

# INTEGRATING BUILDING INFORMATION MODELING (BIM) AND SENSOR TECHNOLOGY FOR FACILITY MANAGEMENT

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**SUMMARY:** 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 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.

**KEYWORDS:** Building Information Modeling (BIM), Navisworks, Revit, Sensors, Facility Management, BIM integration

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# 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.

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 which 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<sub>2</sub>) 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 paper 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<sub>2</sub>), 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<sub>2</sub> to the real-time 3D display and analysis of the historical trends and data. To the best of the authors' knowledge, this is the first paper that utilizes 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. Furthermore, the developed add-in is very flexible and can be easily facilitated for different buildings with only updating the data source where the sensor data is stored. Moreover, with small modifications, the customizable, user-friendly, and highly visual add-in can be integrated with other sensors in the facility such as presence sensors or energy meters. In addition, the open-source code of the add-in provides possibilities for future research in this area and adds value to the previous studies, both scientifically and information sharing point of view (Kazado, 2018). Therefore, the developed technology will 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. This paper first provides an overview of the relevant literature. Then it presents a research method. After that, it gives a detailed description of the case study building. Next, it presents and discusses the three approaches for visualization and analysis of the indoor air temperatures and CO<sub>2</sub>. The final section provides conclusions, limitations and future work.

## 2. PREVIOUS STUDIES

Previous studies indicate that there have been increasing attempts to integrate sensor technology with BIM for improving the life-cycle efficiency of facilities, and they can be classified as (1) enhancing safety management in construction, (2) improving energy performance of buildings, (3) decision support to facility management, and (4) add-ins to BIM software.

### 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 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, 2017). 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 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 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. 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 Applications supporting facility management decision

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 can 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 sensors 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 Summary

Currently, 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 authors' 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.

## 3. RESEARCH METHOD

This paper presents and discusses three approaches for integrating, visualizing and analyzing sensor technology data with the 3D model created within BIM process: (i) Sensor-Revit integration; (ii) Sensor-Revit-Navisworks integration; and (iii) Sensor-Revit-Navisworks-API integration. Figure 1 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.

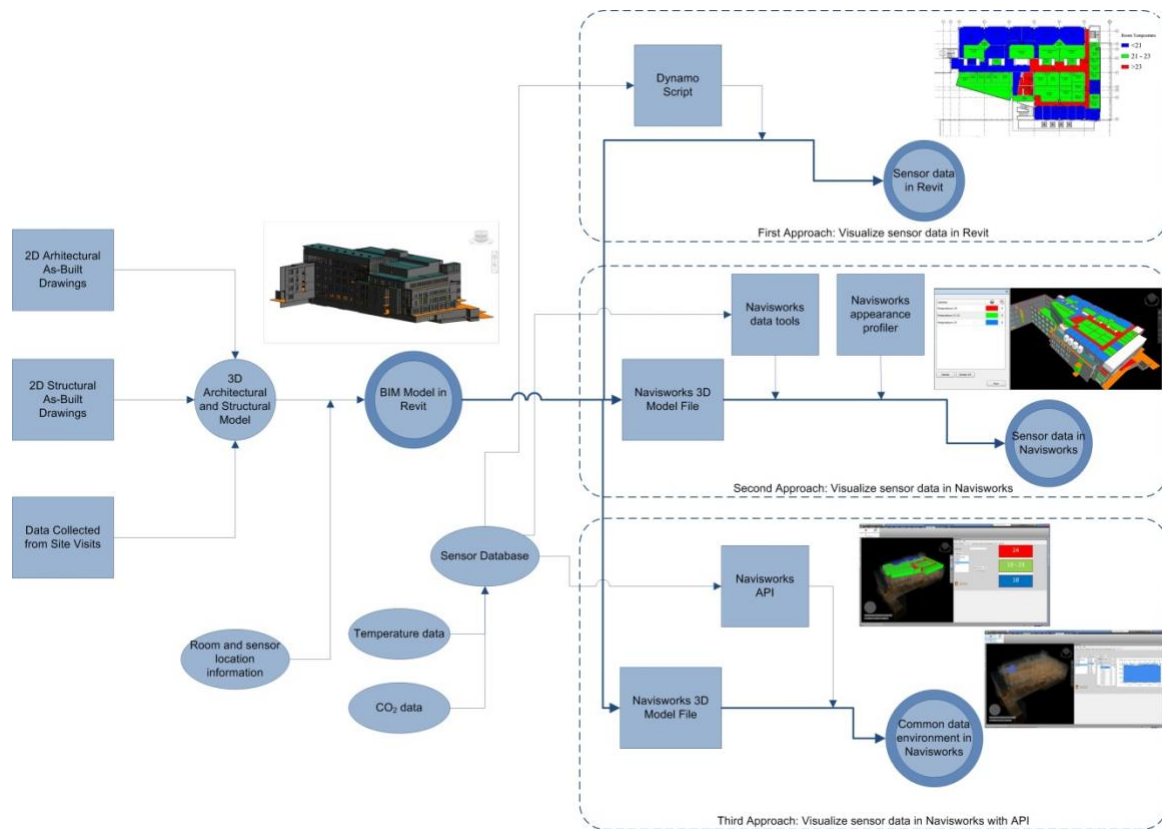


Figure 1: Research methodology process map

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 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 development of different add-ins. Figure 2 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 better understanding of the sensor data require color-coding. In the first approach, the readings from the room temperature and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> data of the selected room along with the historical trends and profiles for in-depth analysis and further interpretation.

