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Development of a Management System to Improve the Energy Efficiency of Public Buildings by Integrating IoT and BIM

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Abstract

Question: How can the building information models be more dynamic using IoT, so that it improves the comfort level of end-users in educational settings?

Purpose: A major challenge for using BIM during the building's life cycle, and especially at the post-occupancy stage is the lack of live information in the model, which reflects the need for a dynamic model. The requirements for quality control of the interior of buildings and ensuring the comfort of residents, especially in the educational environment due to their high importance in providing comfort, improving productivity, and lean maintenance, have increased. The lean maintenance process structure is designed based on five lean principles, which guide and support organizations to pursue maintenance excellence and improve the level of comfort and energy.

Research Method: This study provides a solution that uses environmental data collected through Internet of Things (IoT) sensors to make the model dynamic. This is done by entering the live data into the building information model of a building. For this purpose, a web-based platform is designed that provides the possibility of displaying the level of comfort and control recommendations to improve the level of comfort.

Findings: This study shows that temperature and humidity are the two most effective parameters for the level of comfort. The dynamic building model of the institutional building used in the case study is then created and the level of comfort of its users is evaluated.

Limitations/Implications: One of the limitations of this research is the costly and time-consuming preparation and installation of sensors because just temperature and

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humidity were selected as the effective environmental parameters to collect the environmental parameters affecting the comfort level of users of an educational setting and entering this data into the building information model.

Value for authors: This study improves the comfort level of institutional project users by monitoring live information on a web-based platform significantly.

Keywords: Building Information Modeling (BIM), Internet of Things (IoT), User Comfort, Educational Environments, Institutional Projects, Dynamic Model

Paper type: Full paper

Introduction

Building Information Modeling (BIM) refers to the use of a multi-dimensional model during the planning, design, construction, operation, and maintenance stages of a building or generally a facility. In recent years, BIM has been considered seriously by the construction industry. BIM is used to facilitate the integration process of design and construction that results in optimized cost and time of the project (Atazadeh et al., 2021; Sacks et al., 2011). However, one of the primary steps of BIM is to be used throughout the project lifecycle. Nevertheless, due to lack of a mechanism to store information and control management issues, most building information models are used as static information resources that contain design and construction information only (Chen et al., 2014). Therefore, the main challenge for using BIM, during the operation and maintenance in particular, is lack of live information. Dynamic BIM includes real-time information about the building, such as data collected by various types of IoT sensors installed; therefore, a dynamic model can show the current conditions of the building. In addition, not only is energy efficiency significant for Facility Management (FM), but also indoor human comfort is an essential factor for building occupants. In other words, there should always be a balance between energy consumption and comfort level. The advantages of having a dynamic BIM with real-time data for facility managers include having appropriate opportunity to respond quickly to emergencies, planning for repair and preventive maintenance, better control and management of building data, and identifying patterns and trends of using the building. Through dynamic BIM, facility managers can visualize and monitor the current status of the building and its facilities, so that they can immediately identify a similar problem. This helps them to minimize the cost of repairs during the use of facilities, and prevent unsafe and unpleasant conditions for end-users (Cao et al., 2021; Chen et al., 2014). On the other hand, maintenance shares significant operating costs in an organization. It is considered as the main pillar of organizational performance. Lean thinking can be incorporated into maintenance activities by applying its principles and practices. Lean maintenance is a prerequisite for lean production systems, which greatly contributes to the balance of energy consumption in the building (Wang, 2015).

Generally, traditional methods encounter numerous limitations to collect information from building end-users. Usually, surveys have been used to collect data about the experience of end-users on their living environment. Moreover, hand tools are used for periodic measurement of parameters affecting the end-users' comfort level, which can be time-consuming, costly, and erroneous (Al Barazi, 2018). In addition, permanent evaluation and control of these parameters with the indicators determined based on relevant standards or regulations for timely decisions to provide these indicators, particularly in educational settings, due to its high importance and the regulations set for them, are among the challenges researchers are faced with in this field. On the one hand, progress in the field of measurement, communication, and processing physical and environmental information have made possible continuous monitoring of the building's environmental behavior, which is accessible by IoT devices. In addition, the use of BIM with the capability to integrate with other technologies has filled the gap of management and building interior quality. Since BIM uses static information at the design stage and building modeling, the combination of these technologies allows the dynamic information to enter into the information model through IoT sensors. Thus, there is an opportunity to integrate these two technologies to develop up-to-date and more complete models to identify the unwanted or inefficient energy behaviors, as well as to control the comfort level of users and the building's interior quality (Bottaccioli et al., 2017).

Lack of appropriate environmental comfort can affect students' learning capacity. The researchers examined thermometry conditions in university classrooms. However, other aspects must be considered to assess classroom comfort (Haverinen-Shaughnessy et al., 2015). Recent research on thermal comfort in educational settings such as kindergartens, primary and secondary schools and universities has found that the temperature of thermal comfort of children is different from that of adults and therefore does not meet international standard requirements (Ricciardi and Buratti, 2018).

The purpose of this study is to make BIM dynamic using IoT capabilities with a focus on improving the comfort level of end-users of educational settings. Collecting the environmental parameters affecting the comfort level of end-users of an educational setting by IoT sensors and entering this information in the BIM designed for the desired place is to make the model dynamic. Visualization of the comfort level, alerts and control measures by the system containing dynamic BIM is to improve the comfort level of end-users of educational settings. This research is significant given that better management of the building at the time of operation and maintenance requires a dynamic model of the building that includes accurate and updated information about the building's space and components, so that managers can make correct and timely decisions to improve conditions and reduce the costs of the project while using that model (Chen et al., 2014; Vignali et al., 2021).

Literature Review

In this section, literature on the IoT concept such as Lean Maintenance, Wireless Sensor Network (WSN) and their applications is presented. Moreover, applications of BIM, including BIM maturity and BIM standards such as IFC in the AEC/FM industry are illustrated. Integrating BIM with IoT to create an integrated system and its applications throughout the building lifecycle and use of the obtained dynamic model in the field of energy management and comfort level control are also reviewed in the coming sub-sections.

Lean Maintenance (LM)

Some consider Lean Maintenance to be merely a subset of Lean Manufacturing. But in reality, it is not like that. Lean Maintenance is a management strategy that aims to apply lean principles and goals in the management of physical assets. Lean Maintenance is a prerequisite for the success of Lean Production based on a lean thinking philosophy. The ultimate goal of lean thinking is to provide full value to the customer through processes. that produce zero waste. In this context, waste refers to the use of resources (such as time, labor, inventory, energy, etc.) in any way that does not add value to the final product or service. Lean Maintenance will lead to improved energy consumption and increased comfort level of people. In addition, to obtain world-class performance, maintenance strategies must be linked to production strategies such as Lean Maintenance (Mostafa, Lee, et al., 2015).

Internet of Things (IoT)

The IoT understands when the physical objects are connected to information systems in our lives; this can be used to facilitate live tracking of daily activities. The IoT has some capabilities, including pervasive internet, which is provided by using the sensors embedded in things and their connection to systems that allow communication between people and the network of devices. Atzori et al. (2010) define the IoT in an overview as a combination of three models: internet-oriented (middleware); thing-oriented (sensors); meaning-oriented (knowledge) (Atzori et al., 2010).

