Integrating BIM into sensor-based facilities management operations

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Abstract

Purpose – To mitigate the problems in sensor-based facility management (FM) such as lack of detailed visual information about a built facility and the maintenance of large scale sensor deployments, an integrated data source for the facility's life cycle should be used. Building information modeling (BIM) provides a useful visual model and database that can be used as a repository for all data captured or made during the facility's life cycle. It can be used for modeling the sensing-based system for data collection, serving as a source of all information for smart objects such as the sensors used for that purpose. Although few studies have been conducted in integrating BIM with sensor-based monitoring system, providing an integrated platform using BIM for improving the communication between FMs and Internet of Things (IoT) companies in cases encountered failed sensors has received the least attention in the technical literature. Therefore, the purpose of this paper is to conceptualize and develop a BIM-based system architecture for fault detection and alert generation for malfunctioning FM sensors in smart IoT environments during the operational phase of a building to ensure minimal disruption to monitoring services.

Design/methodology/approach – This paper describes an attempt to examine the applicability of BIM for an efficient sensor failure management system in smart IoT environments during the operational phase of a building. For this purpose, a seven-story office building with four typical types of FM-related sensors with all associated parameters was modeled in a commercial BIM platform. An integrated workflow was developed in Dynamo, a visual programming tool, to integrate the associated sensors maintenance-related information to a cloud-based tool to provide a fast and efficient communication platform between the building facility manager and IoT companies for intelligent sensor management.

Findings – The information within BIM allows better and more effective decision-making for building facility managers. Integrating building and sensors information within BIM to a cloud-based system can facilitate better communication between the building facility manager and IoT company for an effective IoT system maintenance. Using a developed integrated workflow (including three specifically designed modules) in Dynamo, a visual programming tool, the system was able to automatically extract and send all essential information such as the type of failed sensors as well as their model and location to IoT companies in the event of sensor failure using a cloud database that is effective for the timely maintenance and replacement of sensors. The system developed in this study was implemented, and its capabilities were illustrated through a case study. The use of the developed system can help facility managers in taking timely actions in the event of any sensor failure and/or malfunction to ensure minimal disruption to monitoring services.

Research limitations/implications – However, there are some limitations in this work which are as follows: while the present study demonstrates the feasibility of using BIM in the maintenance planning of monitoring systems in the building, the developed workflow can be expanded by integrating some type of sensors like an occupancy sensor to the developed workflow to automatically record and identify the number of occupants (visitors) to prioritize the maintenance work; and the developed workflow can be integrated with the sensors' data and some machine learning techniques to automatically identify the sensors' malfunction and update the BIM model accordingly.

Practical implications – Transferring the related information such as the room location, occupancy status, number of occupants, type and model of the sensor, sensor ID and required action from the BIM model to the cloud would be extremely helpful to the IoT companies to actually visualize workspaces in advance,

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and to plan for timely and effective decision-making without any physical inspection, and to support maintenance planning decisions, such as prioritizing maintenance works by considering different factors such as the importance of spaces and number of occupancies. The developed framework is also beneficial for preventive maintenance works. The system can be set up according to the maintenance and time-based expiration schedules, automatically sharing alerts with FMs and IoT maintenance contractors in advance about the IoT parts replacement. For effective predictive maintenance planning, machine learning techniques can be integrated into the developed workflow to efficiently predict the future condition of individual IoT components such as data loggers and sensors, etc. as well as MEP components.

Originality/value – Lack of detailed visual information about a built facility can be a reason behind the inefficient management of a facility. Detecting and repairing failed sensors at the earliest possible time is critical to ensure the functional continuity of the monitoring systems. On the other hand, the maintenance of large-scale sensor deployments becomes a significant challenge. Despite its importance, few studies have been conducted in integrating BIM with a sensor-based monitoring system, providing an integrated platform using BIM for improving the communication between facility managers and IoT companies in cases encountered failed sensors. In this paper, a cloud-based BIM platform was developed for the maintenance and timely replacement of sensors which are critical to ensure minimal disruption to monitoring services in sensor-based FM.

Keywords Building information modeling, Operational phase, Sensor-based facility management, Fault detection, Smart IoT environments, Sensor management

Paper type Research paper

1. Introduction

Facility management (FM) is focused on the efficient operation and maintenance of commercial and industrial properties. According to the International Facilities Management Association (IFMA, 2009), FM is defined as a multidisciplinary task to provide a satisfactory built environment by coordinating people, places, processes, technology and the environment.

The use of different types of intelligent technologies in the workplace necessitates the connectivity of these technologies through enabling digital platforms. The Internet of Things (IoT) is an enabler of such connectivity that facilitates efficient maintenance decisions. The data collected by the IoT allow FM teams to be more effective in preventing maintenance issues and reducing the time spent on repairs and regular maintenance tasks. Sensors play a significant role in data collection on an IoT platform.