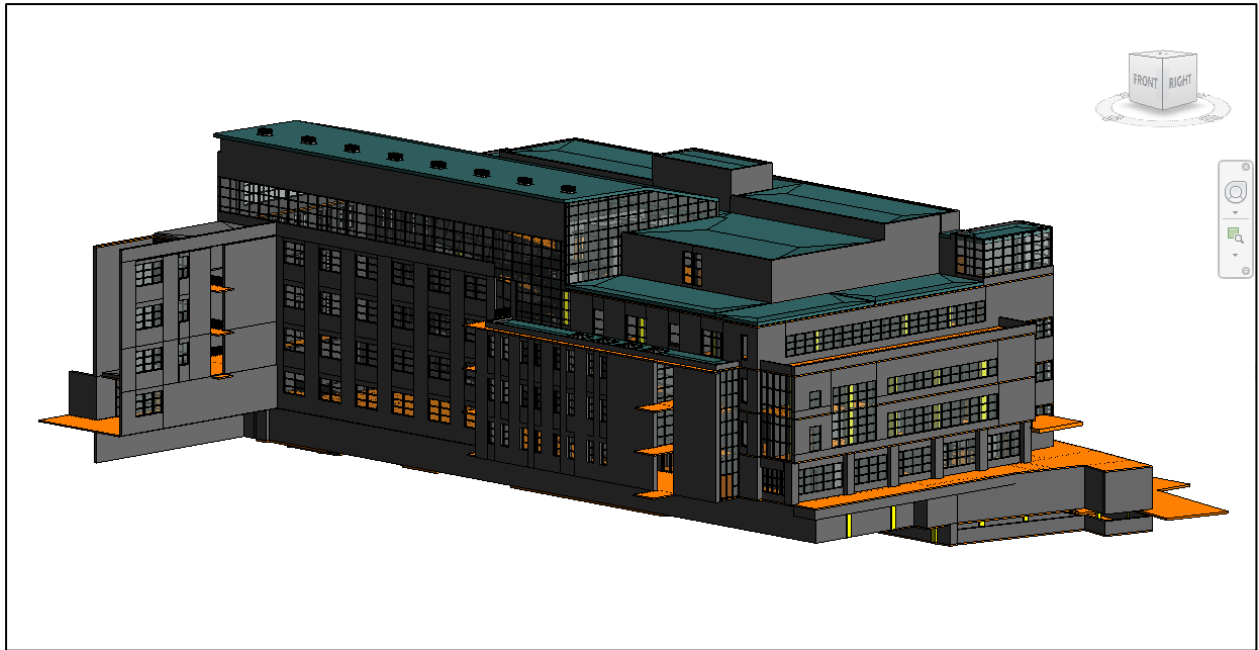


Figure 2: General view of the 3D model in Revit

#### 4. 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 3, the orientation of the EITC is  $26^\circ$  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 3). The E2 building accommodates various space types, including graduate areas, laboratories, fabrication spaces, and offices.

The E2 building was chosen for three main reasons. First, the building has advanced sensors that collect temperature and CO<sub>2</sub> 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<sub>2</sub> readings of each room are available for display and analysis (see Figure 4). 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 5). Moreover as presented in Figure 4 on several occasions the CO<sub>2</sub> levels were above the 700 parts per million (ppm) above outdoor air as recommended by the American Society of Heating and Refrigeration 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 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. 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 in accordance to the needs of decision-makers.