With a user-centered and theoretical description, the IoT is known as the relationship between sensors and actuators that has the ability to collect and analyze data, then display and share information in the form of a platform created by an integrated framework for innovative applications (Gubbi et al., 2013). The IoT can be defined as 'things with virtual identities and characters used in smart spaces, smart interfaces to connect and communicate in various domains such as environment, energy, and user comfort' (eposs, 2008).

WSN (Wireless Sensor Network) sensors are devices with the ability to measure various parameters in the physical world, such as pressure, temperature, humidity, carbon dioxide, light level, motion, water, gas, and electricity (Gokce et al., 2010). In the past, sensors relied on wired connection, such as the use of USB cables that were not flexible for sensor location. With the use of wireless technology and the emergence of WSN that were flexible and cost-effective systems compared to wired systems, the users enjoyed many advantages (Malatras et al., 2008). The WSN facilitates the relationship between the physical world and the digital world by creating a large number of small sensors by wireless protocols connected to each other (Malatras et al., 2008). The hardware platform that makes up the WSN usually includes radio transmitters (RF), micro-controllers, and power supplies. WSNs are currently used for a variety of purposes, such as monitoring the environment, facility management and maintenance, site security, and several other applications (Fei-liang, 2006).

The WSNs are currently available in some Building Management Systems (BMSs) that manage, control, and adjust features of building systems and provide services such as Heating, Ventilation, and Air Conditioning (HVAC), security, electrical systems, lightening, access control, resource monitoring, etc. (Fei-liang, 2006). In the following, five main advantages of using the WSNs in building management is presented according to N.Li and Becerik-Gerber (2011) included: A) better measurement of facility performance and environmental parameters; B) instant access to information; C) presenting the residents' behaviors in the field of energy consumption; D) problem detection and prediction; E) automatic energy control and management while lean maintaining the comfort index.

Using these sensors to transmit information to building models can be very useful (Becerik-Gerber et al., 2011). The next section provides a brief presentation on the BIM and its use/benefits.

Building Information Modeling (BIM)

The BIM is introduced as a way of creating, sharing, exchanging, and managing information throughout the building's lifecycle. BIM database includes information about all aspects of facilities (such as geometry, mechanical systems, construction planning) that is accumulated throughout its lifecycle. BIM standards are being developed rapidly, and various BIM-compliant applications are in the market. Technically, BIM is a CAD model that is connected to a database, such that any project-related information can be stored in it. Therefore, BIM acts as a shared source of information between the building design and implementation teams. The result of such information integration is increased coordination, reduced errors, wastes, and finally, increased quality of the outcome (Berwald, 2008; Vignali et al., 2021).

BIM Standards for Facility Management

With the introduction of BIM to facility management (FM), all building information collected throughout the building lifecycle is stored and this information can be shared with all participants. Industry Foundation Classes (IFC) standard was developed by the Building Smart Alliance (BSA) as the BIM standard to support and facilitate interoperability at various stages of the building lifecycle (Matarneh et al., 2019). This is used as a tool for the exchange of model-based data between applications based on the model of Architecture, Engineering, Construction, and Facility Management (AEC/FM) industries. It is currently supported by many CAD designs and many other applications. At the stages of facility lifecycle, the operation phase includes most of the costs and the whole lifecycle of a facility, while the design and construction phases include just a small part of this cycle. This issue clearly shows the advantages of using BIM in facility management and operation and maintenance stages, which significantly increases the value of facility documents compared to the traditional method without BIM. Becerik-Gerber et al. (2011) states that despite the additional costs for the owner when using BIM in the initial phases of the project (design and construction), the final model has the capability to reduce the owner's operation and maintenance costs (Becerik-Gerber et al., 2011).

BIM Integration with IoT Sensors

Although BIM is accepted in the AEC industry and is widely used today, the issue of integrating BIM with IoT sensors needs more research. According to the studies conducted so far, the integration of BIM and sensors based on the time, place, and how to integrate them is summarized below. Accordingly, there are four common integrations including (Liebich, 2013):

1. Perform experiment at the design stage
2. Simulation and monitoring the building performance
3. Preventive monitoring at the construction stage
4. Facility management at the operation and maintenance stage for better performance of the building and stronger management systems of the building.

Visual integration of sensors with BIM is performed as part of the graphical user interface that sensors are modeled as a part of a 3D model with its specific location. Integration helps various project stakeholders such as architects, engineers, contractors, building performance auditors, and facility managers to collaborate in a virtual environment with real-time data.

Jianli Chen et al. (2014) stated that developing models based on dynamic BIM to display real-time building information, provides various opportunities for facility managers to obtain accurate information about the status of the environment and different systems (Chen et al., 2014). In this regard, they introduced a method to connect sensor data to the BIM model based on IFC. Moreover, it was used to visualize it through developing new plugins in Revit software. Finally, all of the sensor information was easily controlled in the BIM model to evaluate the status.

However, still there are major problems of inefficiency of facility operation and maintenance processes in the systems, including lack of a dynamic model at these stages; lack of interoperability standards between the system, sharing information between stakeholders; and problems related to processing a large volume of data accumulated from various sources. This study seeks to investigate the use of IoT in making the building information models dynamic, so that the comfort level of end-users in educational settings is improved.

The next section describes the research methodology adopted in this study.

Research Methodology

Research is a planned and systematic process that is conducted to discover unknown problems or arrive at a deeper understanding of problems. Human's inherent desire to discover the facts has led to significant advances in research. Accordingly, a variety of research methods have been developed by humans (Kothari, 2004).

As stated earlier, to achieve the main goal of the research, which it to make building information models dynamic using IoT with a focus on improving the comfort level of educational settings and visualizing the comfort level and providing control recommendations to improve it, an appropriate framework has been selected with the help of an appropriate platform to integrate BIM and IoT technologies. In the following, the research method used for this aim is presented.

Collecting environmental data affecting the comfort of users in an educational setting and entering this information in the BIM and visualizing information in the model and providing control recommendations requires a framework to make BIM dynamic and design and develop a platform to calculate and display the comfort level and alerts. This framework includes three layers: 1- physical layer; 2- information layer; and 3- application layer. Figure 1 shows this framework.

The physical layer includes the physical building and the IoT sensor network that provides accurate information from the physical world. In the information layer, geometric information of the physical building is used for the BIM model, which is extracted from the building information model. While, environmental data (such as temperature and humidity) is collected from IoT sensor network. The application layer includes a designed platform that connects the BIM and IoT systems and visualizes information and provides control recommendations. The methods and tools required for each layer are as follow: For the physical layer, it is necessary to select a place to develop the BIM. For the information layer, it is necessary to install the selected sensors at the desired locations and collect and store its information in a database. Moreover, it is necessary to model the desired place by one of the BIM-based modeling software such as Revit. For the application layer, it is necessary to design a platform that visualizes the collected data and model and displays control recommendations to improve the comfort level of each end-user. For this purpose, a web-based platform is used that is designed by programming languages such as PHP and JavaScript.