A study from The National Institute of Standards and Technology's (NIST), (2020) showed that most efficiency-related losses in US capital facilities come from insufficient interoperability among the software systems of computer-aided design, engineering and FM communication, while interoperability issues and a lack of well-integrated information management systems and documentation techniques can make FM an expensive task. The most significant FM cost portion is allocated to data verification and validation, data transfer, interoperability and information delays (Gallaher *et al.*, 2004). One of the main challenges in sensor-based FM is in the data visualization stage in which 2D vector graphics are used because these are not sufficiently interactive and can only be manipulated by a trained operator (Reeser *et al.*, 2015). Lack of detailed visual information about a built facility can be a reason for that facility's inefficient management. Given the importance of health monitoring applications, it is critical to monitor and maintain the functionality of the IoT deployment continuously. Hence, detecting and repairing failed sensors simultaneously is critical to ensure the monitoring systems' functional continuity. On the other hand, the maintenance of large-scale sensor deployments has become a significant challenge.

To mitigate these problems, an integrated data source for the facility's life cycle should be used. Building information modeling (BIM) provides a useful visual model and database used as a repository for all data captured or created during the facility's life cycle. Currently, BIM is increasingly applied to FM in the operations and maintenance stage. Simultaneously, IoT technology can be used to acquire operational data on building facilities to support FM. BIM can be used for modeling the sensor-based system for data collection, serving as a source of all information for smart objects such as the sensors used for that purpose. Although few researchers have investigated the integration of BIM with sensor-based monitoring systems (Suprabhas, 2016; Kazado *et al.*, 2019; Chang *et al.*, 2018; Kensek, 2020), most of them have focused exclusively on the automatic transmission of sensor information to BIM models. Providing an integrated platform using BIM to improve communication between FM and IoT companies in the event of sensor failure has received the least attention in the technical literature. The main objective of this paper is to conceptualize and develop a BIM-based system architecture for fault detection and alert generation for malfunctioning FM sensors in smart IoT environments during the operational phase of a building for the maintenance and timely replacement of sensors.

2. Building information modeling

The architecture, engineering and construction (AEC) industry has been seeking a useful tool for reducing projects' cost and time to completion and for increasing productivity and quality (Azhar *et al.*, 2008). Typically, there are hundreds to thousands of documents for each project, and human interpretations are required to tie them together. Effective coordination between design disciplines and the communication of design information to the field is a constant challenge. BIM has significantly altered the way building information is managed by the AEC industry. It incorporates digital modeling software to design and manage a project more efficiently (Nassar, 2010). BIM breaks down the barriers between disciplines by encouraging knowledge sharing throughout the project's life cycle. BIM improves constructability and can shorten the project's completion time. In a BIM project, multiple documents are not used in traditional ways (Australian Construction Industry Forum [ACIF], 2014); instead, they are digitized and added to a BIM software database. All information is built into an intelligent BIM model so that users need not look at separate drawings, schedules and specifications for the information on a particular element or a component in the project.

BIM is an organized collection of building data in a 3D building model (Graphisoft, a Nemwtschek Company, 2015). The model is a virtual equivalent of the actual building and its elements (Graphisoft, a Nemwtschek Company, 2015). These intelligent elements are the digital prototype of the physical elements, including walls, columns, windows, doors and stairs. The model allows us to simulate the building and understand its behavior before the commencement of construction. The building-related data can be easily archived in the BIM model for future use, analysis, retrieval and maintenance.

3. Utilizing building information modeling in sensor-based facilities management

BIM models can be valuable tools in FM because they are essentially 3D model interfaces with links to information on the building components and the equipment that needs to be maintained. For instance, information about installation, operation and maintenance manuals; spare part lists; and construction materials can be stored in a BIM model. The applications of BIM for operation and FM can include record modeling, preventive maintenance scheduling, building system analysis, asset management, space management, tracking and disaster planning.

For managing older buildings, BIM integrated within the clouds generated by a 3D scanning of the building can be used to overcome the absence of data. This process can serve several purposes, including spatial analysis, renovation and retrofitting. Using Web services and cloud-based hosting, the project's participants (e.g. owners, facility managers, engineers and contractors) can secure access to the shared data. FM companies have recently added value and have increased profit margins by using IoT solutions to reduce costs and increase value to end users.

A significant number of studies have been conducted to integrate BIM into the monitoring system, but it remains challenging. Wang *et al.* (2013) found that applying BIM in monitoring systems can improve the effectiveness of monitoring processes. Valinejadshoubi *et al.* (2017, 2018a) investigated the feasibility of using BIM in the structural health-monitoring process. They demonstrated the feasibility of creating, visualizing and managing sensor data and information in a BIM model for structural health monitoring. Valinejadshoubi *et al.* (2018b) developed a BIM-based integrated model to rapidly detect structural damage using strain values. Suprabhas and Nicholas Dib (2017) developed an application that integrates sensor data collected using a wireless sensor network; the application reports the data via a virtual model of the building to aid FM personnel in the early detection of defects. Cahill *et al.* (2012) examined the implementations of BIM to potentially support a static data value from a sensor data source to assist stakeholders in making appropriate decisions regarding a building's life cycle. Zhang *et al.* (2015) developed an FM tool to support energy management in buildings.

The benefits to the FM discipline of using sensors are numerous, and the failure of these sensors can increase operational costs and lead to undesirable consequences. A sensor takes measurements at regular intervals and helps facility managers make decisions based on a combination of captured sensor data. If a sensor suddenly fails or malfunctions, the building facility manager should inform the IoT companies at the earliest possible juncture to fix the problem because such a failure can negatively affect or even interrupt the monitoring system, and accordingly, any decision based on the data. Therefore, timely maintenance of failed sensors is critical in such deployments to ensure minimal monitoring service disruption. Despite the importance of timely detection of a failed sensor in IoT monitoring, it has received the least attention in the literature. To mitigate this issue, an integrated BIM-based workflow was developed to integrate the associated sensor maintenance-related information to a cloud-based tool to provide a fast and efficient communication platform between the building facility manager and IoT companies for intelligent sensor management.

