used to create a unique database in the Microsoft Excel platform, which is stored on the university server. Additionally, a separate Excel database that contains average daily temperatures calculated from the sensor readings during the three months is also developed and saved on the university server. Room numbers are used as the linking tool for the integration of a sensor database and model elements. Considering that the room numbers data need to be unique and are case sensitive, a quality control process is performed to ensure their uniformity.

The database containing average daily temperatures is used for 3D visualization of each room's temperature at the selected date. In the add-in, color-coding is defined for the room temperatures and similar to the previous, blue is applied for the temperatures that were below 21ºC, green is used for temperatures that were between 21ºC to 23ºC, and red

is specified for the temperatures that were above 23ºC. After that, the add-in is used through the OLeDB connection to read the temperature data from the database for each room element in the model at the selected date. Last, to create better insights and visual presentation, the appearance of the model element is adjusted based on the pre-defined color codes, whereas all other elements are changed to transparent mode. Figure 28 shows the visual representation of the implemented approach on the example of the fifth floor. The color-coding was also applied to the daily average CO_2 concentration database, and blue is assigned to concentrations below 400ppm, green for concentrations between 400ppm and 600ppm, whereas red color is selected for concentrations above 600ppm (see Figure 29).

It should be noted that the temperature and CO_2 sensor data readings are not permanently stored in the model elements property. Instead, an instant reading is performed, and the appearance of the model elements is adjusted temporarily based on the temperature and CO_2 level data. Therefore, in every run of the add-in, a new connection is generated with the database and appearance of model elements revised following the updated temperature and CO_2 level data. This approach provides flexibility to integrate with live sensor databases and instantly update the appearance of model elements with latest available sensor data.
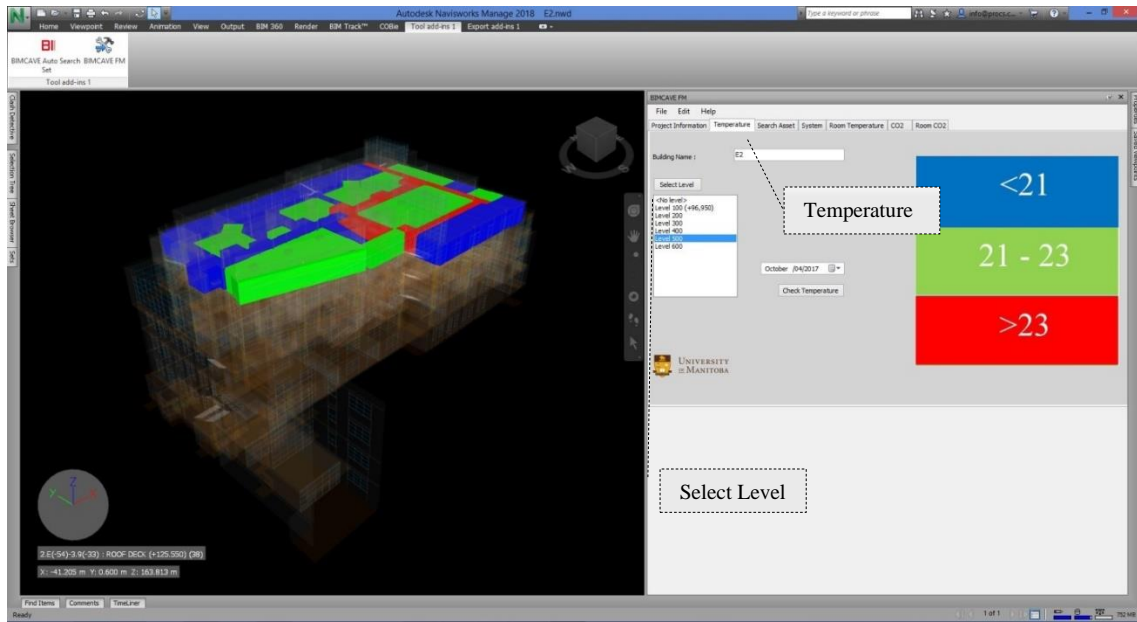
Figure 28 - Sample temperature data for the fifth floor
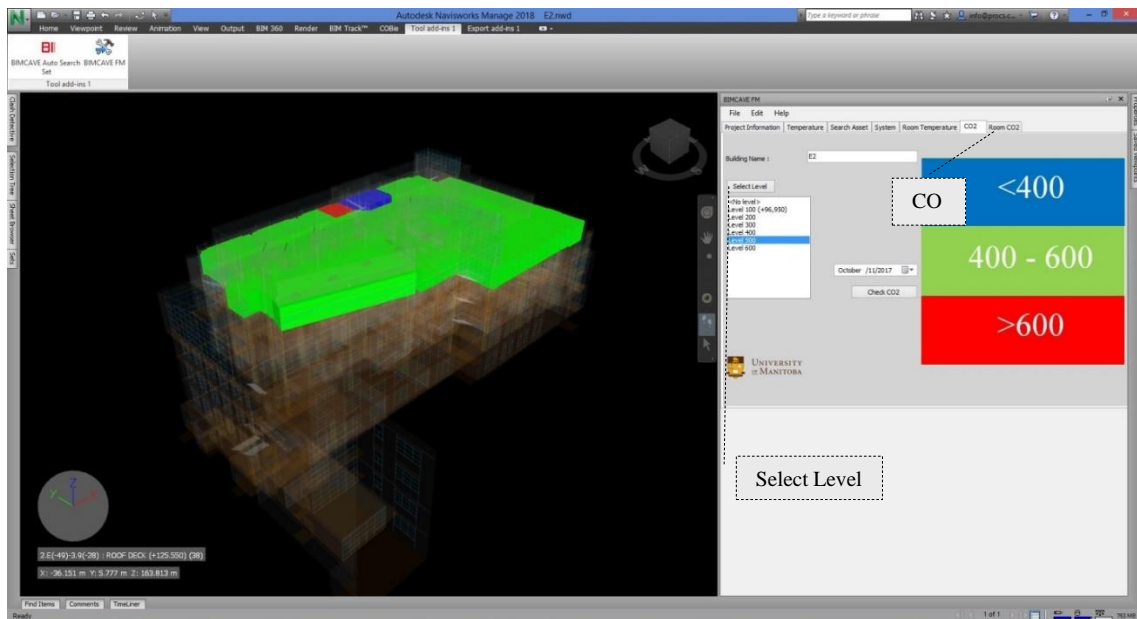
Figure 29 - Sample CO$_2$ data for the fifth floor