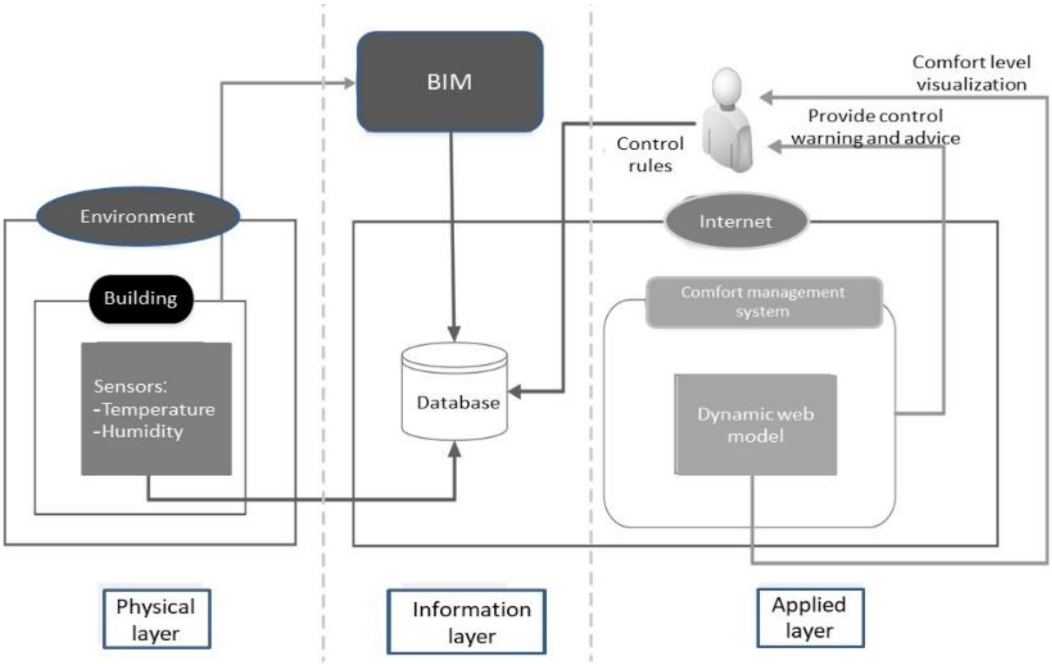

Figure 1. The required system layers to integrate BIM and IoT

The MQTT protocol was used to transfer the sensor data to the server, and MySQL database was used to store information. MQTT protocol is a Machine to Machine (M2M) protocol to connect IoT that communicates with the help of sensors. MQTT (Message Queuing Telemetry Transport) is a publish-subscribe messaging protocol that is also registered in ISO standard (ISO/IEC PRF 20922). This protocol operates on the IP/TCP protocol. It is designed for connections to remote locations, in which a small footprint of code is needed, and/or the network's bandwidth is limited. The publish-subscribe messaging model requires a message broker. The communication of this protocol is based on client-server communication, and is located in the network layer.

The communication structure of this protocol is communicating between a sample sensor such as temperature and a server that can be a device such as laptop or a virtual server. Thus, it is possible that the temperature and humidity data collected by the sensors are transmitted to the server by this protocol and stored in the database. For this purpose, just set the MQTT configuration on the WiFi module with the help of IDE.

As mentioned, MQTT uses the publish/subscribe model for its communications. In this case, each device or server in this protocol publishes its information to the MQTT server, which acts as a broker. The temperature or humidity sensor publishes its information using a special subject, such as temperature, on the server. Anyone who wants to access this information or create a subscription, should have that specific subject that here is temperature, to receive the information from the server. In fact, MQTT devices or customers can be both publisher and subscriber. There is no limitation for the number of subjects in MQTT. Moreover, each device can put its data on several subjects. In addition, to increase the security of using this protocol for communication between devices and the server, a username and password is always needed beside the device ID to set it on the safe communication mode between the device and the server.

After connecting the WiFi module to the micro-controller and selecting the appropriate protocol to connect the IoT system to the server, the next step is to set the controller to transfer data to the server by the MQTT protocol. To do this, setting the sensor module needs to take place. In other words, the code related to that part should be completed. For this purpose, after adding the required libraries to the Arduino IDE software and identifying its related module, the command code. As mentioned above, in order to connect through the MQTT protocol, a username and password beside the sensor ID are needed to create a safe communication path. At this stage, the username and password are generated by the server and set on the controller. An example of this code is presented in the Figure 2.

```
void reconnect()
{
  // Loop until we're reconnected
  while (!client.connected())
  {
    Serial.print("Attempting MQTT connection...");
  // Attempt to connect (clientId, username, password)

    if (client.connect(device_id, "cloud_username", "cloud_password"))
    {
    Serial.println("connected");
    client.subscribe("esp8266/dht_control"); // write your unique ID here
    }
    else
    {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 5 seconds");
   // Wait 5 seconds before retrying
      delay(5000);
    }
  }
}
```

Figure 2. Setting the MQTT username and password on the micro-controller

By implementing the mentioned stages, the temperature and humidity data are measured by the nodes, formed by the sensor modules, from around the sensors installed in the desired location. Then, the data was compiled by the Arduino board as the micro-controller and energy supplier for sensors, and introduced by WiFi modules installed on the board and protocol, and transferred to the desired server and saved in its database. In the next section, the research findings are presented.

Research Findings Analysis

Table 1 presents information about the building selected as the case study, as well as the selected sensors to collect data, and the tools required for research implementation and platform design.

Table 1. Specifications of the case study, and tools required for the research implementation

Project title	Roger Williams University
User	University of Liberal Arts
Building name	School of Law
Facility Manager	Facility Operations Group
Location	Bristol, Rhode Island, USA
Year of construction	1993
Number of floors	3
Foundation	10000 m2
Sensor models	DHT11
Type of sensors	Temperature, Humidity
Number of sensors	130
Model type	3D BIM
Model output standard	IFC
Modeling software	Revit
Platform name	BIMGate
Platform type	the web
Platform language	PHP, JavaScript, C#
Communication protocol	MQTT
Database	MySQL
Comfort index	PMV

In order to collect data, DHT11 temperature-humidity sensors were used. Thus, to continue the research, two parameters of temperature and humidity have been selected as the environmental data required for collection as well as thermal comfort index or PMV as the index representing the comfort level of building interior users. Also in this research, a platform called BIMGate has been designed to capture the data collected by the IoT sensors in the building information model to make it dynamic. Web-based programming languages such as JavaScript and PHP have been used to develop it. Moreover, the MQTT protocol was used to transfer the sensor data to the server, and MySQL database was used to store information.