4. Research methodology

In this case-based research study, the author developed a sensor-based FM integrated with a cloud-based service tool, which can be used for real-time communication between different disciplines. A seven-story office building, shown in Figure 1, was simulated in Autodesk Revit software. Sensors typically used in FM, such as occupancy detection sensors, temperature sensors, humidity sensors, and CO_2 sensors, were modeled and placed in their designated locations in the building's BIM model. Parameters such as *Sensor Name*, *Model*, *Mark*, *Website* and *Comment* were used for the sensors' identification, and parameters such as *Level* and *Station* were used to identify the sensors' location. Rooms were assigned to each specified space on all floors to work as the sensors' stations (locations) in the BIM model. Information such as sensors' models and sensors' marks (physical IDs) were given to the building facility manager by the IoT company to accommodate them into their central BIM model upon installing the sensory system in the building.

Figure 1. 3D view of the case-study building

For effective and fast communication between the facility manager and IoT company in case of a sensor failure, a real-time BIM-based communication platform was developed in this study. To create this platform, a workflow was designed in Dynamo to automatically extract and send all information such as the sensor's type, model and exact location from the detailed BIM model to the IoT company whenever a sensor failure was reported to the facility manager. In case of a diagnosis of multiple sensor failures, sensor replacement can be prioritized by considering the average number of daily occupants in each room based on the occupancy sensor data.

Cloud-based collaboration and data exchange service applications such as Flux, Konstru or Speckle can be used to send notifications to the IoT company through their wireless devices, such as personal smartphones and to receive sensor failure notifications and all essential information from the BIM model. Figure 2 illustrates the dataflow schema used in this study.

5. Integrating sensor-based facility management with building information modeling

5.1 Placing sensors in the building information modeling model

Categories in Revit include column, beam, floor, roof, door and window. There is also a category pertinent to specialty equipment, enabling the inclusion of sensor classes such as

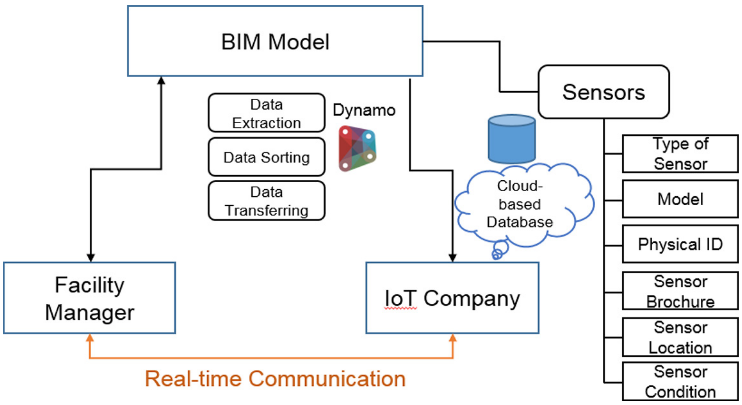

Figure 2. Developed dataflow schema

IfcSensor and *IfcSensorType*. In Revit, each category has its own industry foundation class (IFC) name; for example, a column is *IfcColumn,* and a roof is *IfcRoof*.

Four sensors – occupancy, temperature, humidity and CO_2 – are used in this study. These are shown in Table 1 along with their respective purposes. Each sensor was modeled and placed in its appropriate location in the building's BIM model. Two sets of parameters were defined for each sensor. The first includes *Ifc ExportType* and *IfcExportAs*, and the second includes *Name*, *Station*, *Level*, *Model*, *Mark* and *Sensed Data*. The *Station* parameter was defined to show where sensors were installed. The *Mark* parameter was determined to map virtual sensors in the BIM model onto their real-world sensors. This was designed to link the collected data from each physical sensor stored in the data acquisition system with virtual sensors in the BIM model through Web-based methods such as the internet protocol address and programming methods such as the application programming interface. After defining the four aforementioned sensors, these sensors were placed in their locations in the BIM model.

Figure 3 shows the location of sensors in each room of Level 1 in 2D and 3D views. As shown in Figure 3, the temperature sensor, CO_2 sensor, humidity sensor and occupancy sensor are displayed by the colors red, violet, blue and green, respectively.

5.2 Creating a schedule of sensors used in the building information modeling model

After placing all sensors in their locations, their information can be sorted and managed. The BIM software can provide the schedule table for each type of 3D element. As many parameters as are needed can be considered in the table. As illustrated in Figure 4, parameters such as *Name*, *Station*, *Level*, *Model*, *Mark* and *Sensed Data* were considered in the sensor schedule table. As mentioned earlier, the physical sensors' specific IDs must be provided and assigned manually to each sensor in the model using the *Mark* parameter. The ID numbers shown in the *Mark* column in the schedule table were hypothetical in this study. The *Station* parameter was used to indicate the location of each sensor in the model. In the BIM model, each element had a specific ID. By using the elements' ID, the exact position of each sensor was marked in the model. In the *Station* column, sensors' locations were