Graphical presentation of the historical sensor data in the software is generated through the integration with a unique database created from the temperature and CO$_2$ readings. The historical sensor data of a selected room is collected from the database within a

defined time interval. Three critical steps had to be defined for accessing the historical

data through the add-in. First, the building floor has to be selected from the indexed list

of levels. Second, the room list is formed specifically for the selected floor, and therefore

the room number has to be selected. Third, the time interval has to be selected from the

two date-time pickers. After all, selections are made, the add-in creates a spline area type

graphic showing trend of change for the temperature (if Room Temperature tab is

selected) or CO_2 level (if Room CO_2 tab is chosen). Furthermore, to enable more precise

visualization, only the selected room element is visible, whereas all other elements are

transparent. Figure 30 and Figure 31 show the implemented approach for temperature and

CO_2 data, respectively.
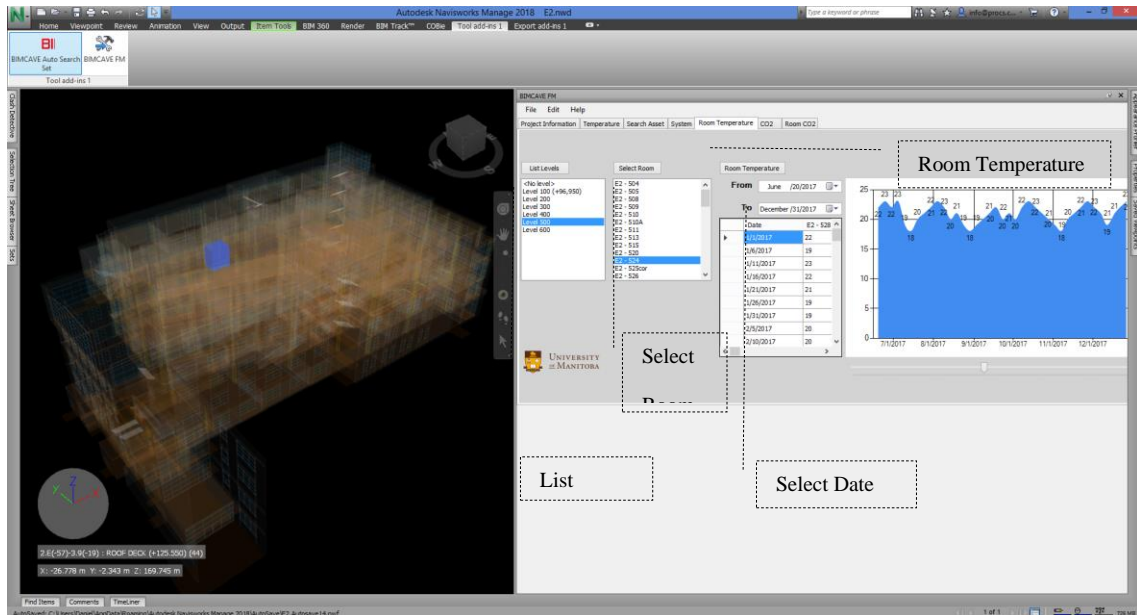
Figure 30 - Sample room temperature historical data presentation
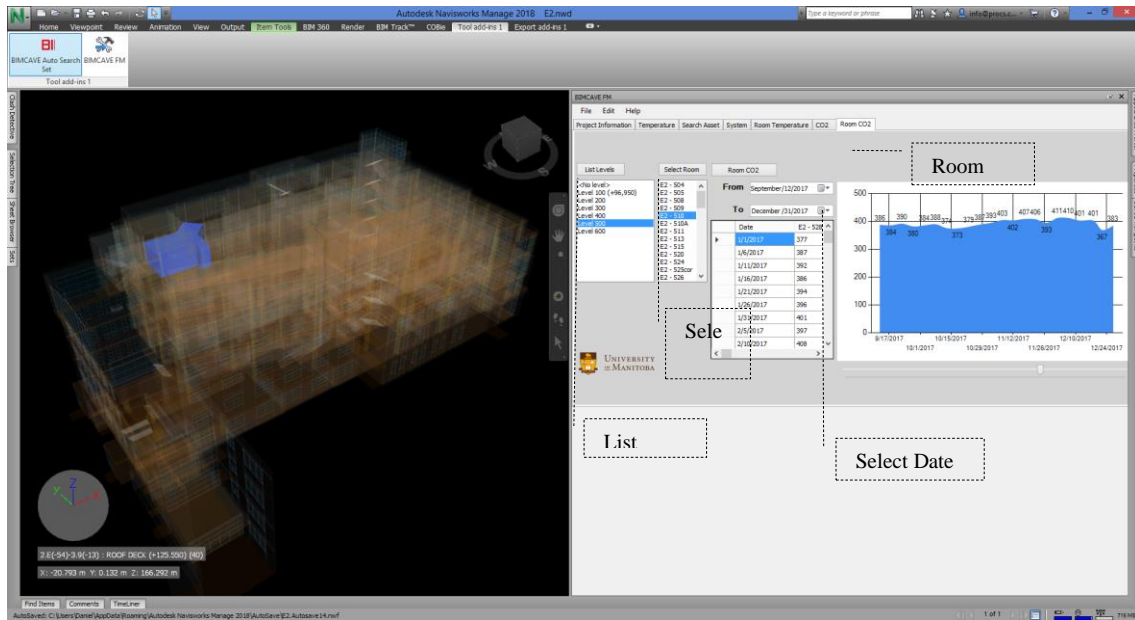
Figure 31 - Sample room CO_2 historical data visualization

Developed add-in would provide facility managers with valuable information that can be used for the development of strategies and measures for improving the indoor environmental quality and energy performance of the building. For example, managers can use the real-time temperature and CO_2 readings to introduce immediate changes to the operation of the HVAC systems to improve indoor air quality in the spaces occupied by large groups of people (e.g., during the exam or class). Visualization of the sensor data can also provide information about the performance of HVAC equipment and possible malfunctions. Furthermore, the historical data can be used for the development of different HVAC operation strategies for saving energy consumption while maintaining or even improving the indoor environmental quality. For instance, lowering the set-back temperatures or reducing the airflow during the unoccupied hours.