In order to collect environmental parameters affecting the comfort level of institutional project users, at first it is necessary to select an appropriate educational project that for this research. The selected building was the Roger Williams University Law School building. Then, it is necessary to implement the IoT system and install the required sensors for temperature and humidity. In order to calculate the thermal comfort index, two main parameters of temperature and humidity are required. In the conducted case study, 130 wireless sensors were installed in the building of Roger Williams University Law School, which were DHT11 temperature-humidity sensors. The implemented IoT system to collect the environmental data affecting the comfort level has four main components including, sensor module to measure the environmental parameters, power module with micro-controller to collect data and adjust sensors, WiFi module to connect the system to the network or gateway, and finally, a server to store information. In this research, DHT11 temperature-humidity modules, Arduino power board and module model UNO R3, WiFi module model ESP8266 ESP-01, and server BIMGate with MySQL database along with MQTT protocol were used to measure, collect, transfer, and store information.

Thus, the implemented IoT system to collect the environmental data impacting comfort level has four main components: DHT11 sensor module to measure the environmental parameters; power module with Arduino micro-controller model UNO R3 to collect data and adjust sensors; WiFi module model ESP8266 ESP-01 to connect the system to the network or gateway and transfer data; and BIMGate server with MQTT protocol and MySql database to store information, its introduction and how to adjust and communicate it. This system revealed that collecting temperature and humidity data as two environmental parameters indeed reflects the comfort level of the building's interior users in Roger Williams University Law School. It should be noted that this research has used the existing market tools to create and test the IoT system in the selected case study. These existing tools helped the authors to measure the temperature and humidity data. In the following, the process of recording this dataset in the building information model is described, leading to a dynamic model.

Entering the collected data in the building information model

In order to enter the collected data by IoT in the building information model and display the temperature and humidity information as well as the thermal comfort index on the model dynamically, a 3D BIM model is required to enter the desired model with standard output in the platform designed for this purpose. In this research, the model of law school building including different spaces and components, such as doors, windows, walls, etc. has been designed by Revit software. The output with IFC standard was used to enter the BIM information in the system in the form of geometric and semantic data. Moreover, the BIMGate platform was designed to enter and integrate sensor data in the design model. In the following, the tools required in implementing this process and how to enter data in the model by the platform is described.

In this research, Revit software was used to model building information of the Roger Williams University Law School building with 3 floors and an approximate infrastructure of 10,000 m2. All building components such as doors, windows, walls, floors, ceilings, and spaces are modeled according to the available maps of the place, presented in Figure 3.

Moreover, to export the model from the Revit software to the platform designed under web, IFC standard is used. It should be noted that the BIM model of school building used in this research has been prepared through CAD and Revit.

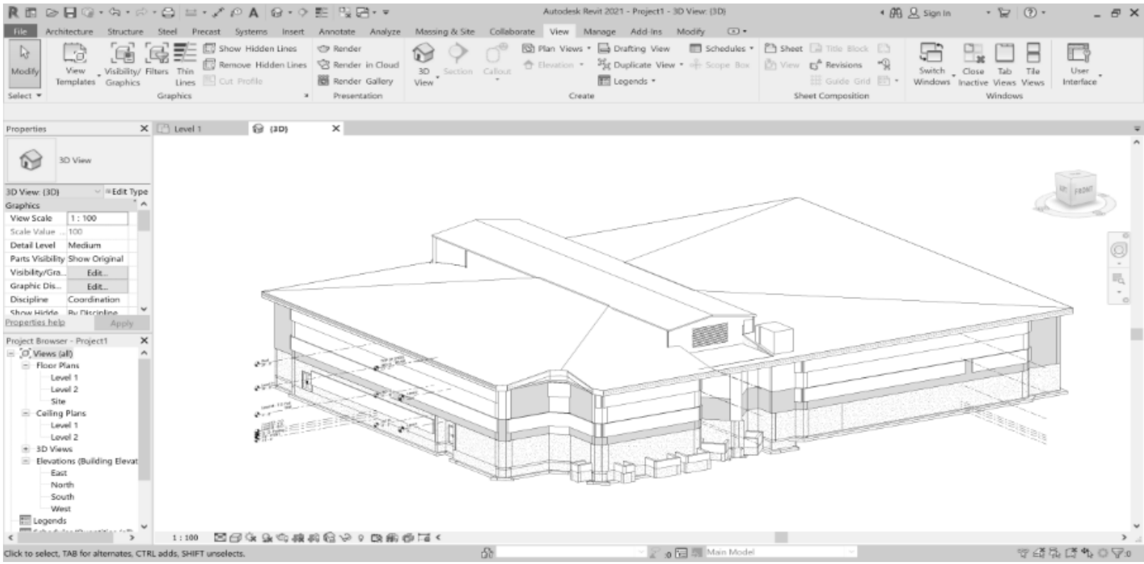

Figure 3. BIM model of the school building designed by Revit

In this research, the BIMGate is designed with programming languages of PHP and JavaScript. This system is programmed in such a way that makes it possible to introduce the IoT sensors on the one hand and to introduce the desired model with a suitable standard output on the other hand to the system. The data collected by the sensors are displayed in a 3D model and dynamic operations of the building information model are performed. This platform is composed of various components and parts, and includes three main sections of Devices, Models, and Alerts. Figure 4 shows the Dashboard of the platform. The first section of the platform is related to devices or IoT sensors. It is designed so that the data collected by the sensors are displayed on line. It includes an API on the server side to receive sensor information and store it in the database and display it numerically and graphically on the user side.

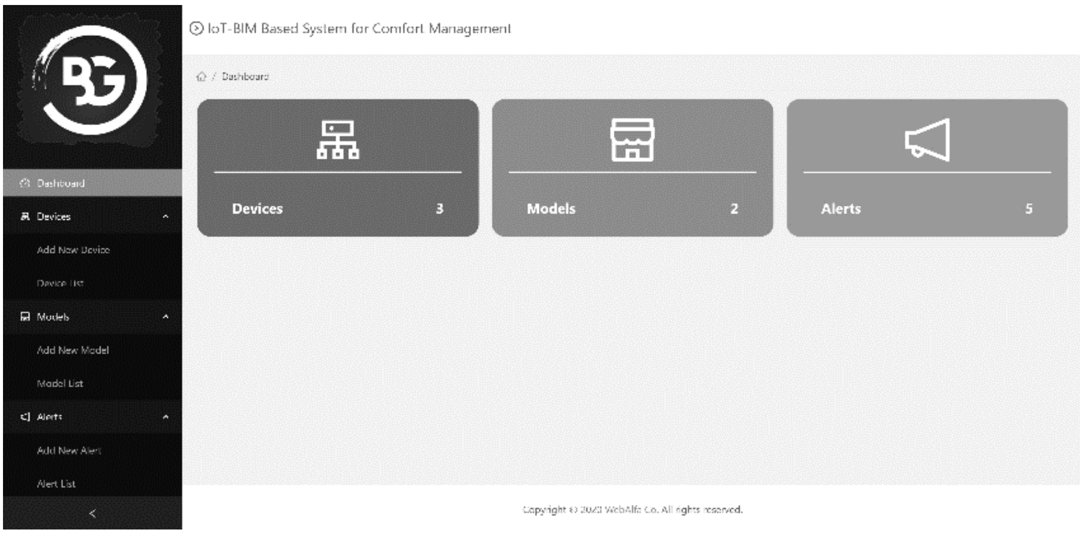

Figure 4. Dashboard of the platform on the BIMGate platform

In order to add a new sensor to the platform, the sensors are introduced to the system through the 'Devices' menu and 'Add New Device' on the page by entering the specifications of the desired sensor.