Figure 3: The case study building

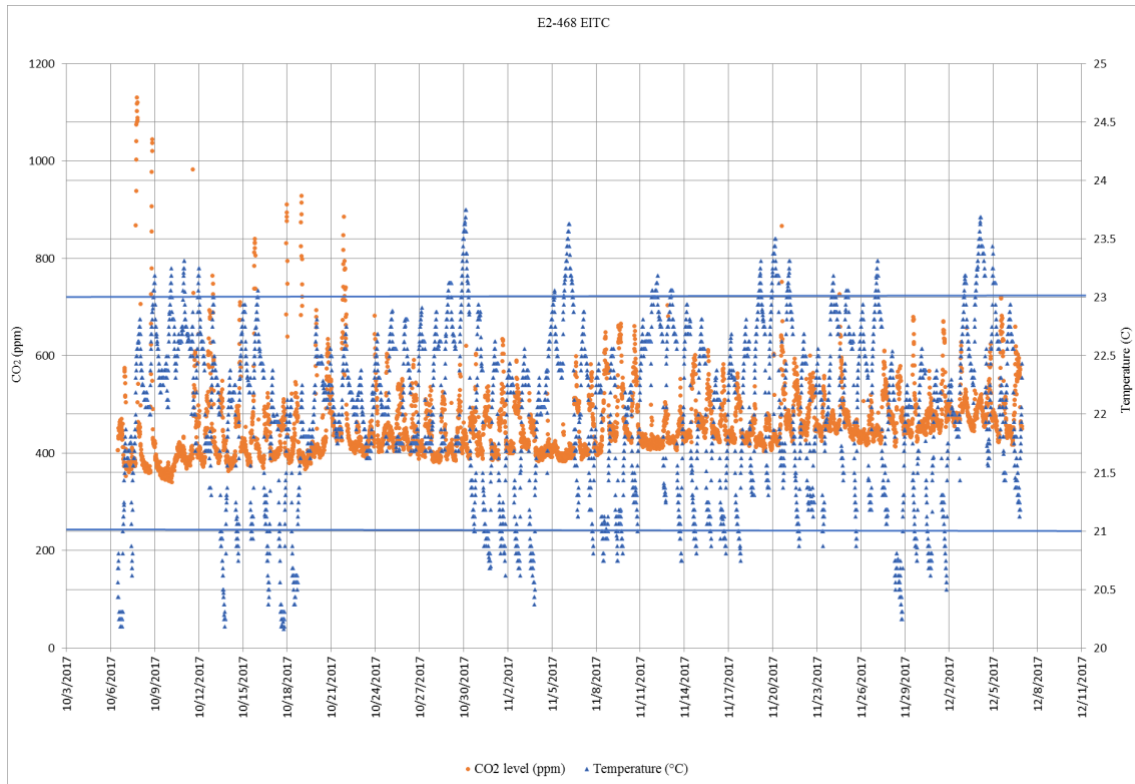


Figure 4: Room E2-468 temperature and CO<sub>2</sub> data for two months

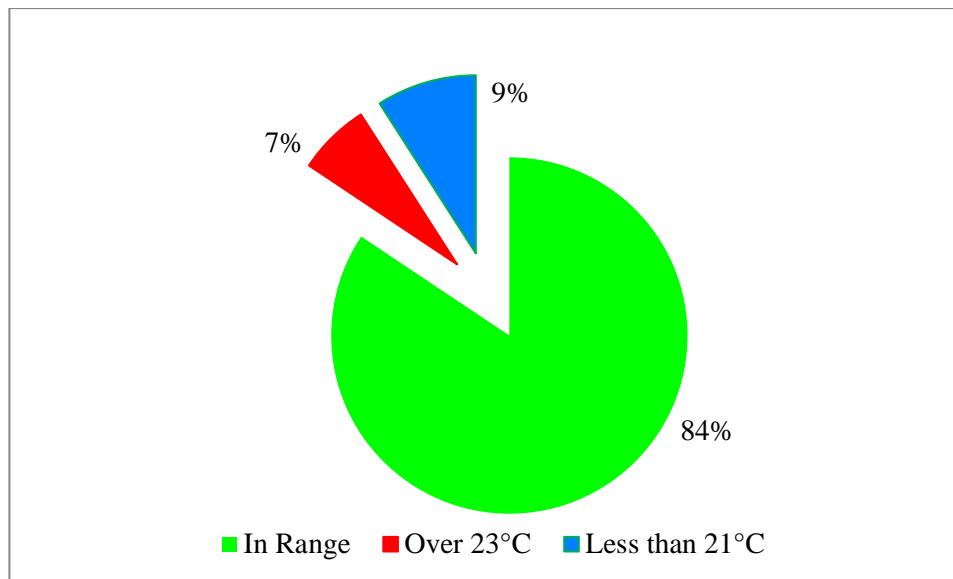


Figure 5: Room E2-468 temperature data analysis for two months

## 5. SENSOR-REVIT INTEGRATION

In the first approach, the 3D Revit model is used to visualize temperature and CO<sub>2</sub> 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 sensors database. Two new attributes are generated in Revit software for temperature and CO<sub>2</sub> 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<sub>2</sub> attributes value to the Revit model. In the first Dynamo script, Revit model room element attributes such as unique room number, temperature, CO<sub>2</sub>, and element ID are exported and a database template is created in Microsoft Excel. Next, temperature and CO<sub>2</sub> 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<sub>2</sub> parameters with values are imported to Revit software, and room elements are made visible in 2D view for visualizing the temperature and CO<sub>2</sub> 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<sub>2</sub> parameter values that were previously loaded to the room elements. As presented in Figure 6, different colors are utilized for defining specific temperature ranges (e.g., below 21°C, between 21°C and 23°C, and above 23°C). Furthermore, as illustrated in Figure 7, a similar approach is applied for the color-coding of the CO<sub>2</sub> levels (e.g., below 400ppm, between 400 and 600ppm, and over 600ppm).