This 3D presentation of a level can also be used effectively for reviewing the surrounding sensor data of a specific room and analyzing potential reasons for failure in a specific

room. Floor-based visual data gives very detailed information about the performance of a building in different dates and opens the way for curative activities. Moreover, based on the data available, it is possible to foresee the potential performance characteristics of future building developments and design more energy-efficient facilities.

Graphically presenting the historic temperature and CO_2 level change of a selected room in the building with 3D model data available is giving access to all data collected through the life cycle of the facility. Each model element in a 3D model created in the BIM process has information collected during the design and construction phases of the facility. Sensor data provides the available information from the operation of the facility and access to all this data in a combined platform increases facility operators' decision-making capabilities.

5.6 Results and Discussion

One of the main queries for the facility management staff is to identify the room and all surrounding rooms when they receive a complaint about temperature from the end-users (X. Liu and Akinci 2009). To react appropriately and solve the issue promptly, the building managers need to observe the real-time temperature data, historical readings, as well as obtain various information about the performance and operation of the facility.

To the best of the author's knowledge, this is the first paper that utilizes widely used software Navisworks for the development of a user-friendly add-in program that integrates the existing building sensor technology and BIM process. Furthermore, the developed add-in is flexible, and with small modifications, it can be easily integrated

with other building sensors (e.g., presence sensors or energy meters) as well as applied in different buildings. Consequently, the developed technology can be used to reduce buildings' energy consumption and optimize their operation while providing high indoor environmental quality in the spaces that are used by the occupants. Moreover, adding value to similar work, this study contributes to open source software as it provides full script at the Mendeley Data to be adapted and modified by anyone (Kazado 2018). As a result, knowledge is shared so that the entire community can benefit from the collective innovation.

This paper presents three different approaches for integration of the building sensor technology and the BIM process to create a common data platform for the visualization of indoor environmental parameters (e.g., temperature and CO_2) that would enable facility operators to obtain the required information. Figure 32 summarizes and compares the capabilities of the three approaches: (i) Sensor-Revit integration with built-in functions of Revit software; (ii) Sensor-Revit-Navisworks integration with built-in functions of Navisworks software; and (iii) Sensor-Revit-Navisworks-API integration with the add-in developed. Integration of sensors with the Revit model utilizing the built-in functions of Autodesk Revit is an easy and straightforward approach that can provide building managers with real-time information about the indoor air temperature level and CO_2 concentration within the space of interest. Nevertheless, it has several limitations, such as only 2D data visualization, which makes it difficult to perceive the areas surrounding the space of interest, enables accidental model changes, does not allow viewing of the historical data, and does not allow a search of the building assets. The second approach integrated the Revit model and sensor data through the functions of

Autodesk Navisworks Manage to allow real-time 3D visualization of the parameters that cannot be edited by the building managers and can be used to rapidly identify the problematic areas and instantaneous reactions. However, similar to the first approach Sensor-Revit-Navisworks integration does not allow viewing of the historical data and thus hinders understanding the long-term behavior of the indoor environment and development of adequate mitigation strategies. To address limitations associated with these two approaches, we utilized .net application within Autodesk Navisworks to develop an open-source add-in that enables real-time display of the sensor data, viewing of historical data over the specified period, and search of the individual assets within the building (Kazado 2018).

Functions	First Approach Sensor-Revit integration	Second Approach Sensor-Revit-Navisworks integration	Third Approach Sensor-Revit-Navisworks-API integration
Visualization individual room in 2D	✔	✔	✔
Actual sensor data in 2D	✔	✔	✔
Access to asset database in BIM	✔	✔	✔
Non editable model	✘	✔	✔
Visualization individual room in 3D	✘	✔	✔
Actual sensor data in 3D	✘	✔	✔
Project general information	✘	✘	✔
Search individual assets	✘	✘	✔
Sensor data for varied dates	✘	✘	✔
Historical sensor data table	✘	✘	✔
Graphical historical sensor data	✘	✘	✔

✘ This function is not applicable for the approach
✔ This function is applicable for the approach

Figure 32 - Comparison of the functions for each approach

There are some challenges related to the implementation of the developed add-in. For example, even though Navisworks software is widely utilized during the construction phase of a project, it is not often used by the facility managers during the building operation. Furthermore, the use of add-in requires the purchase of the Navisworks license

as well as the training of staff. Another challenge is related to the requirement of 3D model of the facility. While this might be an obstacle for older buildings, many new buildings are developed and constructed within the BIM process.

The future research will include the development of a google-like virtual model-based browsing technology for the facility lifecycle (Sacks et al. 2018), based on historical and current data to reduce the overall building energy consumption. To achieve this, the BIM models of mechanical and electrical services will be added to the existing models to provide information about the performance of the equipment and development of different operation strategies for reducing energy consumption while maintaining or even improving the indoor environmental quality. Moreover, further work will also involve a comparison of the design and actual energy consumptions, which can be used in the building energy certification procedures.