After introducing and entering the sensor specifications in the system, the MQTT credential related to the desired sensor is developed. Then, this information is introduced to the micro-controller of the desired sensor to create send information to the system. After setting the username and password created by the system on the micro-controller, the system automatically detects the sensor and stores the information sent by it with the defined name for that sensor and in the specific section created for that sensor in the platform database. The list of the devices added to the system can be viewed in the Device List section and can be deleted and edited.

After completing the above mentioned stages, the information collected by the sensors, i.e. temperature and humidity in the time period defined on the micro-controller in the Device Data section of the device introduced to the system can be observed statistically and graphically, which is shown in the Figure 5.

Figure 5. Graphical display of data of the sensor on the BIMGate platform

After introducing the sensor to the system, it is time to introduce and add the building information model to the system. The second section of the BIMGate platform is related to the models. In order to introduce the BIM model to the system and its 3D display in the web space, this platform is designed, which includes an API on the server side to receive models' file and store it in the database and display it in the 3D form on the user side. This job is done through 'Models' menu and 'Add New Model' section by a form available on the page that should be filled out by the specifications of the desired model.

For this purpose, the BIM file designed by the modeling software, which is Revit in this research, should have an output with an ifc. suffix or any other BIM-based suffix such as rvt. or nwc. It should be entered in the system through the mentioned menu and be uploaded in the server of the system. The list of models added to the system in the 'Model List' section can be observed, deleted, and edited. It is possible to separately upload different models in the system, including the architecture, structures, and facilities, and match them to each other automatically by the platform and display them.

After performing the mentioned stages, the model introduced to the system in the 3D form and based on the ifc structure or other file structures uploaded in the web can be seen in the Viewer section of the platform, which is shown in the Figure 6. This job is done by Autodesk Forge, and has all the display and analysis features of the model such as rotation, movement, measurement, cutting, etc.

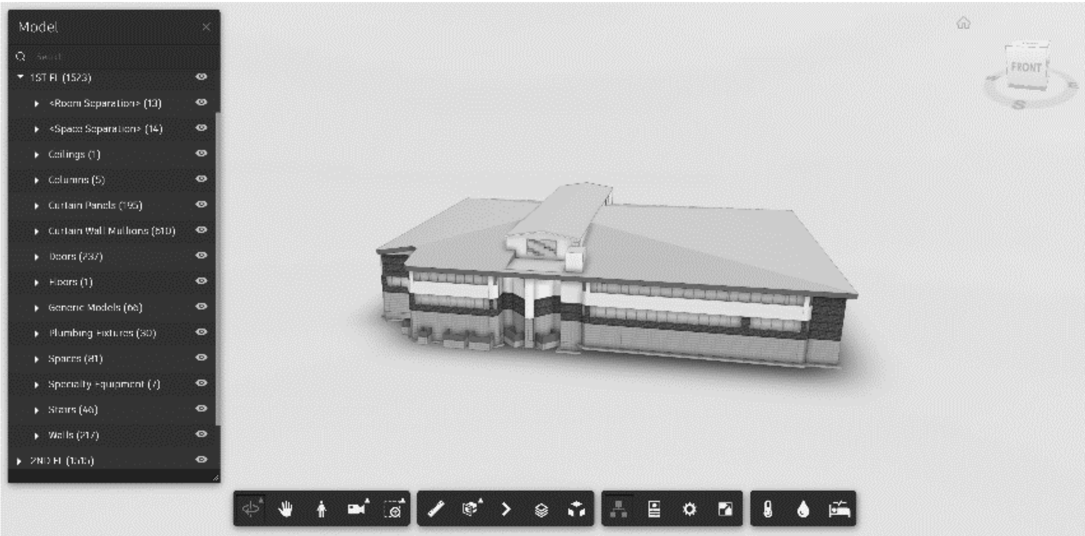

Figure 6. 3D display of the BIM model on BIMGate platform

In this system, Autodesk Forge has been used to display the 3D model in the form of a dynamic web page.

In fact, Forge is a set of applied programming interfaces that provides many possibilities such as connecting people, processes, and information in a shared cloud data environment for users and developers. Moreover, it includes design, construction, and operation tools for communication between Autodesk software and third-party applications. One of the benefits of Forge applied in this system is the capability to convert the BIM output files, such as ifc, into SVC file and display it by Forge Viewer tool on the web page. It adds various features to the model such as display tools, measurement and analysis, as well as display and management of information, such as IoT data, in addition to displaying the 3D model.

Moreover, in order to complete second section of the BIMGate platform, i.e. the model section, a plugin was designed for the system that if changes and updates are made in the model by the modeling software, these changes will be applied in the platform and web page, in order to facilitate making the building information model dynamic, and the platform be able to automatically update the model. The way this plugin works is such that after addressing the storage location of the file to the plugin, in the case of any change in the modeling file after its update and storage in the desired folder, the plugin will automatically upload the model output file to the server during the specified time intervals. Thus, the updated model will be displayed on the web page and maintains its dynamic feature not only on the issue of environmental data, but also regarding the 3D model of BIM.

In the BIM model, each element is identified by a specific ID, which this ID is in the ifc output of the model. So, each of the spaces and elements in the model designed and introduced to the system has a specific ID. In addition, each sensor after being introduced to the system gets a unit ID, through which is introduced to the system. Thus, the platform allows the ID related to the sensor to be connected to its corresponding space. As Figure 7 shows, by clicking on each element and selecting the 'Assign Device' option and then selecting the relevant sensor, the operation of assigning data of IoT sensors to the building information model is performed. Therefore, it is possible to display the data collected by the sensors numerically and graphically at the place the desired sensor is connected to the relevant section in the model. Thus, the model leaves the static state, which contains only the initial modeled information, and becomes a dynamic model that contains live environmental data.