Table 1.
Types of sensors used in this study

Type	Location	Application	Benefits
Occupancy sensor	On the wall/ceiling	To detect the presence or absence of people in a space to activate and deactivate the lights	Lighting energy savings Increased comfort level
Temperature sensor	On the wall (should not be near outside doors/windows)	HVAC environmental control	Heating energy savings Increased comfort level
Humidity sensor	On the ground/wall	Monitoring the humidity levels in any room of a building	Preventing unsafe or undesirable moisture levels in the room
CO_2 sensor	On the same wall as the temperature sensor (48 in, or 122 cm, is standard)	Monitoring the room's CO_2 level	Increased indoor air quality

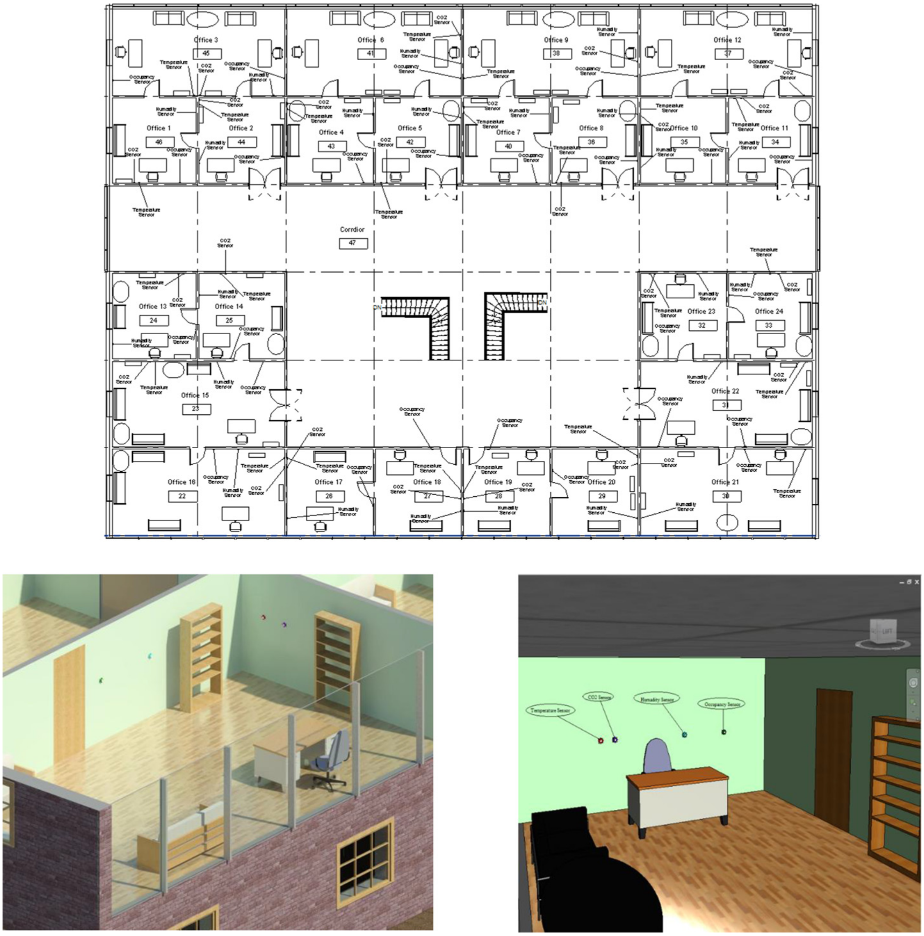

Figure 3.
Visualization of sensors in 2D and 3D views in the BIM model

identified by the room ID where they were installed. Figure 4 shows the sensors' schedule table in the BIM model for offices 1 to 5 and the sensors' locations in each office.

6. Results

Cloud-based applications can improve mobility and accessibility. Cloud-based application tools can take data from different sources and combine them into one online navigation 3D model. The model provides access to all building data and associated operation manuals, manufacturer specs, equipment catalogs and images. It can help facility managers be involved in a real-time collaborative environment. Facility managers will have access to the building data from anywhere with an internet connection at any time, which can help when making significant decisions. It can improve the real-time collaboration between team members, such as engineers and facility managers.

The emerging cloud-BIM technology is considered to be an enabling tool that can deal with the standalone nature of traditional BIM. It can lead to higher levels of cooperation and

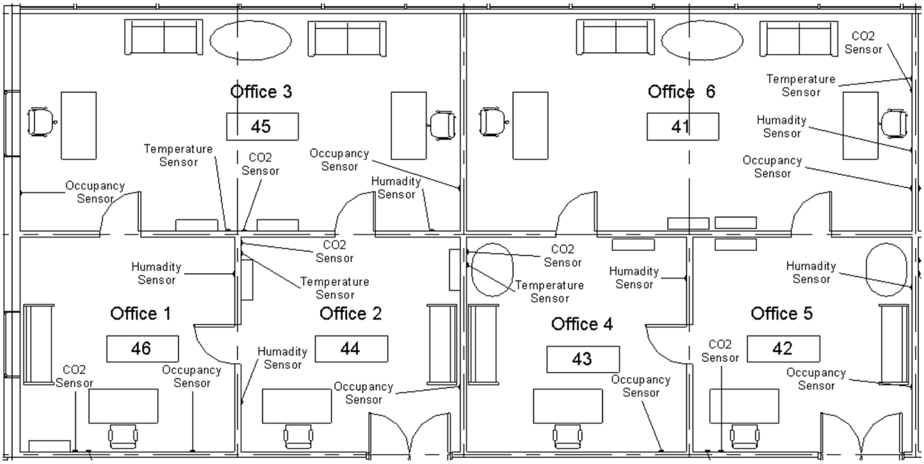

Figure 4.
Sensor schedule table created in the BIM model and location of sensors in 2D view