6 Conclusions, Limitations, and Future Work

6.1 Conclusions

In this thesis, a comprehensive study for BIM process including the early design stage, construction phase, and operation phase has been carried out. Unlike the majority of previous studies, it focuses on the use of BIM process for buildings` whole life-cycle with the aim of creating a common data environment for the facilities. Therefore, this study provides valuable tools for decision-makers to evaluate, monitor, visualize, and record the characteristics of the building efficiently. In addition, the open-source codes of the developed add-ins provide possibilities for future research in this area and add value to the previous studies, both scientifically and information sharing points of view. In this regard, the work presented herein is the first to utilize widely used software Navisworks for development of a user-friendly add-in program that integrates the existing building sensor technology and BIM process to provide real-time data characterization and trending. Consequently, the study demonstrated with this thesis includes new approaches that can be valuable assets for both academia and industry. The main conclusions drawn from this study for each phase of construction can be summarized as follows:

I. Design Phase - This research showed that building's shape and orientation have a strong impact on energy consumption in cold climates (e.g., Winnipeg, Canada). In addition, this work evaluated the potential use of the software in the BIM process that can be used to facilitate early design decisions for more energy-efficient buildings. The energy consumption calculated for alternative orientations for each shape showed that the

building`s shape and orientation have significant impact on the overall energy performance. For example, the lowest annual fuel energy consumption has calculated for Shape-01 at the base run whereas Shape-04 has approximately 27% higher annual fuel consumption at the base run. Furthermore, the annual electric energy consumption of Shape-04 at the base run was 24,635kWh higher than the Shape-3 at the base run that has the lowest electric energy consumption. Moreover, the average values for building orientations of all shapes demonstrated that the 45° building orientation has the lowest energy use while the 270° building orientation had the maximum EUI and annual fuel energy use, and the maximum annual electric energy use was at the 315° building orientation. Finally, the results show that the EUI calculated for larger surface-area-to-volume shape was approximately 20% higher than the smallest exposed surface-area-to-volume shape.

This study also attempts to expand the available research work and studies regarding the use of BIM process in early design stage in extreme climates such as Winnipeg, Canada where temperatures fluctuate from +35°C in summer to -40°C in winter. All of the models were created at a specific geographic location at Winnipeg with the same building area and volume. Thus, the findings from this study can serve as a useful guide for the effect of alternative shape and building orientation on energy consumption in cold climates. The important conclusions are drawn as listed below:

- The building`s shape and orientation have a direct effect on overall energy consumption in cold climates. However, the change in electricity consumption and fuel consumption does not follow the same trend with the energy intensity change.

- The geographic decisions given at the early design development phase of a project can have an effect up to 20% change in the energy consumption.

- The BIM process and energy analysis software provide opportunities at the early design stage for analyzing the alternative solutions related to the building`s energy consumption.

II. Construction Phase - The study proposed a novel approach for monitoring the site progress with element-based tracking method that links the individual model elements and their status. The site progress monitoring of a complex data-center building was investigated for six months period using the developed method. Additionally, the proposed color coding for visualization increased the planning ability of decision-makers and allowed easier foreseeing of the potential problems. Moreover, the 3D visual results of the progress in BIM process show the level of detailed information for model element`s status provided a higher level of understanding of the progress at site.

Additionally, the successful operation of the developed add-in enabled to load of multiple parameters to selected individual model elements. For instance, the use of the 4D scheduling method would require the creation of additional 263,904 activities, whereas in our case we defined two additional statuses only. Therefore, the application of the element-based site progress tracking method with the incorporation of the developed add-in may offer a better solution in terms of available information and easy visualization.

The important conclusions are drawn as listed below:

- The proposed element-based site progress monitor tracking is applicable for the case study building including MEP services. The proposed approach determined the progress more accurately compared to 4D BIM process.

- The custom developed add-in program enabled to smoothly load multiple parameters to selected individual model elements.

- The proposed approach increased the detail of information available to decision-makers related to site progress.

III. Operation Phase - The research presented the potential to improve the facilities operation where the decision-makers can measure, monitor, visualize, and record the characteristics of the building more efficiently. The study presented three approaches: (i) Sensor-Revit integration with built-in functions of Revit software; (ii) Sensor-Revit-Navisworks integration with built-in functions of Navisworks software; and (iii) Sensor-Revit-Navisworks-API integration with the add-in developed for integration of the sensor database and the BIM process.

The results of the first approach have provided information about the indoor air temperature level and CO_2 concentration in a 2D environment for building managers through a smooth and simplistic process for the EITC building. Furthermore, the results of the second approach have demonstrated the sensor data in a 3D visualization platform and have provided building managers with real-time information about the space of interest. Moreover, the results of the add-in application within Navisworks addressed the limitations associated with these two approaches and demonstrated the historical and actual sensor data in 3D environment.

Additionally, this is the first study that utilizes the Navisworks software for development of a user-friendly add-in program that integrates the existing building sensor technology and BIM process to provide real-time data characterization and trending. The results from this study show the software that is compatible with different software packages and does not allow users make any model revisions, offer a better solution for facility operators. Thus, according to findings, the add-in developed for Navisworks software are likely to perform better than any development for BIM authoring software.

The results from integration with the developed add-in showed that the platform can lead to a common data environment including all information collected during design and construction phases. Therefore, the developed platform may allow facility managers real-time analysis, optimization, and visualization of large data sets to better manage energy consumption, optimize space, and reduce operating costs while enhancing occupant comfort and health. Furthermore, visualization and analysis of historical data can facilitate development of both immediate and long-term implementation of various energy-efficiency strategies, solutions, and technologies.

The important conclusions are drawn as listed below:

- Despite the simplicity of using Revit and Navisworks in-built functionalities, the add-in developed for Navisworks software has the biggest potential to improve the facilities operation.
- The first approach can be used to visualize the actual sensor data in a 2D environment, the second approach is suitable for visualizing the actual sensor data in a 3D environment whereas the third approach can visualize both historical and

actual sensor data, provide graphical representation, and provides information to improve in-depth analysis.

- The BIM – FM integration method proposed in this thesis was able to accurately visualize the information for the EITC building. The graphical presentation of sensor data with 3D model data gave access to all information collected through the life cycle of the facility.

6.2 Limitations

The main limitation of this thesis is the need for both BIM authoring software such as Autodesk Revit and model review software Navisworks for implementation of the developed add-ins. Also, the 3D model including the information of the facility created in the BIM process is required. Furthermore, the BIM authoring and review software of the same vendor has a smooth data sharing process, but the interoperability among various software vendors may present a gap. Although, these limitations might be an obstacle for existing facilities that are not built within the BIM process, many new facilities are being designed and constructed using BIM process.

The other limitations of the study can be listed as follows:

- There are several limitations of using BIM and energy simulation software at the concept design stage like: the predefined HVAC templates, fixed level of occupancy, and detailed analysis for daily or hourly cannot be performed.

- The energy simulation software uses predefined values for the building elements and alternative template building elements are limited. Therefore, the results are valuable assets for comparing the alternative design solutions.