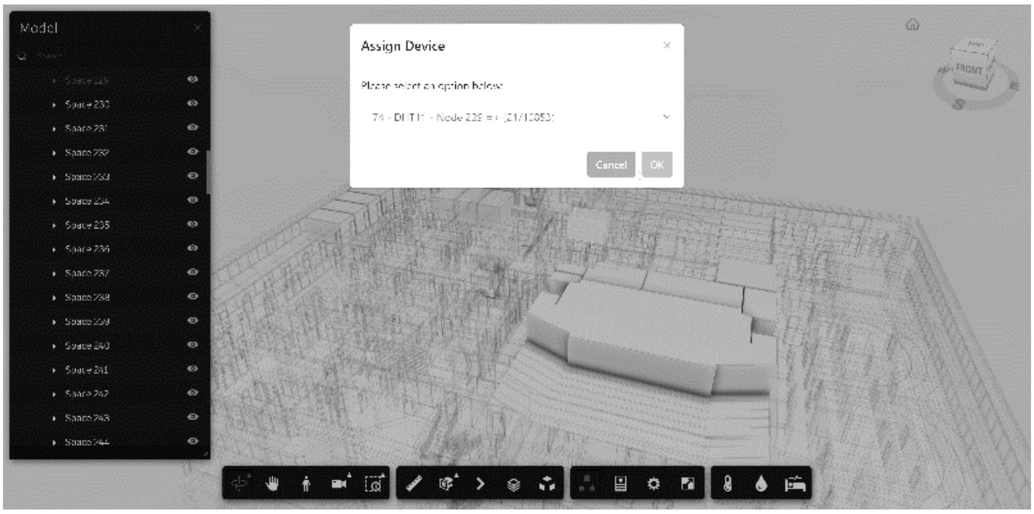

Figure 7. Assigning sensors to the relevant elements of the model on the BIMGate platform

Generally, this system has been programmed and developed in such a way that allows the building user or facility manager to change and update the model using the modeling software at any time and any manner desired. These changes are applied automatically in the designed platform.

After modeling by the Revit software and having an ifc suffix output, the model of the school building is introduced to the BIMGate platform and entered in the system. In addition, the data collected by DHT11 sensors is introduced to the specified section and entered in the system by MQTT protocol. Then, the platform connects them to each other, according to the capability of assigning the sensor to the model in which it is programmed and based on the ID of model elements and sensors. In this way, the collected data is entered in the designed building information model and a dynamic building information model is created. In the following, the way of visualizing the comfort level of users by a platform designed to control their comfort is addressed.

Visualization of users' comfort level

This research is mainly focused on improving the end-users' comfort level in the building's interior. For this purpose, the proposed platform composed of BIM and the IoT sensors have been applied, and in order to measure the comfort level, the index introduced by ISO7730 standard has been used. This index is known as thermal comfort index or PMV, and its range is-3 to +3. In order to calculate this index, some parameters such as metabolic heat rate, effective mechanical power, air temperature, average radiant temperature, clothing insulation, relative humidity, and relative speed of wind are required. According to this standard, its ideal value is between -0.5 and +0.5. Figure 8 shows grading and coloring of the thermal comfort index.

Figure 8. Grading and coloring the thermal comfort index

In this research, according to the case selected for the study, the initial hypotheses based on the reference article and the accepted range introduced in the standard for similar conditions, are as follows:

- The metabolic heat rate is assumed equal to 70 w/m2, because human activity in the building with educational application is usually in the form of standing or sitting.
- The effective mechanical power is assumed equal to 0 w/m2, because usually the value zero is considered for calculating the comfort level of building interior.
- The clothing insulation is assumed equal to 0.11 m2K/W, because this experiment was performed in winter, in which the users usually wear long-sleeved and thick clothes (this value is different for summer and summer clothes and is assumed equal to 0.08 m2K/W).
- The average radiant temperature is assumed equal to the air temperature, because in this case, these two parameters are slightly different from each other.
- The relative air speed is assumed equal to 0.1 m/s, because this experiment is performed in winter and in the building interior and air conditioners are off. (this value is different for summer and is assumed equal to 0.2 m/s).

The parameters used in calculating the thermal comfort index have specific intervals according to the introduced standard. Moreover, the effects of each parameter are different based on the introduced formula, as follows:

- The temperature is normally between 10 to 30˚C and is the most effective parameter in calculating the thermal comfort index.
- The average radiant temperature is normally between 10 to 40˚ C and is a very effective parameter in calculating the thermal comfort index.
- The metabolic heat rate (and also the effective mechanical power) is normal between 46 and 232 W/m2 and is a very effective parameter in calculating the thermal comfort index.
- Insulation or clothes is normal between 0 and 0.31 m2/w and is a very effective parameter in calculating the thermal comfort index.
- The relative humidity is normally between 30 to 60 percent and is a parameter with medium effect in calculating the thermal comfort index.

- The relative air speed is normally between 0 to 1 m/s and is a parameter with the least effect in calculating the thermal comfort index.

In the BIMGate platform, another plugin has been designed for the second section of the platform to calculate and visualize the comfort level. And, for its implementation, the PHP programming language has been used.

How this system works to calculate the comfort level is such that the platform automatically records the temperature and humidity data entered in the system by IoT sensors and with the help of the hypotheses determined in the previous stage and the function introduced above as the PMV, which shows the thermal comfort level. This value varies over time based on different values of temperature and humidity observable in the statistical section of the sensors, as shown in the Figure 9.

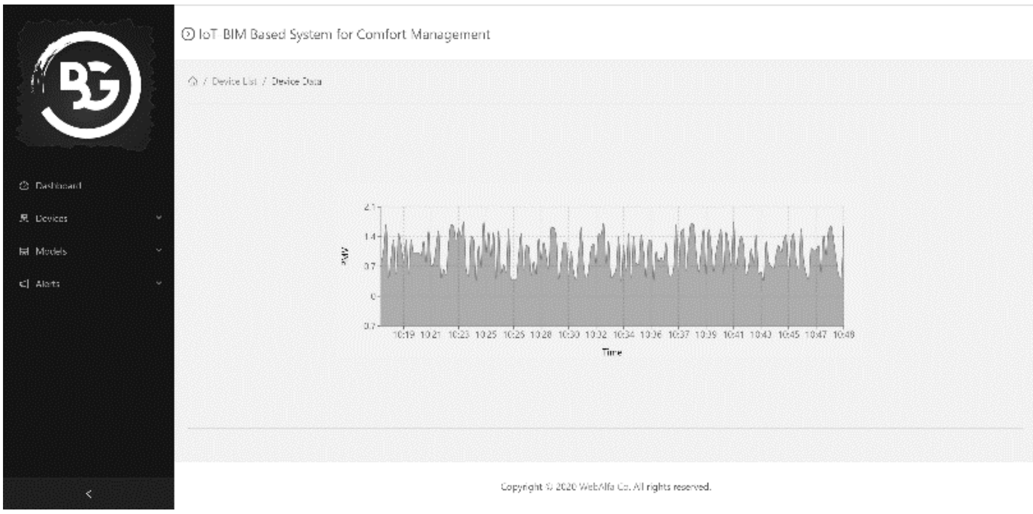

Figure 9. The graphical display of comfort index on the BIMGate platform

Moreover, in order to visualize the comfort level, based on coloring in Figure 8, this system operates in such a way that first analyzes the various spaces of the model introduced to the platform based on their assigned sensors and the index value calculated by the system. Then, it displays them based on the defined coloring and along with the live values of the data. Thus, it visualizes the comfort level based on the PMV value and the defined coloring presented in Figure 10. In addition, this system has the capability of visualization and live display of the temperature and humidity data or any other sensor defined in the platform.

Alerts and control recommendations

The third section of the BIMGate platform is related to alerts, and is designed to introduce alerts and new recommendations to the system as well as detecting the unsuitable conditions in the dynamic model. It includes an API on the server side to receive border conditions of parameters from the user and specifying them in the 3D model on the user side by the plugin introduced in the previous section. This job is done through ‘Alert’ menu and the ‘Add New Alert’ option. For this purpose, at first the border conditions related to temperature, humidity, or comfort index as well as recommendations for the determined status are introduced to the system through the mentioned menu and by the system manager.