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<sub>2</sub> 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 user unintentionally deletes or alters some element within the model. Fourth, similar to other BIM-based authoring tools; Revit lack 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).





Figure 6: Visualize temperature sensor data in Revit



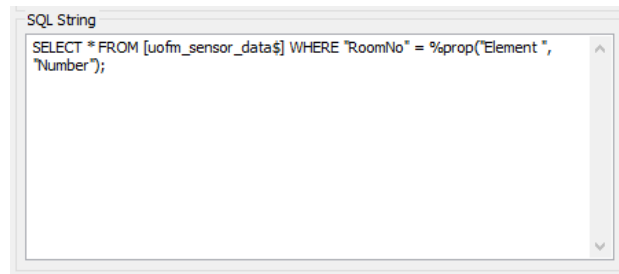
Figure 7: Visualize CO2 sensor data in Revit

## 6. 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 CO2 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<sub>2</sub> data for each room. The utilization of “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 8 illustrates an example implementation of the query with the SQL statement.



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

Figure 8: 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 9, different color schemes are assigned to the ranges of temperature parameter values: less than 21°C, between 21°C and 23°C, and over 23°C. Additionally, as shown in Figure 10, different color coding schemes are used to visualize CO<sub>2</sub> concentrations grouped in three categories: under 400ppm, between 400-600ppm, and over 600ppm.

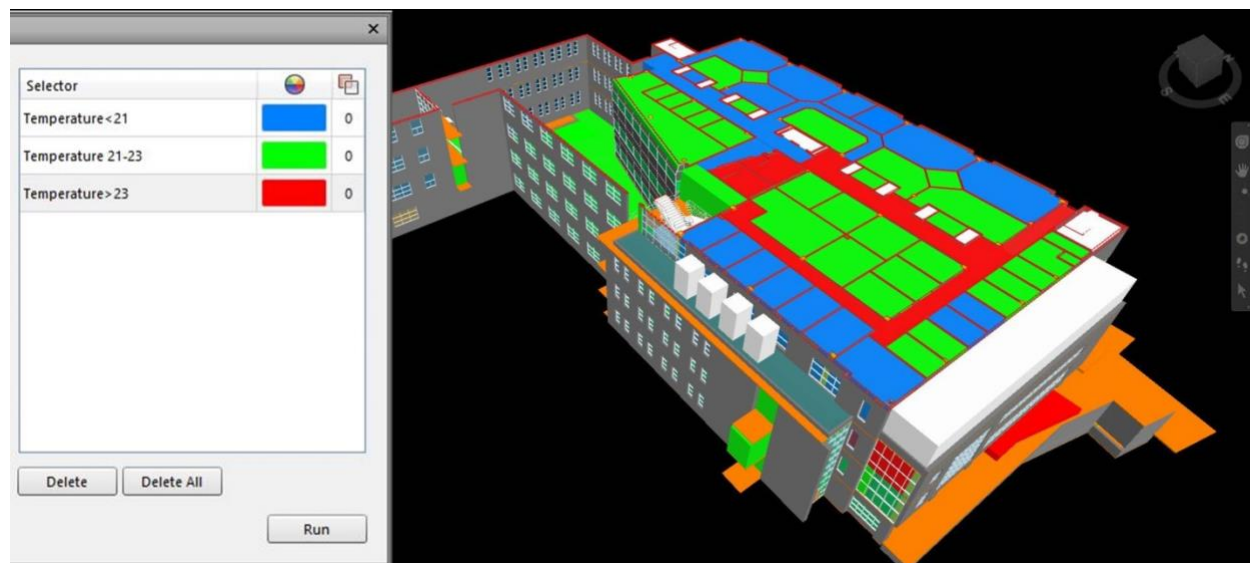


Figure 9: Visualize temperature sensor data in Navisworks

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 group 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 the adequate mitigation measures and strategies.