collaboration and can provide an effective real-time communication platform for project team members (Wong *et al.*, 2014). For example, if the building facility manager notices that some sensors in the building are not working, then he or she, through a cloud-based application, can inform the service personnel from the IoT company and ask them to replace the sensors and provide the sensors' locations, ID numbers and model and specifications. Simultaneously, he or she can inform the building manager to ensure that the specified room is unoccupied at specific times. In this study, Dynamo was used to integrate the BIM model with a Web-based service. Dynamo is a visual programming and computational design tool that extends BIM with the data and logic environment of a graphical algorithm editor, and it is ultimately linked with the BIM environment. Building data from the model are extracted, sorted, updated and shared with a third party in the cloud-based environment.

Room-related parameters such as *Name*, *Level*, *Room ID*, *Occupancy* and *Number of Occupants* as well as sensor-related parameters such as *Sensor Name*, *Sensor Station*, *Mark*, *Comments* and *Website* were extracted from the BIM model and sent to a cloud-based collaboration and data exchange service application such as Flux, Konstru or Speckle to share them between the IoT company and the building manager and inform them about any updated information.

Figures 5–7 show the modules developed in Dynamo to extract, combine and sort *Rooms* and *Sensors* information from the BIM model and automatically update them in the cloud-based platform. As shown, an appropriate relationship between the nodes is essential for automating this process. The building facility manager provides information such as the names and occupancy status of the rooms. The number of occupants can be provided either by the facility manager or as detected by occupancy sensors. The rooms' location is derived from the BIM model. The IoT company provides the sensors' names, physical IDs and websites. The sensors' location is provided from the BIM model, and the facility manager supplies information about the status of the sensors.

As shown in Figure 8, it is assumed that occupancy sensors in office number four and office number five are not working correctly. Therefore, the building facility manager can request the IoT company to replace the failed sensors and ask the building supervisor to ensure the associated rooms are unoccupied according to the maintenance schedule. Consequently, parameters in the cloud are automatically updated through *Dynamo*, and the