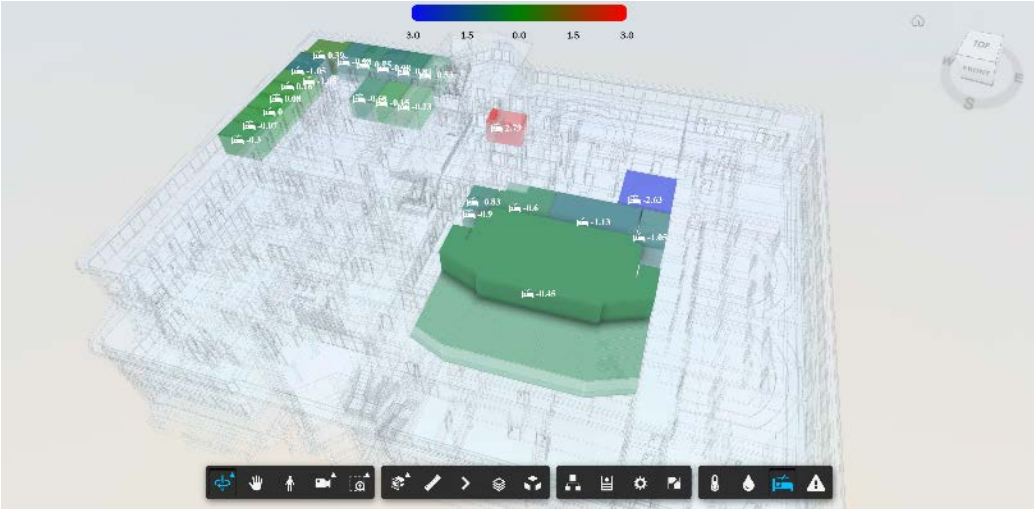

Figure 10. Visualization of end-users' comfort level by the BIMGate platform

Moreover, it is possible to determine the alerts with different border conditions for various sensors defined in the system. After introducing these alerts and determining their related recommendations, their list is observable in the 'Alert List' section, and can be removed or edited.

After performing the above stages, the system automatically provides the recommendations introduced for that condition to the end-user, which reflects the real conditions in the desired location. Then, it displays the alerts to the user to improve the status quo, which is presented in the Figure 11.

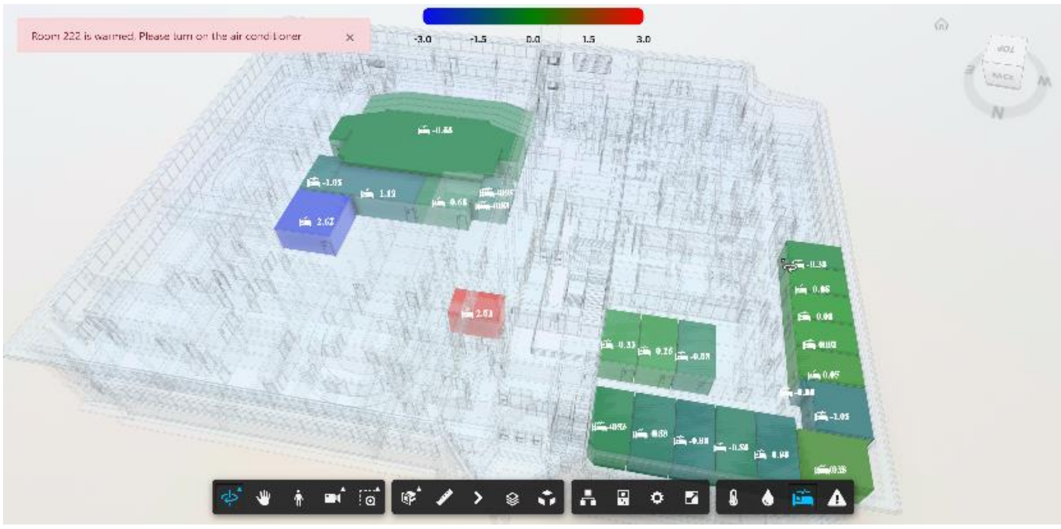

Figure 11. Providing alerts and control recommendations on the BIMGate platform

At this stage, the user or facility manager improves the energy consumption and comfort level with the help of the introduced platform and by tracking unfavorable conditions of comfort and by setting the heating and cooling devices based on the alerts and recommendations provided by it.

Thus, after defining the border conditions of the parameters and new recommendations in the alert section, the system automatically evaluates the status of the model and displays the recommendations provided by the system administrator. By setting the heating and cooling devices with the help of alerts for comfort level it is optimized that improves the energy consumption and comfort level. The next section discusses the findings and implications of this research.

Discussion

Lean Maintenance is a critical issue among the management activities of a manufacturing organization. In other sectors where capital projects and facilities represent significant assets and the means for revenue generation, Lean Maintenance strategies must be linked to energy consumption strategies and improving comfort levels in building environments. In addition, effective maintenance strategies reduce the waste of materials, spare parts and maintenance equipment and increase the quality of people's comfort level (Mostafa, Dumrak, et al., 2015).

According to review of the studies conducted by previous researchers, it was concluded that traditional methods for collecting information about building spaces to evaluate the comfort level of its users face many limitations. Traditionally, to collect the data about end-users' experience, it was necessary to use surveys. And in order to periodically measure the parameters affecting their comfort, it is necessary to use hand tools, which is time-consuming, costly, and erroneous (Al Barazi, 2018; Fantozzi and Rocca, 2020). Moreover, permanent evaluation and control of these parameters with the indices determined based on the relevant standards or regulations for timely decisions to improve these indices and the comfort level of users are among the challenges in this field. However, on the one hand, advances in the field of measurement, communication, and processing physical and environmental information have made possible continuous monitoring of the building's environmental behavior.

Thanks to the IoT tools, access to these possibilities is easy. Some of these tools have been leveraged with the application of building information modeling (BIM) as a 3D model with a database rich in information about building components and facilities with the ability of integration with other technologies. These steps have filled the gap in the issue of productivity management and controlling the comfort level and quality of the building interior. However, since BIM technology uses static information in the design stage and building modeling, it lacks updated and immediate information about the building's environmental conditions. Therefore, combining these two technologies makes it possible to enter dynamic information in the building information model by the IoT. Thus, there will be an opportunity to integrate these two technologies to develop updated and complete models for identifying the unwanted or inefficient energy behaviors, controlling users' comfort indices, building interior quality, and generally building lifecycle management and control, including at the operation and maintenance stage (Bottaccioli et al., 2017).

Although previous researchers in the field of integrating IoT and BIM have made efforts to fill these gaps, reviewing their studies shows that most of the systems introduced by these researchers just transferred the environmental information collected by sensors to the BIM-based software environment. Besides being expensive, heavy, and specialized, these platforms cannot be displayed on other devices and are not applicable for normal users, which are some of the challenges in this field and have not used BIM and just rely on visualizing the information of sensors beside the BIM graphical model.