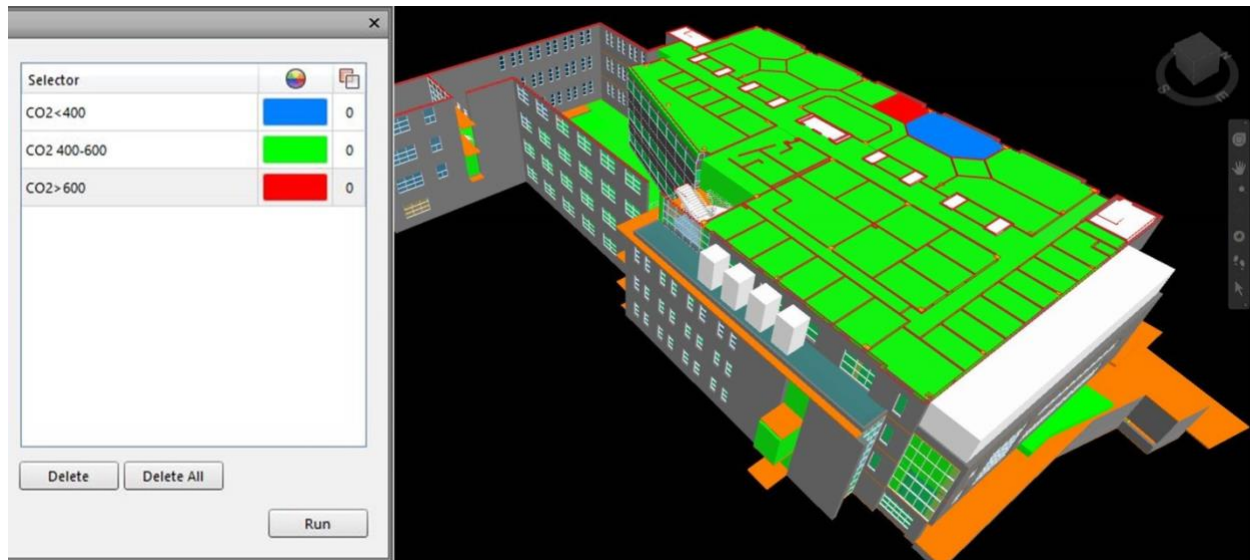


Figure 10: Visualize CO2 sensor data in Navisworks

## 7. 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 CO2 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 of 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 11, whereas the full script can be downloaded from the Mendeley Data (Kazado, 2018).

Additional information about the facility may greatly benefit the operators. For example, general information about the building such as building's name, the total number of assets, the total number of rooms and 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 12 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 13 shows an example of the applied approach.