- The limitation for the element-based tracking method for construction monitoring is the missing relation between construction planned/actual dates that are defined in the work schedule and the progress information monitored on the model elements. However, new parameters that can be defined within the developed add-in may be used to load and monitor data from the work schedule.

- The first two approaches for sensor technology and BIM process integration has limitations such as: enables accidental model changes, does not allow viewing of the historical data, and does not allow a search of the building assets.

- It should be noted that the results and findings of this study reflects the outcomes from the case study buildings and the results may differ for different complexity or size building types located in different climates.

6.3 Future Work

The recommendations for future work can be summarized as follows:

- In present work, the effect of six primary building shapes on energy consumption in cold climates is presented. Therefore as potential future work, alternative building shapes considering the different climates recommended being carried out.

- The work related with the construction phase was based on the four main statuses of building elements. However, the other element statuses that can be potentially used to better assess the progress include "ordered," "shipped," "received," "critical," "waiting for inspection," or "on hold". In this regard, future research works can involve these statuses and compare the results with the data from the construction site.

- The developed add-in for sensor technology and BIM process integration is very flexible that can be easily facilitated for different buildings and other sensors in the facility. Future work will include the development of mechanical and electrical services 3D models and integration of additional sensors information such as presence sensors or energy meters.

- It is also worth mentioning that results and findings presented herein for integrating the BIM processes with design, construction, and operation phases of the facility have developed on separate platforms. For the best results, a virtual model-based browsing technology can be elaborated that collaborates with the information created by all stakeholders. The future research should include the development of a common platform for all phases of the facility that can visualize the whole historical and current information collected during the lifecycle to reduce the overall building energy consumption and improve efficiency.

Bibliography

Abanda, F. H., and L. Byers. 2016. "An Investigation of the Impact of Building Orientation on Energy Consumption in a Domestic Building Using Emerging BIM (Building Information Modelling)." *Energy* 97: 517–27. http://dx.doi.org/10.1016/j.energy.2015.12.135.

Abdelsayed, Maged, and Ronie Navon. 1999. "An Information Sharing, Internet-Based, System for Project Control." *Civil Engineering and Environmental Systems* 16(3): 211–33. https://doi.org/10.1080/02630259908970263.

Aksoy, U. Teoman, and Mustafa Inalli. 2006. "Impacts of Some Building Passive Design Parameters on Heating Demand for a Cold Region." *Building and Environment* 41(12): 1742–54.

AlAnzi, Adnan, Donghyun Seo, and Moncef Krarti. 2009. "Impact of Building Shape on Thermal Performance of Office Buildings in Kuwait." *Energy Conversion and Management* 50(3): 822–28. http://dx.doi.org/10.1016/j.enconman.2008.09.033.

Allen, P a. 1986. "An Integrated Power and Building Services Management System." *INTELEC '86 - International Telecommunications Energy Conference*: 525–30.

Alves, Miguel, Paulo Carreira, and António Aguiar Costa. 2017. "BIMSL: A Generic Approach to the Integration of Building Information Models with Real-Time Sensor Data." *Automation in Construction* 84(November 2016): 304–14. http://dx.doi.org/10.1016/j.autcon.2017.09.005.

Andersson, Brandt, Wayne Place, Ronald Kammerud, and M. Peter Scofield. 1985. "The Impact of Building Orientation on Residential Heating and Cooling." *Energy and Buildings* 8(3): 205–24.

Andriamamonjy, Ando et al. 2015. "Sensor Handling in Building Information Models . Development of a Method and Application on a Case Study." *Building Simulation 2015*: 472–78.

ANSI/ASHRAE Standard 62.1-2016. 2016. *Ventilation for Acceptable Indoor Air Quality*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Araszkiewicz, Krystyna. 2017. "Digital Technologies in Facility Management – the State of Practice and Research Challenges." *Procedia Engineering* 196(June): 1034–42. http://dx.doi.org/10.1016/j.proeng.2017.08.059.

Arslan, Muhammad, Zainab Riaz, Adnan Khalid Kiani, and Salman Azhar. 2014. "Real-Time Environmental Monitoring, Visualization and Notification System for Construction H&S Management." *Journal of Information Technology in Construction* 19(September 2013): 72–91.

Attar, Ramtin et al. 2010. "BIM-Based Building Performance Monitor." *SimAUD 2010* (August): 2010. http://www.autodeskresearch.com/publications/bimdashboardvideo.

Autodesk Inc. 2018a. "Autodesk Navisworks." https://www.autodesk.com/products/navisworks/overview.

———. 2018b. "Autodesk Revit." https://www.autodesk.com/products/revit/overview.

———. 2018c. "Dynamo." http://dynamobim.org/.

Azhar, Salman. 2011. "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry." *Leadership and Management in Engineering* 11(3): 241–52.

Becerik-Gerber, Burcin, Farrokh Jazizadeh, Nan Li, and Gulben Calis. 2012. "Application Areas and Data Requirements for BIM-Enabled Facilities Management." *Journal of Construction Engineering and Management*.

BENTLEY SYSTEMS. 2018. "AECOsim." https://www.bentley.com/en/products/brands/aecosim.

Bottaccioli, Lorenzo et al. 2017. "Building Energy Modelling and Monitoring by Integration of IoT Devices and Building Information Models." *2017 IEEE 41st Annual Computer Software and Applications Conference (COMPSAC)*: 914–22. http://ieeexplore.ieee.org/document/8029717/.

Bynum, Patrick, Raja R. A. Issa, and Svetlana Olbina. 2012. "Building Information Modeling in Support of Sustainable Design and Construction." *Journal of Construction Engineering and Management* 139(1): 24–34.

Cahill, B, K Menzel, and D Flynn. 2012. "BIM as a Centre Piece for Optimised Building Operation." *eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2014* (2): 549–555.

Cao, Shi Jie, and Hua Yan Deng. 2019. "Investigation of Temperature Regulation Effects on Indoor Thermal Comfort, Air Quality, and Energy Savings toward Green Residential Buildings." *Science and Technology for the Built Environment* 25(3): 309–21. https://doi.org/10.1080/23744731.2018.1526016.