Although Chi-Chang Liu et al. (2016) and Kai-Ming Chang et al. (2017) have used the Predictive Mean Vote (PMV) method to calculate the comfort level of educational settings, other parameters affecting the comfort level and their prioritization were not identified (Chen and Chang, 2017; Liu et al., 2016). The system provided by Marzouk and Abdelaty (2014) for monitoring the thermal comfort in the subway (Marzouk and Abdelaty, 2014), and the system introduced by Chi-Chang Liu et al. (2016) to facilitate the study of details of the building energy status, do not automatically display the data collected by sensors similar to how the system provided in this research does in visualizing the users' comfort level (Fantozzi and Rocca, 2020). The system provided by Chen et al. (2017) and Kai-Ming Chang et al. (2017) to manage the energy and to control the comfort level only displayed the environmental data graphically or in the form of time. No solutions were provided to make alerts or control recommendations for timely decision making, which the system designed in this research does(Chen and Chang, 2017; Chen et al., 2017). Dave et al. (2018) also provided a web-based platform to display the status of environmental parameters. However, one of the main differences between the BIMGate web platform in this research and Otaniemi 3D platform is in visualizing the parameters in a 3D environment, which is done in the Dave platform in two dimensions (Dave et al., 2018; Di Giuda et al., 2020).

This research provides a solution to convert the static BIM models that contain only modeled information at the design stage into dynamic BIM models that contain updated information from the post-design stages, such as the operation and maintenance stages. For this purpose, this research has suggested a system, in which the data collected by the IoT sensors, after transmission by an appropriate security protocol and storage in the database, can be displayed on their covered locations in a 3D model developed by Autodesk Forge service in a web-based platform.

Generally, it can be said that the main difference between this research and similar studies is in converting the building information model into a dynamic model with updated data from the building interior, which can be displayed on different devices without any pre-requisite. It is also possible to calculate the comfort index by historical data recorded by sensors to visualize the comfort index and provide appropriate recommendations to improve comfort levels and reduce energy consumption. Moreover, this system has the capability to automatically update the model after each change and edit in the original file of the model by the modeling software.

The system developed in this research is also able to add various types of models and sensors with diverse communication protocols, which can be used by building's facility manager and residents. The systems proposed by previous studies often don't perform automatically the process of integrating and transferring the data of sensors to the model, and don't have the capability to display the data live in a 3D model. In addition, these models cannot be displayed on different devices such as mobile, tablet, and computer simultaneously and optimally, and need some pre-requirements such as Revit software to be implemented. Moreover, previous systems display the data of the users' comfort, and don't help the system administrator with alerts and control recommendations to improve the comfort level and energy consumption. In these systems, the user should control the comfort level and energy consumption based on their own diagnosis. The next section examines the research contributions, limitations and future directions.

Conclusion

At the beginning of the research process, the problem and the necessity of conducting this research were stated. Accordingly, the problem of the lack of a dynamic information model to manage the operation and maintenance stages of the building was raised. Then, it was shown that this dynamic model can be useful for monitoring and controlling the necessary parameters at the operation and maintenance stages of the building, such as users' comfort in educational settings. Also, process maintenance shares significant operating costs in an organization. By applying Lean Maintenance, this process can be significantly improved.

Lean Maintenance (LM) is a prerequisite for lean manufacturing, and, therefore, for the transfer of lean thinking to any sector. The Lean Maintenance process structure is designed based on five lean principles, which guide and support organizations to pursue maintenance excellence and improve the level of comfort and energy (Mostafa, Lee, et al., 2015). Also, to measure, collect, analyze, and display information at these stages for its better and faster management, it is necessary to use modern technologies such as IoT and BIM. In addition, the research goal and question were stated with the main aim of providing a framework for entering the sensors' information in the building information model to produce a model with dynamic data. Based on this proposed model, a case study about controlling the comfort level in a university was conducted according to the identified priorities in the buildings.

To achieve the research aim, the integration of IoT and BIM was used as the research method, the survey method as a tool to collect data, the predictive mean vote method as the data analysis method, and the programming languages PHP and JavaScript as the required tools. Moreover, in order to collect the environmental data affecting the comfort level, the IoT system was implemented that has three main components including DHT11 sensor module to measure the environmental parameters, UNO R3 Arduino micro-controller or power module to receive and collect data from sensors. The BIMGate server or gateway with MQTT protocol and MySQL database to transfer and store information was introduced and how to set and communicate them was described.

Using this system, temperature and humidity data were collected as two environmental parameters affecting the users' comfort level in the building interior of Roger Williams University Law School. Also, the model of the faculty building was introduced to the relevant section and entered in the system after modeling by Revit software and outputting it with ifc suffix in the BIMGate platform. On the other hand, the data collected by DHT11 sensors was also introduced to the relevant section and entered in the system by MQTT protocol. Then, the platform connected them to each other based on the assigned capability programmed in it and the IDs related to the model elements and sensors. Thus, the collected data were entered in the designed building information model. In this way, a dynamic building information model was developed. Finally, by the plugin designed for the BIMGate platform, the comfort level of the faculty building's users was visualized with the help of PMV index and coloring and grading defined in the system for this index and according to the existing standard. Moreover, after defining the parameters' border conditions and new recommendations in the alerts section, the system automatically evaluated the status of the model. Then it displayed the determined recommendation by the system administrator to the user. By adjusting the heating and cooling devices with the help of alerts, the comfort level was optimized that improved the energy consumption and comfort level.

One of the achievements of this research for science and industry is integrating two IoT and BIM technologies by the designed platform, which can be used for other scientific and research fields such as optimizing the environmental parameters. Also, we can refer to the display, track, and visualization of IoT sensors' data by BIM technology and the designed platform that one of its applications is for smart houses. Moreover, dynamization and updating building information models by IoT technology and the designed platform is another achievement used for managing, operating, and lean maintaining the facilities.

One of the limitations of this research is the costly and time-consuming preparation and installation of sensors. Because of this, just temperature and humidity were selected as the effective environmental parameters to collect the environmental parameters affecting the comfort level of users of an educational setting and entering this data in the building information model. In addition, another limitation of this research is that some parameters affecting the comfort level are non-measurable or approximate. For this reason, to visualize the comfort level and provide alerts and control recommendations by the system including a dynamic building information model, just the thermal comfort index has been used. The value of some of the parameters for its calculation is assumed based on the research conditions. Because according to the selected parameters in this research and the standards to determine the comfort level in the building's interior, just this index has been introduced and its range in different conditions has been specified. Some suggestions for future research include:

- •Applying other sensors such as light, sound, air speed in addition to temperature and humidity sensors to measure accurately the comfort level, and examining other aspects of comfort that are not studied in this research.
- Implementing the solution proposed in this research in environments other than educational settings, such as medical settings, in which the comfort level and health are very important.
- The use of the proposed framework in this research in fields other than comfort, such as energy management and green buildings, to improve the energy efficiency and achieving sustainable development.

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