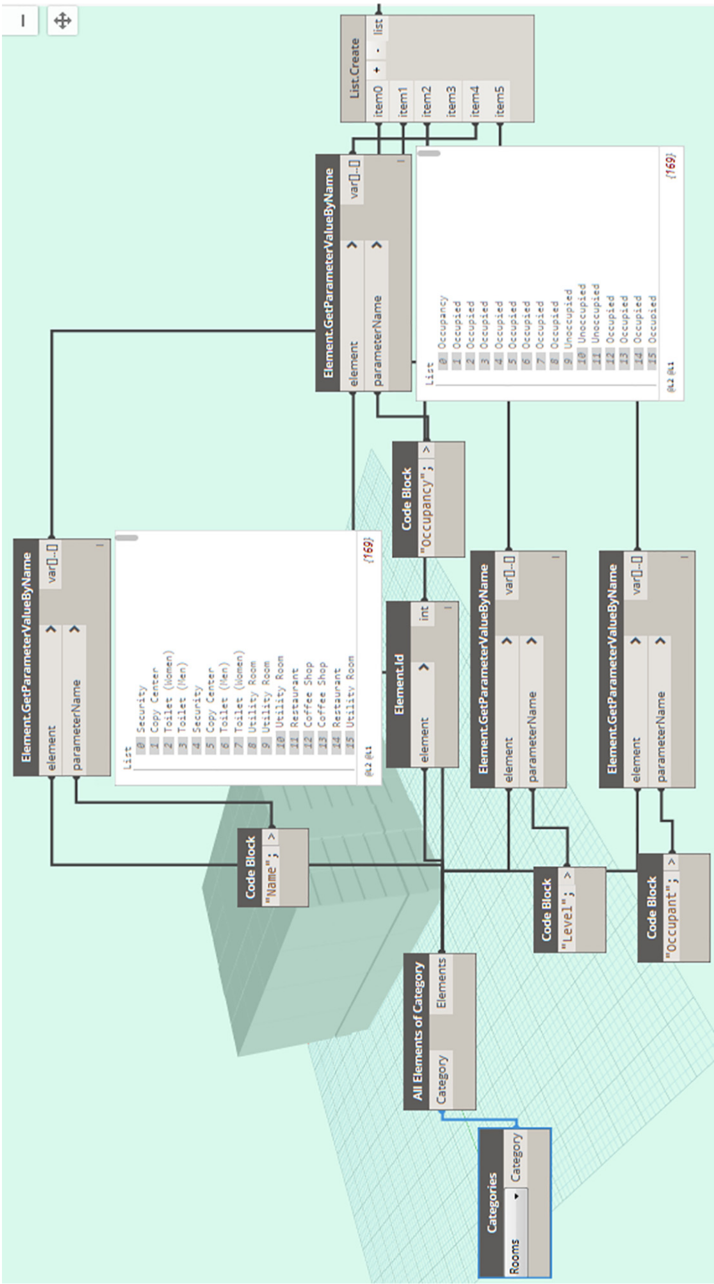

Figure 5.
Extracting, combining and sorting room information from the BIM model

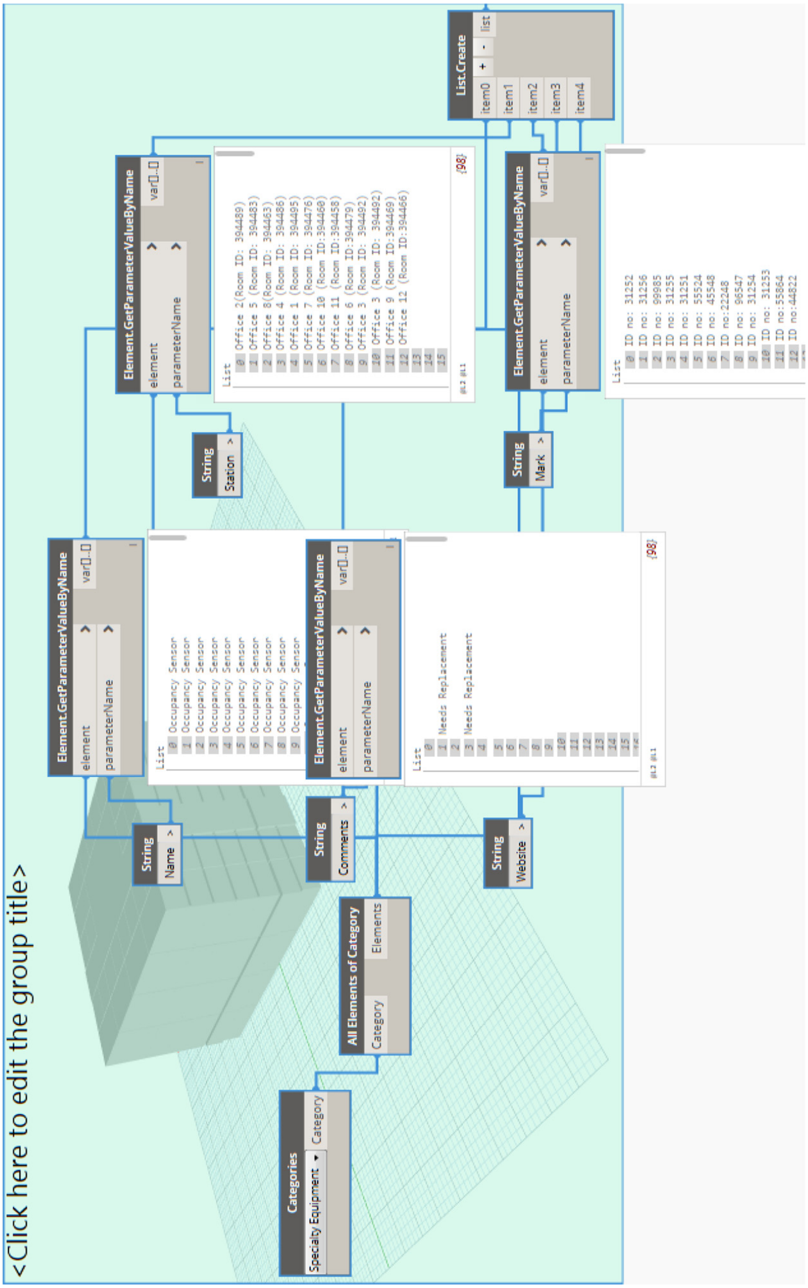

Figure 6.
Extracting, combining and sorting sensor information from the BIM model