Catalina, T, J Virgone, and V Iordache. 2011. "Study on the Impact of the Building Form on the Energy Consumption." *Proceedings of the 12th International Conference of the International Building Performance Simulation Association*: 1726–29. http://www.ibpsa.org/proceedings/BS2011/P_1563.pdf.

Catalina, Tiberiu, Joseph Virgone, and Eric Blanco. 2008. "Development and Validation of Regression Models to Predict Monthly Heating Demand for Residential Buildings." *Energy and Buildings* 40(10): 1825–32.

Chen, J, T Bulbul, JE Taylor, and G Olgun. 2014. "A Case Study of Embedding Real-Time Infrastructure Sensor Data to BIM." *Construction Research Congress 2014*: 269–78.

Chen, Lijuan, and Hanbin Luo. 2014. "A BIM-Based Construction Quality Management Model and Its Applications." *Automation in Construction* 46: 64–73. http://dx.doi.org/10.1016/j.autcon.2014.05.009.

Chen, Xiu Shan, Chi Chang Liu, and I. Chen Wu. 2018. "A BIM-Based Visualization and Warning System for Fire Rescue." *Advanced Engineering Informatics* 37(October 2017): 42–53. https://doi.org/10.1016/j.aei.2018.04.015.

Cheng, Min Yuan et al. 2017. "BIM Integrated Smart Monitoring Technique for Building Fire Prevention and Disaster Relief." *Automation in Construction* 84(June): 14–30.

http://dx.doi.org/10.1016/j.autcon.2017.08.027.

Cheung, Weng Fong, Tzu Hsuan Lin, and Yu Cheng Lin. 2018. "A Real-Time Construction Safety Monitoring System for Hazardous Gas Integrating Wireless Sensor Network and Building Information Modeling Technologies." *Sensors (Switzerland)* 18(2).

Dave, Bhargav, Andrea Buda, Antti Nurminen, and Kary Främling. 2018. "A Framework for Integrating BIM and IoT through Open Standards." *Automation in Construction* 95(August): 35–45. https://doi.org/10.1016/j.autcon.2018.07.022.

Dong, Shuang, Heng Li, and Qin Yin. 2018. "Building Information Modeling in Combination with Real Time Location Systems and Sensors for Safety Performance Enhancement." *Safety Science* 102: 226–37.

Geletka V., Sedláková A. 2012. "Impact of Shape of Buildings on Energy Consumption ©." : 252–58. http://lib.lp.edu.ua/bitstream/ntb/16694/1/47-Geletka-252-258.pdf.

Gerges, Michael et al. 2017. "An Investigation into the Implementationof Building Information Modelingin the Middle East." *Journal of Information Technology in Construction* 22(July 2016): 1–15.

Gerrish, Tristan et al. 2017. "Using BIM Capabilities to Improve Existing Building Energy Modelling Practices." *Engineering, Construction and Architectural Management* 24(2): 190–208.

Getuli, Vito, Silvia Mastrolembo Ventura, Pietro Capone, and Angelo L C Ciribini. 2016. "A BIM-Based Construction Supply Chain Framework for Monitoring Progress and Coordination of Site Activities." *Procedia Engineering* 164(June): 542–49. http://dx.doi.org/10.1016/j.proeng.2016.11.656.

Golparvar-fard, Mani, A M Asce, and Feniosky Pe. 2015. "Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models." 29(1): 1–19.

Golparvar-Fard, Mani, Feniosky Peña-mora, Carlos A. Arboleda, and Sanghyun Lee. 2009. "Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs." *Journal of Computing in Civil Engineering* 23(6): 391–404. http://ascelibrary.org/doi/10.1061/%28ASCE%290887-3801%282009%2923%3A6%28391%29.

GRAPHISOFT. 2018. "Archicad." http://www.graphisoft.com/archicad/.

Guillen, A. J. et al. 2016. "Building Information Modeling as Assest Management Tool." *IFAC-PapersOnLine* 49(28): 191–96. http://dx.doi.org/10.1016/j.ifacol.2016.11.033.

Guven, G et al. 2012. "Providing Guidance for Evacuation during an Emergency Based on a Real-Time Damage and Vulnerability Assessment of Facilities." In *Computing in Civil Engineering (2012)*, https://ascelibrary.org/doi/abs/10.1061/9780784412343.0074.

Hallberg, Daniel, and V??ino Tarandi. 2011. "On the Use of Open Bim and 4D Visualisation in a Predictive Life Cycle Management System for Construction Works." *Electronic Journal of Information Technology in Construction* 16: 445–66.

Hammad, Amin, Cheng Zhang, Yongxin Hu, and Elaheh Mozaffari. 2006. "Mobile Model-Based Bridge Lifecycle Management System." *Computer-Aided Civil and Infrastructure Engineering* 21(7): 530–47.

Hewlett-Packard Development Company. 2014. "How To Control Revit File Sizes."

https://www8.hp.com/nz/en/pdf/november-augi-advertorial_tcm_194_1910147.pdf (July 10, 2018).

Hu, Zhen Zhong, Pei Long Tian, Sun Wei Li, and Jian Ping Zhang. 2018. "BIM-Based Integrated Delivery Technologies for Intelligent MEP Management in the Operation and Maintenance Phase." *Journal of Information Technology in Construction* 115: 1–16. https://doi.org/10.1016/j.advengsoft.2017.08.007.

International Energy Agency. 2013. "Technology Roadmap. Energy Efficent Building Envelopes." *Oecd*: 68. https://www.iea.org/publications/freepublications/publication/TechnologyRoadmap EnergyEfficientBuildingEnvelopes.pdf.

———. 2017a. "Energy Technology Perspectives." https://www.iea.org/buildings/ (September 20, 2018).

———. 2017b. "Energy Technology Perspectives 2017." https://www.iea.org/buildings/ (September 20, 2018).

Jalaei, Farzad, and Ahmad Jrade. 2014. "Integrating BIM with Green Building Certification System, Energy Analysis, and Cost Estimating Tools to Conceptually Design Sustainable Buildings." *Construction Research Congress 2014* 19: 140–49. http://ascelibrary.org/doi/10.1061/9780784413517.015.