The 15 minutes interval temperature and CO2 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.

```

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.HasPropertyByDisplayName("Element", "Category") _
.EqualValue(VariantData.FromDisplayString(PropertyValue)))
s2.SearchConditions.Add(SearchCondition.HasPropertyByDisplayName("Item", "Layer") _
.EqualValue(VariantData.FromDisplayString(propertyValue1)))
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.ToString()
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 11: Representation of the database connection

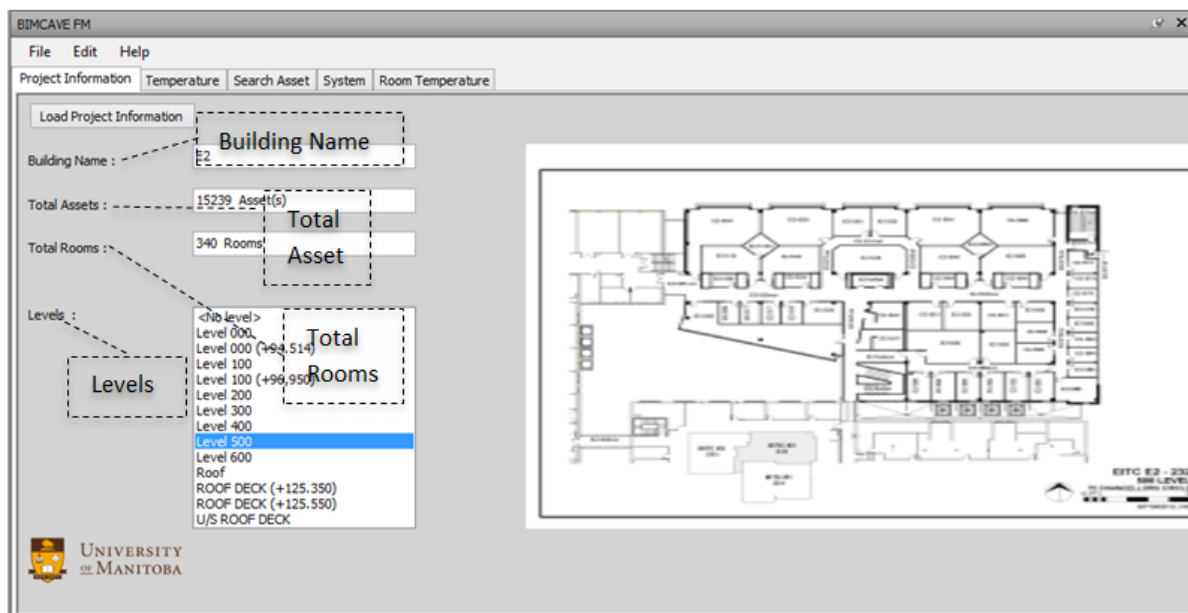


Figure 12: Project information sample

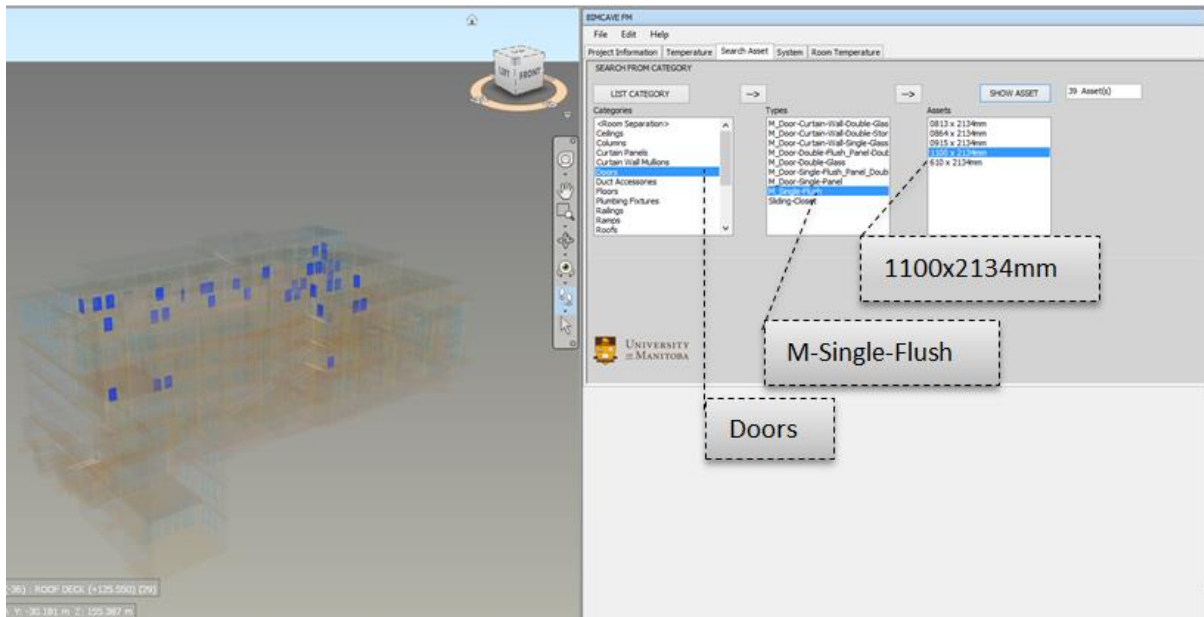


Figure 13: Search asset function result for selected door type

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 21°C, green is used for temperatures that were between 21°C to 23°C, and red is specified for the temperatures that were above 23°C. 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 14 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<sub>2</sub> 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 15).

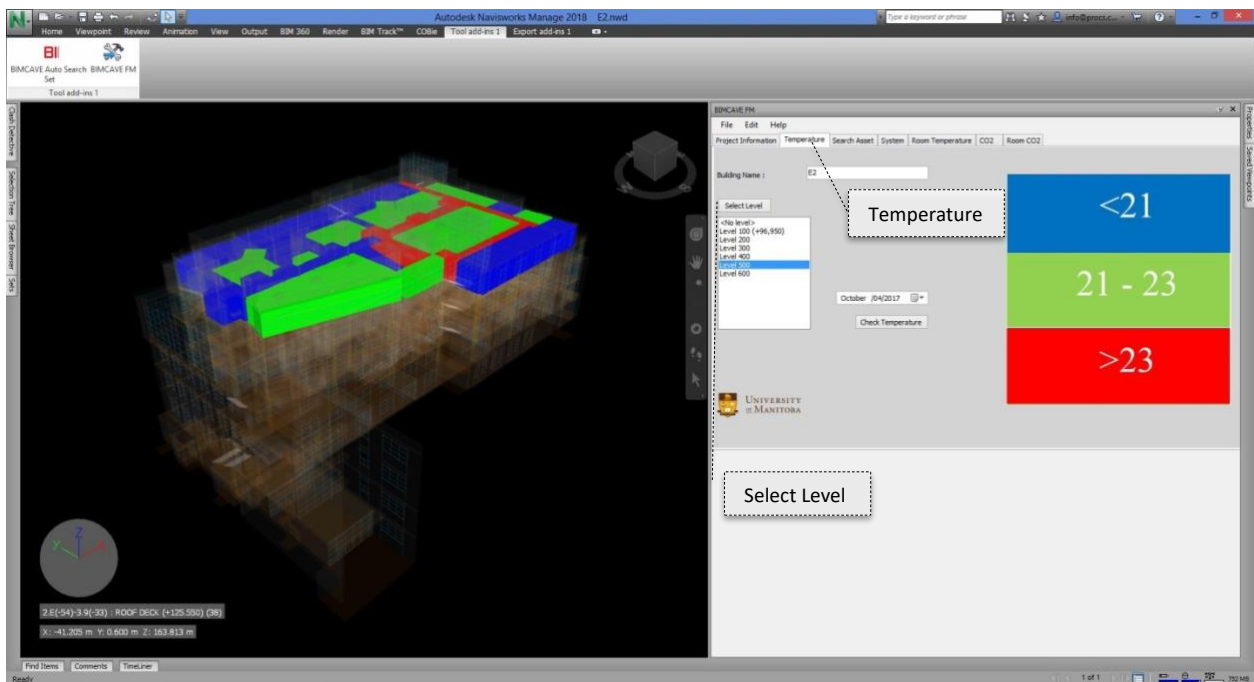