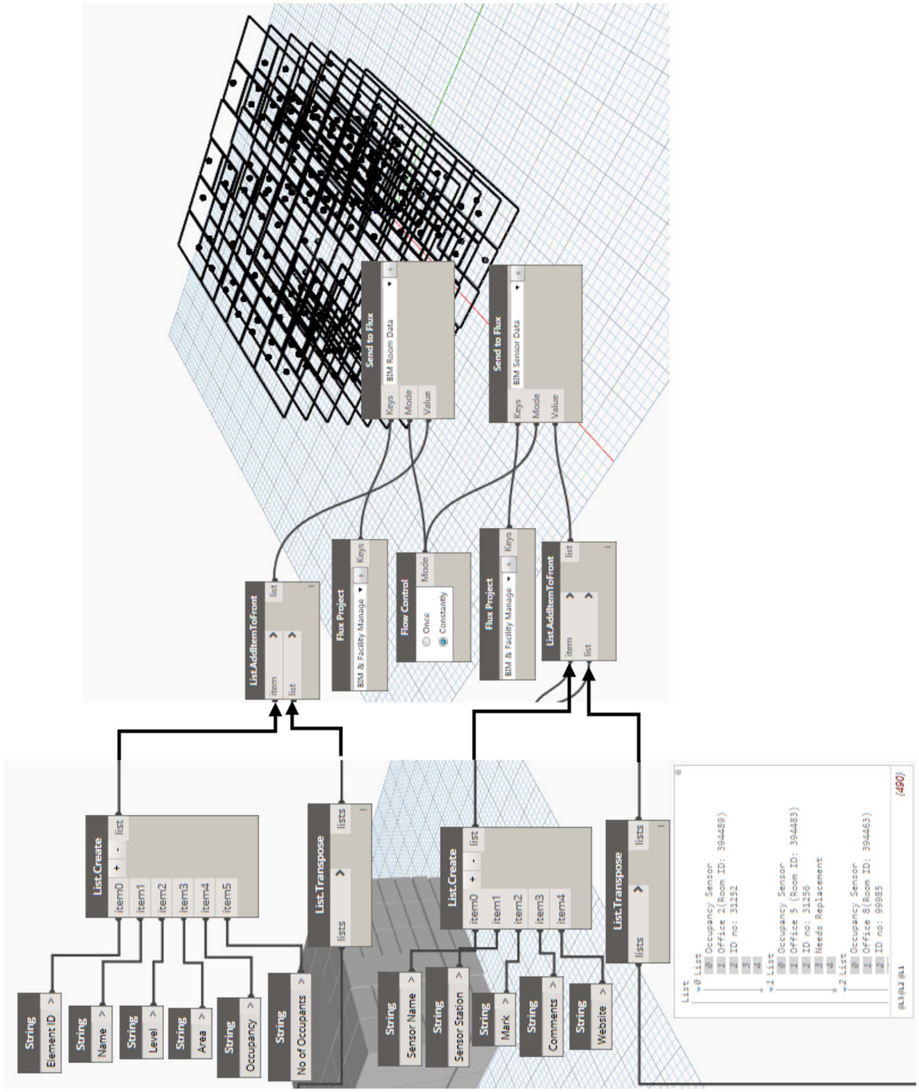

Figure 7.
Integrating BIM model into a cloud-based database

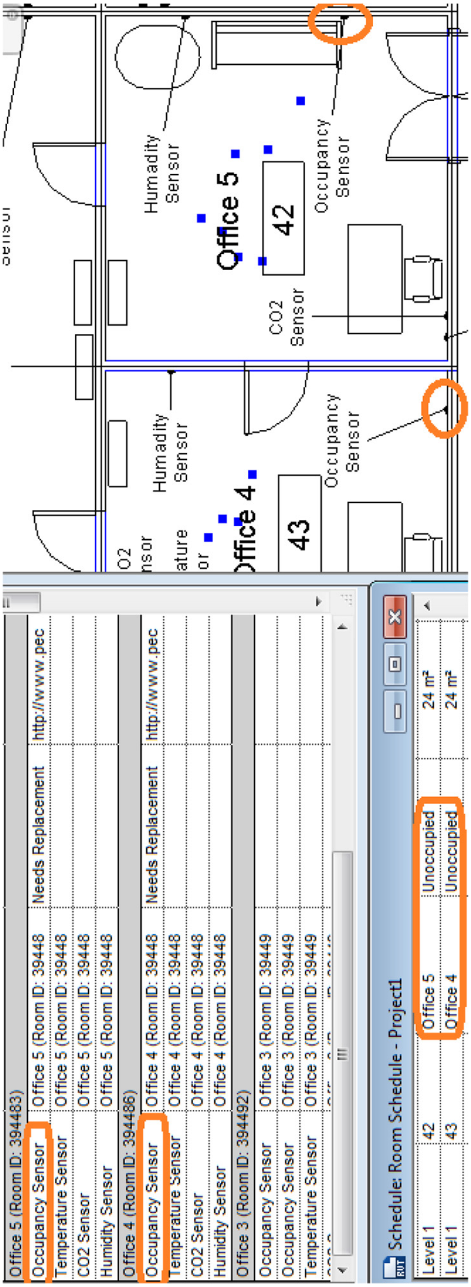

Figure 8.
Updating some of the parameters of sensor and room elements in the BIM model

IoT company, as well as the building manager, will both be informed simultaneously about these requests through their desktop computer or smartphone, email and/or iPad (Figure 9). Therefore, the IoT company's service personnel will be informed of the failed sensors' location, ID number and specifications. Some other parameters, such as the preferred replacement date and time and sensors image, can also be added to this list.

As explained in this section, the parameters of the virtual sensors in the BIM model can be successfully updated by building facility managers and transferred to the cloud-based database to generate an alert for malfunctioning FM sensors in smart IoT environments to be used by the IoT company.

6.1 Discussion

Building maintenance is a complex process that requires a significant flow of information and a quick call to action. Despite this, many facility managers do not have access to a unique platform with centralized information, where they can check the status of all operations, including any failure reports. The solution may involve centralizing all daily work and using mobile devices to register every failure and to manage and monitor the next steps in real time. To address this issue, this study introduced an automated, integrated workflow to use BIM information to provide a fast and efficient communication platform between the building facility manager and the