———. 2015. "Integrating Building Information Modeling (BIM) and LEED System at the Conceptual Design Stage of Sustainable Buildings." *Sustainable Cities and Society* 18: 95–107. http://dx.doi.org/10.1016/j.scs.2015.06.007.

Johansson, Mikael, Mattias Roupé, and Petra Bosch-Sijtsema. 2015. "Real-Time Visualization of Building Information Models (BIM)." *Automation in Construction* 54: 69–82. http://dx.doi.org/10.1016/j.autcon.2015.03.018.

Kamari, Aliakbar, Christian Laustsen, Steffen Peterson, and Poul H Kirkegaard. 2018. "A BIM-Based Decision Support System for the Evaluation of Holistic Renovation Scenarios." *Journal of Information Technology in Construction (ITcon)* 23(June): 354–80.

Kazado, Daniel. 2018. "Add-in for a Case Study for Integration of Sensor Technology with BIM for Facility Management Using Navisworks." 1. https://data.mendeley.com/datasets/xryftwb62n/1 (November 27, 2018).

Kazado, Daniel, Miroslava Kavgic, and Esin Ergen. 2019. "Construction Progress Visualisation for Varied Stages of the Individual Elements with BIM: A Case Study." In , 110–16. https://ec-3.org/publications/conferences/2019/paper/?id=172.

Kensek, K. M. 2014. "Integration of Environmental Sensors with BIM: Case Studies Using Arduino, Dynamo, and the Revit API." *Informes de la Construcción* 66(536): e044. http://informesdelaconstruccion.revistas.csic.es/index.php/informesdelaconstruccion /article/view/3575/4027.

Kim, Changwan, Changmin Kim, and Hyojoo Son. 2013. "Automated Construction Progress Measurement Using a 4D Building Information Model and 3D Data." *Automation in Construction* 31: 75–82. http://dx.doi.org/10.1016/j.autcon.2012.11.041.

Kim, Changyoon, Byoungil Kim, and Hyoungkwan Kim. 2013. "4D CAD Model Updating Using Image Processing-Based Construction Progress Monitoring." *Automation in Construction* 35: 44–52.

http://dx.doi.org/10.1016/j.autcon.2013.03.005.

Krishnamurthy, Sudha et al. 2008. "Automation of Facility Management Processes Using Machine-to-Machine Technologies." *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 4952 LNCS: 68–86.

Lee, Donghwan, Gichun Cha, and Seunghee Park. 2016. "A Study on Data Visualization of Embedded Sensors for Building Energy Monitoring Using BIM." *International Journal of Precision Engineering and Manufacturing* 17(6): 807–14.

Lee, Gaang Ghang Gaang et al. 2012. "A BIM- and Sensor-Based Tower Crane Navigation System for Blind Lifts." *Automation in Construction* 26: 1–10. http://dx.doi.org/10.1016/j.autcon.2012.05.002.

Lee, Jaewook et al. 2013. "An Integrated Approach to Intelligent Urban Facilities Management for Real-Time Emergency Response." *Automation in Construction* 30: 256–64. http://dx.doi.org/10.1016/j.autcon.2012.11.008.

Liu, Chi-chang, Wei-liang Kuo, Ruei-shiue Shiu, and I-chen Wu. 2015. "Estimating and Visualizing Thermal Comfort Level via a Predicted Mean Vote in a BIM System." (2014): 1421–27.

Liu, Sha, Xianhai Meng, and Chiming Tam. 2015. "Building Information Modeling Based Building Design Optimization for Sustainability." *Energy and Buildings* 105: 139–53. http://dx.doi.org/10.1016/j.enbuild.2015.06.037.

Liu, Xuesong, and Burcu Akinci. 2009. "Requirements and Evaluation of Standards for Integration of Sensor Data with Building Information Models." In *Computing in Civil Engineering (2009)*, Reston, VA: American Society of Civil Engineers, 95–104. http://cedb.asce.org/cgi/WWWdisplay.cgi?172272.

Liu, Z., and Z. Deng. 2017. "A Systematic Method of Integrating BIM and Sensor Technology for Sustainable Construction Design." *IOP Conf. Series: Journal of Physics: Conf. Series* 910: 012071.

Love, Peter E.D., Jingyang Zhou, and Jane Matthews. 2019. "Project Controls for Electrical, Instrumentation and Control Systems: Enabling Role of Digital System Information Modelling." *Automation in Construction* 103(March): 202–12. https://linkinghub.elsevier.com/retrieve/pii/S0926580518307787.

Mahalingam, Ashwin, Rahul Kashyap, and Charudatta Mahajan. 2010. "An Evaluation of the Applicability of 4D CAD on Construction Projects." *Automation in Construction* 19(2): 148–59. http://dx.doi.org/10.1016/j.autcon.2009.11.015.

Malatras, Apostolos, Abolghasem Hamid Asgari, and Timothy Baugé. 2008. "Web Enabled Wireless Sensor Networks for Facilities Management." *IEEE Systems Journal* 2(4): 500–512.

Mardookhy, Minoo et al. 2014. "A Study of Energy Efficiency in Residential Buildings in Knoxville, Tennessee." *Journal of Cleaner Production* 85: 241–49. http://dx.doi.org/10.1016/j.jclepro.2013.09.025.

Marzouk, Mohamed, and Ahmed Abdelaty. 2014a. "BIM-Based Framework for Managing Performance of Subway Stations." *Automation in Construction* 41: 70–77. https://doi.org/10.1016/j.autcon.2014.02.004.

———. 2014b. "Monitoring Thermal Comfort in Subways Using Building Information Modeling." *Energy and Buildings* 84: 252–57. http://dx.doi.org/10.1016/j.enbuild.2014.08.006.

McNeel North America. 2018. "Rhino." https://www.rhino3d.com/.

Melzner, Jürgen, Sijie Zhang, Jochen Teizer, and Hans-Joachim Bargstädt. 2013. "A Case Study on Automated Safety Compliance Checking to Assist Fall Protection Design and Planning in Building Information Models." *Construction Management and Economics* 31(6): 1–14. http://dx.doi.org/10.1080/01446193.2013.780662.