Figure 14: Sample temperature data for the fifth floor

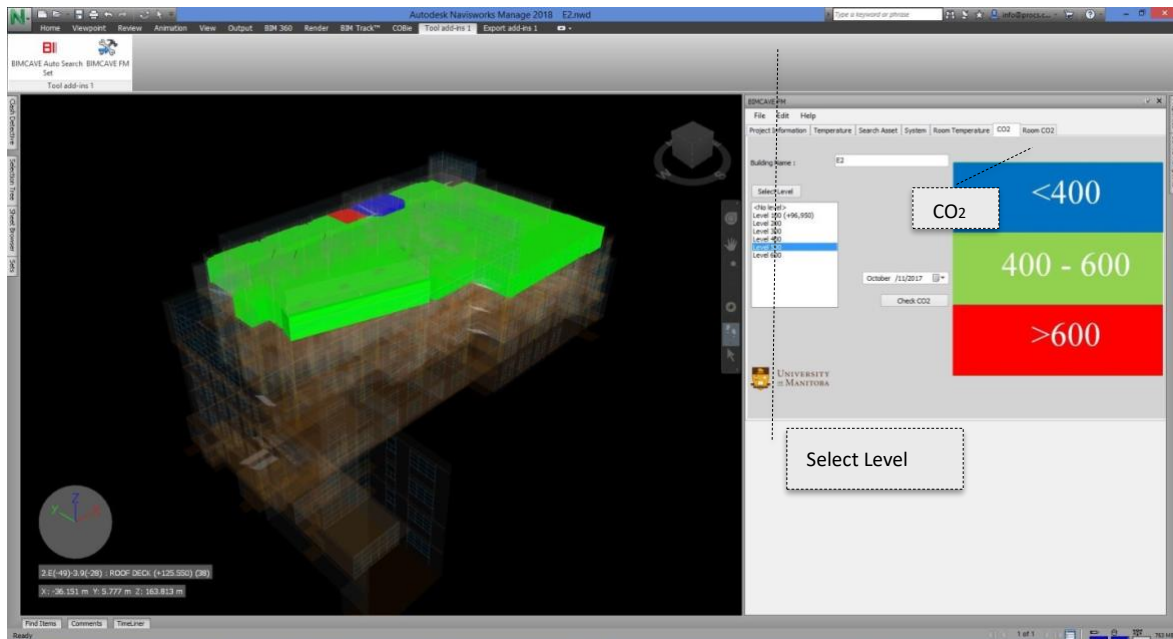


Figure 15: Sample CO<sub>2</sub> data for the fifth floor

It should be noted that the temperature and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> level data. This approach provides flexibility to integrate with live sensor database and instantly update the appearance of model elements with latest available sensor data.

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<sub>2</sub> 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<sub>2</sub> level (if Room CO<sub>2</sub> tab is chosen). Furthermore, to enable more precise visualization, only the selected room element is visible whereas all other elements are transparent. Figures Figure 16 and Figure 17, show the implemented approach for temperature and CO<sub>2</sub> data, respectively.

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<sub>2</sub> 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 CO2 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 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.

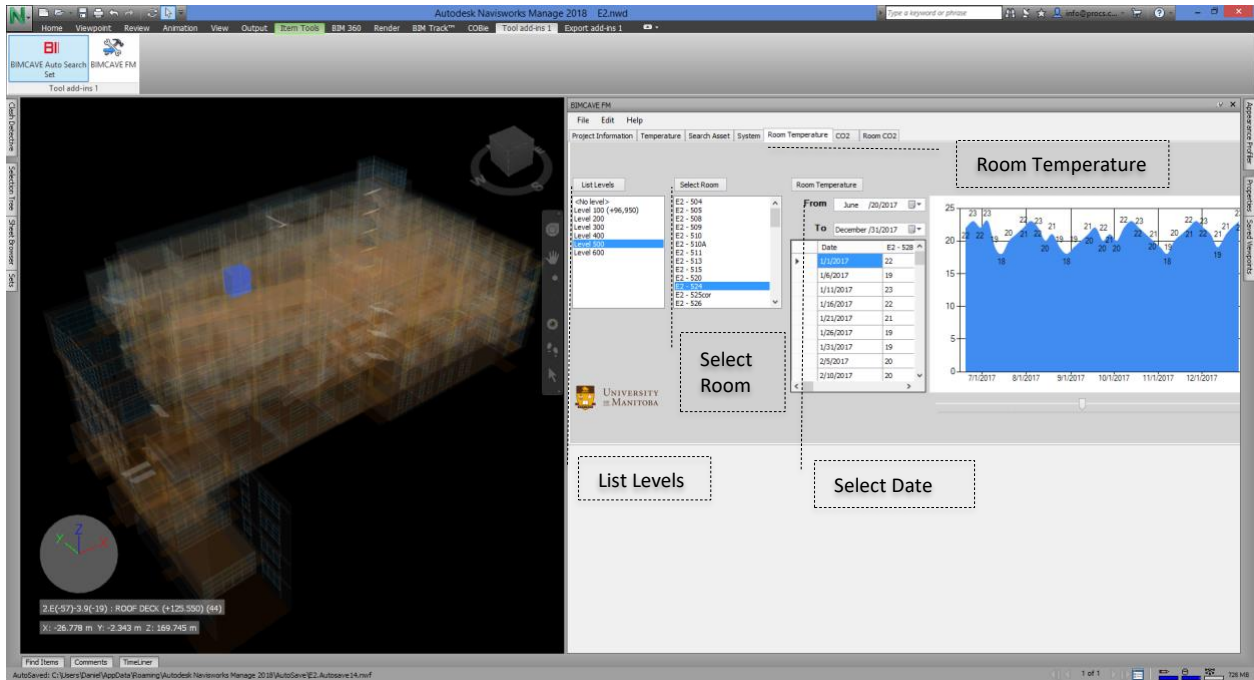


Figure 16: Sample room temperature historical data presentation