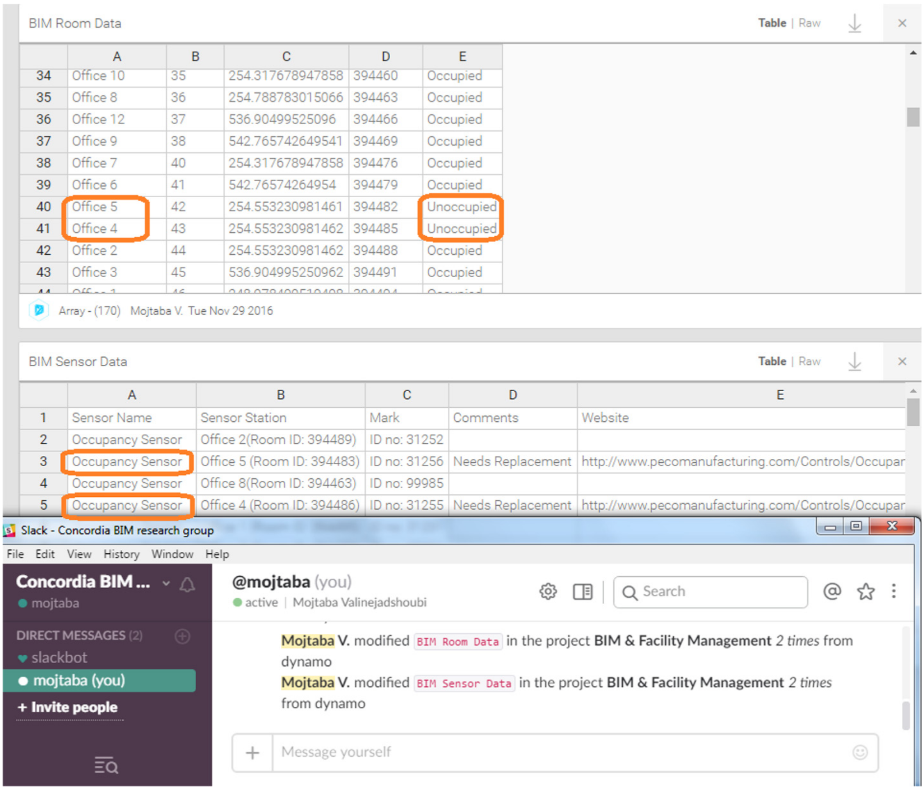

Figure 9. Real-time notification and updating of rooms and sensors status in a cloud database

IoT companies for sensor replacement management in case any sensor failure or sensor malfunction occurs in the building.

In this study, the BIM model was developed to accommodate all essential parameters. Two types of parameters were used to identify the type and location of each virtual sensor in the BIM model. To develop a real-time BIM-based communication platform, an integrated workflow (including three specifically designed modules) was developed in Dynamo to automatically extract and send all essential information such as the sensor's type, model and location to the IoT company in the event of sensor failure. The integration of the monitoring system into the BIM would improve the sensors' operation and maintenance plan during the building operational phase by helping the facility managers inspect the monitoring system and the sensors' performance and by sending the relevant information to the model in the event of any sensor failure and/or malfunction. It would then transfer all essential information to the IoT company for timely sensor replacement to ensure minimal disruption to monitoring services.

The developed framework also benefits preventive maintenance work. The system can be set up according to the maintenance and expiration schedules, automatically sharing alerts with FMs and IoT maintenance contractors in advance about the IoT parts replacement. For effective predictive maintenance planning, machine learning techniques can be integrated into the developed workflow to efficiently predict the future condition of individual IoT components like data loggers and sensors as well as MEP components. For instance, when temperature sensors are used to monitor the thermal condition of different rooms in a building, a threshold can be defined, according to a specific standard or energy policy, to send an automatic thermal comfort alert to the cloud to inform the building FMs whenever the operating temperature exceeds the predefined thresholds. When FMs receive thermal discomfort alerts, they can initiate a root cause analysis to identify and locate the problem. For sensor fault detection, machine learning techniques can also be used in the developed system to establish, for example, the initial thermal pattern of each room using temperature sensors to find malfunctioning sensors when the sensor records a different thermal pattern than another sensor in the same room.

Transferring related information such as the room location, occupancy status, number of occupants, type and model of the sensor, sensor ID and required action from the BIM model to the cloud would help the IoT companies to visualize the workspaces in advance and to plan for timely and effective decision-making without any physical inspection, thereby reducing the inspection cost. It would also help support maintenance planning decisions, such as prioritizing maintenance works, by considering different factors such as the importance of spaces and number of occupancies.

However, there are some limitations in this work, which are as follows:

(1) Although the present study demonstrates the feasibility of using BIM in the maintenance planning of monitoring systems in the building, the developed workflow can be expanded by integrating some types of sensors like occupancy sensors into the developed workflow to automatically record and identify the number of occupants and visitors to prioritize the maintenance work.

(2) The developed workflow can be integrated with the sensors' data and machine learning techniques to automatically identify the sensors' malfunctions and update the BIM model accordingly.

7. Conclusion

IoT technology dramatically reduces operation and maintenance costs. Using IoT sensors, the building equipment maintenance can be automatically scheduled. One of the most significant inefficiencies in building operations is the general lack of access to credible building and sensor information. This study's author investigated BIM's capability in sensor information management using cloud services in smart IoT environments during a building's operational phase. The research has highlighted the applicability of BIM in an efficient and rapid sensor failure management system. Based on the study presented here, the following conclusions are made:

- The information within BIM allows better and more effective decision-making for building facility managers.
- Integrating building and sensor information from BIM into a cloud-based system can facilitate better communication between the building facility manager and the IoT company for effective IoT system maintenance.
- The system developed in this study was implemented, and its capabilities were illustrated through a case study. The developed system (including three specifically designed modules) was able to automatically extract, read and transfer all essential information to a cloud database to be used by an IoT company for timely sensor replacement.
- The use of the developed system can help facility managers take timely actions in the event of any sensor failure and/or malfunction to ensure minimal disruption to monitoring services.

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