Mousa, Michael, Xiaowei Luo, and Brenda McCabe. 2016. "Utilizing BIM and Carbon Estimating Methods for Meaningful Data Representation." *Procedia Engineering* 145: 1242–49. http://dx.doi.org/10.1016/j.proeng.2016.04.160.

NBS. 2016. "NBS National BIM Report 2016." : 35. https://www.thenbs.com/knowledge/national-bim-report-2016 (January 4, 2019).

———. 2017a. "NBS National BIM Report 2016." : 27. https://www.thenbs.com/knowledge/national-bim-report-2016 (January 4, 2019).

———. 2017b. "NBS National BIM Report 2017." : 21. https://www.thenbs.com/knowledge/nbs-national-bim-report-2017 (January 4, 2019).

———. 2018. "NBS National BIM Report 2018." : 27. https://www.thenbs.com/knowledge/the-national-bim-report-2018 (January 4, 2019).

Nemetschek. 2018. "Allplan." https://www.allplan.com/us_en/.

Parasonis, Josifas, Andrius Keizikas, and Diana Kalibatiene. 2012. "The Relationship between the Shape of a Building and Its Energy Performance." *Architectural Engineering and Design Management* 8(4): 246–56.

Park, Jaehyun et al. 2017. "Visualization for Daily 4D BIM." 143(10): 1–12.

Pärn, E. A., and D. J. Edwards. 2017. "Conceptualising the FinDD API Plug-in: A Study of BIM-FM Integration." *Automation in Construction* 80: 11–21.

Pärn, E. A., D. J. Edwards, and M. C.P. Sing. 2017. "The Building Information Modelling Trajectory in Facilities Management: A Review." *Automation in Construction* 75: 45–55. http://dx.doi.org/10.1016/j.autcon.2016.12.003.

Rebitzer, Gerald. 2002. "Integrating Life Cycle Costing and Life Cycle Assessment for Managing Costs and Environmental Impacts in Supply Chains." In *Cost Management in Supply Chains*, eds. Stefan Seuring and Maria Goldbach. Heidelberg: Physica-Verlag HD, 127–46.

Reinhardt, Jan, Burcu Akinci, and James H Garrett Jr. 2004. "Navigational Models for Computer Supported Project Management Tasks on Construction Sites." *Journal of Computing in Civil Engineering* 18(October): 281–90.

Riaz, Zainab et al. 2017. "BIM and Sensor-Based Data Management System for Construction Safety Monitoring." *Journal of Engineering, Design and Technology* (November): 00–00. http://www.emeraldinsight.com/doi/10.1108/JEDT-03-2017-0017.

Riaz, Zainab, M. Arslan, Adnan K. Kiani, and Salman Azhar. 2014. "CoSMoS: A BIM and Wireless Sensor Based Integrated Solution for Worker Safety in Confined Spaces." *Automation in Construction* 45: 96–106. http://dx.doi.org/10.1016/j.autcon.2014.05.010.

Sacks, Rafael, Chuck Eastman, Ghang Lee, and Paul Teicholz. 2018. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*. 3rd ed. John Wiley & Sons, Inc., Hoboken, NJ.

Shih, Naai-jung, and Ping-hung Wang. 2004. "Point-Cloud-Based Comparison between

Construction Schedule and As-Built Progress : Long-Range Three-Dimensional Laser Scanner ' s Approach." *Journal OF Architectural Engineering* 10(September): 98–102.

Son, Hyojoo, and Changwan Kim. 2010. "3D Structural Component Recognition and Modeling Method Using Color and 3D Data for Construction Progress Monitoring." *Automation in Construction* 19(7): 844–54. http://dx.doi.org/10.1016/j.autcon.2010.03.003.

Thabet, Walid, and Jason D Lucas. 2017. "A 6-Step Systematic Process for Model-Based Facility Data Delivery." *Journal of Information Technology in Construction (ITcon)* 22(August 2016): 104–31. http://www.itcon.org/2017/6.

Turkan, Yelda, Frederic Bosche, Carl T Haas, and Ralph Haas. 2012. "Automated Progress Tracking Using 4D Schedule and 3D Sensing Technologies." *Automation in Construction* 22: 414–21. http://dx.doi.org/10.1016/j.autcon.2011.10.003.

Tuttas, S., A. Braun, A. Borrmann, and U. Stilla. 2014. "Comparision of Photogrammetric Point Clouds with BIM Building Elements for Construction Progress Monitoring." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 40(3): 341–45.

Wang, Hongxia et al. 2013. "Integration of Bim and Live Sensing Information To Monitor Building Energy Performance." *Proceedings of the 30th CIB W78 International Conference*: 344–52.

Wetzel, Eric M., and Walid Y. Thabet. 2018. "A Case Study towards Transferring Relevant Safety Information for Facilities Maintenance Using BIM." *Journal of Information Technology in Construction (ITcon)* 23(March 2018): 53–74. https://www.itcon.org/2018/3.

Wong, Johnny Kwok Wai, Janet Ge, and Sean Xiangjian He. 2018. "Digitisation in Facilities Management: A Literature Review and Future Research Directions." *Automation in Construction* 92(October 2017): 312–26. https://doi.org/10.1016/j.autcon.2018.04.006.

Wu, Wei, Wenjia Li, Deify Law, and Woonki Na. 2015. "Improving Data Center Energy Efficiency Using a Cyber-Physical Systems Approach: Integration of Building Information Modeling and Wireless Sensor Networks." *Procedia Engineering* 118: 1266–73.

Yu, Kevin, Thomas Froese, and Francois Grobler. 2000. "A Development Framework for Data Models for Computer-Integrated Facilities Management." *Automation in Construction* 9: 145–67.

Zhang, Jianchao, Boon-Chong Seet, and Tek Lie. 2015. "Building Information Modelling for Smart Built Environments." *Buildings* 5(1): 100–115. http://www.mdpi.com/2075-5309/5/1/100/.

Zhang, Yunfeng, and Linjia Bai. 2015. "Rapid Structural Condition Assessment Using Radio Frequency Identification (RFID) Based Wireless Strain Sensor." *Automation in Construction* 54: 1–11. http://dx.doi.org/10.1016/j.autcon.2015.02.013.