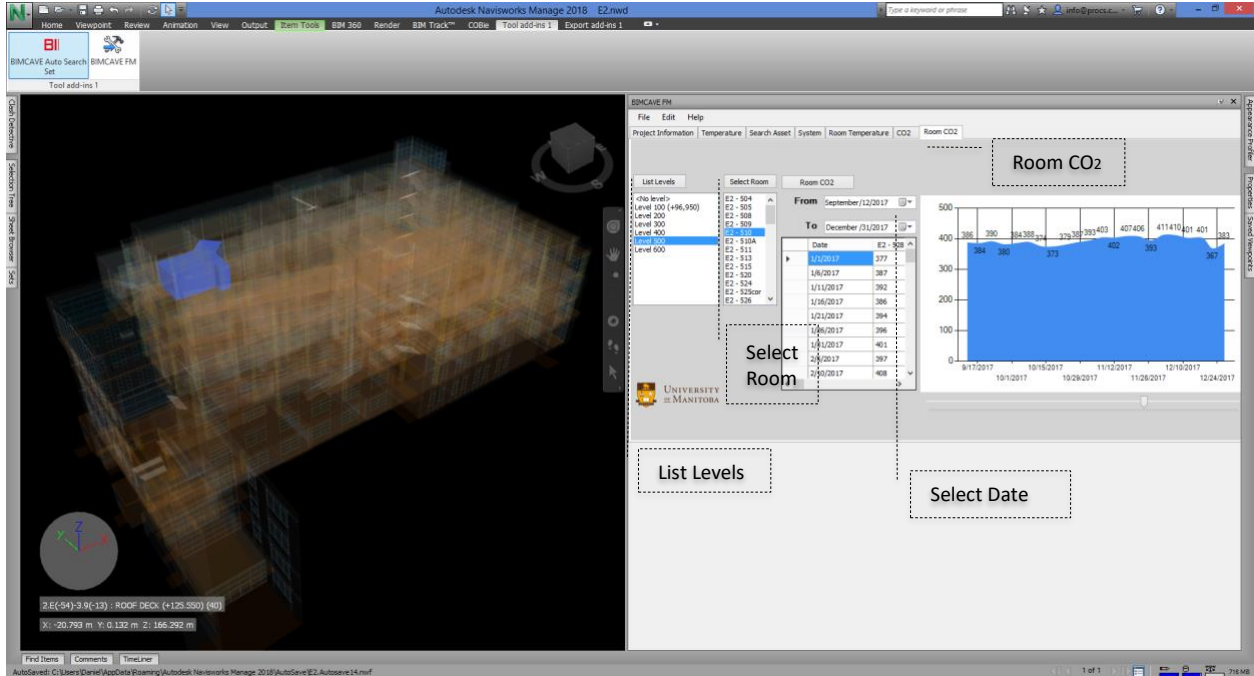


Figure 17: Sample room CO2 historical data visualization

## 8. CONCLUSION

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 (Liu and Akinici, 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 authors' knowledge, this is the first paper that utilizes widely used software Navisworks for 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<sub>2</sub>) that would enable facility operators to obtain the required information. Figure 18 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 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<sub>2</sub> 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 about 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).

	First Approach	Second Approach	Third Approach
Functions	Sensor-Revit integration	Sensor-Revit-Navisworks integration	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 18: 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 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 comparison of the design and actual energy consumptions, which can be used in the building energy certification procedures.

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