# Value of 3D Gaming Engine Based Virtual Models in Understanding Behaviors of Facility Operators during FM

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**Abstract**
The use of building information models (BIMs) in facility operations and management has gained momentum and has been explored both in academia and in the industry to enable access to accurate and up-to-date facility information, understand what sensors tell in a given spatial context and take actions on maintenance requests. One of the challenges in the facilities management (FM) industry is the lack of mechanisms that enable constant navigation within BIMs without the need to generate custom views, interaction with components' information and decision making. One way of addressing this challenge is to convert BIMs to 3D virtual models through gaming engines. The study aims at evaluation of 3D virtual models in capturing the behaviors of facility operators. The research findings show that 3D virtual models are effective in increasing the perception of facility operators as compared to the current practice through document and building automation system based interfaces, both of which lack the spatial context associated with facility spaces and systems.

**Keywords:** Visualization, virtual models, facilities management

## 1 Introduction

Building information models (BIMs) are a part of project deliverables in new vertical construction projects as more and more owners require BIMs as a final deliverable on their projects. Given that models are available to owners, the use of BIMs to get accurate and up-to-date facility information throughout the operation phase has been widely explored. One of the challenges of using BIMs in facilities management (FM) phase is the lack of mechanisms for facility operators that enable navigation within BIMs, interaction with component information and usage of models for effective FM decision making. Commercially available BIM authoring tools provide mechanisms to generate views for navigation within models, however such views should be generated each time a project personnel need a custom view based on their preferences. One way to eliminate the need for custom view generation for facilities management use is to convert BIMs to 3D virtual models using gaming engines. A game engine provides a platform, which is composed of a rendering engine (to display 3D graphics), a physics engine (to detect collusions) and many other components such as scripting, sound, and memory management (Zerbst & Duvel 2004). Gaming engines provide opportunities to quickly generate navigable virtual models and use these models for facilities management tasks as if one plays games in 3D environment. Navigation, interacting with components and component information are possible within 3D virtual models and can be customized depending on the requirements of FM tasks.

This research study evaluates the value of 3D virtual models in understanding the behaviors of facility operators during facilities management. Specifically, the research will evaluate the 3D virtual models and their impact on decisions of facility operators when they respond to corrective maintenance of heating, ventilating, air conditioning (HVAC) related issues and sensor monitoring for prompt situational awareness on building HVAC systems. This paper will provide the details of the virtual models developed for the purpose of capturing behaviors of facility operators during facilities operation and maintenance tasks and the user studies conducted with facility operators using these virtual models. The virtual models were displayed both in immersive settings and in desktop settings to understand the implications of one to one scale immersed settings on the perception of facilities operators on the displayed facility information and their projection to decision making.

The paper is organized as the following: first an overview of related research studies on virtual modeling in architectural, construction, engineering and facilities management (AEC/FM) is provided in Section 2. The research method, which includes the development of scenarios from real life settings, the implementation of 3D virtual models, and conducting user studies, is detailed in Section 3. Section 4 provides the initial findings on the user studies conducted with facility operators using desktop and immersive settings to evaluate the value of virtual models for FM through user studies. Conclusions and future work are discussed in Section 5.

## 2 Related Background Work

Virtual modeling is defined as computer generated 3D objects that simulate the real world scenes and the physical objects in those scenes. It has a long history in the construction industry, starting with Virtual Reality Modeling Language (VRML) representations of construction projects, equipment and material (Retik 1997). So far, it has been used for various purposes including construction safety training (e.g., Sacks et al 2013, Zhao & Lucas 2014, Park & Kim 2013), planning and monitoring (e.g., Retik 1997), preconstruction planning (e.g., Waly & Thabet 2003, Huang et al 2007), design development (e.g., Savioja et al 2003, Calderon et al 2000) and design review (e.g., Woksepp & Olofsson 2006). These studies mainly evaluated the value of virtual models in improvement of the construction processes they focused on and did not focus on facilities management phase of construction projects. The study presented in this paper will make an attempt to evaluate the value of virtual models in facilities maintenance and sensor monitoring. The research builds on an earlier work conducted by the authors that evaluated the impact of different visualization forms (e.g., text overlays, symbols/icons and color coding) on 2D and 3D representation of facility spatial information while displaying semantic information embedded to components (Yang & Ergan 2014).

The previous study by the authors provided insights about when 2D versus 3D representation of facility spatial information would be valuable and how much of efficiency and accuracy each evaluated visualization form could bring to facility operators' decision making processes. For instance, the study showed that when facility operators are familiar with the spatial layout and physical context and the information is presented to them in 3D, they pinpoint sensor related issues during monitoring of facilities in a shorter amount of time. Whereas, if they are not familiar with the spaces, they perform better when the same information is presented in 2D (Yang & Ergan 2014). The research presented in this paper will take the previous work as a point of departure and evaluate the impact of virtual worlds on the accuracy and efficiency of decisions of facility operators.

With the new BIM authoring tools that enable exchanging project information in various formats, it is possible to input the design information to virtual modeling tools and gaming engines. Various gaming engines are available, including Unity3D, CryEngine, Unreal Engine, Virtools, Creator, Quest3D, and Panda3D with strengths and weaknesses in graphical displays, support for 3D, user friendliness, ease of conversion from BIMs, ease of development of scripts, the platforms they target (e.g., Windows, Unix, Android, iOS), scripting languages they allow (e.g., JavaScript, C++, Python), and accessibility by developers (i.e., open source or not) (Pauwels et al 2011). Among the ones that support 3D virtual models, the authors selected a powerful game engine that enables interoperability with various 3D file formats (e.g., 3DMax, Maya), provides development in different platforms, is user friendly and is an open-source platform. The next section provides how the selected gaming engine was used to create the virtual models by importing BIMs from commercially available authoring tools.

## 3 Research Method

The research method is discussed under four subsections including (a) the objective of the study and the overview of the facilities analyzed, (b) an overview of the user studies and scenarios generated from real life settings, (c) the description of the developed virtual models, and (d) an overview of the participants of the study.

### 3.1 Objective of the study and the overview of the facilities analyzed

The objective of this research was to evaluate the value of virtual models for supporting facilities management tasks. Two facilities management tasks were evaluated as the authors had the privilege to work with the facility operators on a daily basis for more than six months. These two tasks included (a) responding to HVAC related work orders for troubleshooting, and (b) monitoring of sensors and HVAC equipment statuses within their spatial context to get a situational awareness about how the spaces are conditioned and whether any action is required. The second task is especially important when content in the conditioned spaces are sensitive to ambient conditions (e.g. lab specimen, delicate plants in a greenhouse) and the threshold values for sensors should be maintained at all times. The authors used the "*time to complete an assigned task*" in both scenarios and "*accuracy of the final decision for the assigned task*" given by facility operators in scenario B as metrics to evaluate the value of virtual models.

For HVAC troubleshooting, facility operators need to collect clues from the facility and the HVAC system components for pinpointing the possible cause(s) of a reported problem among all candidate components. A cause could be a faulty fan, damper, sensor failure, or a space related issue that could impact the room condition (e.g., existence of heat generating equipment in a space reported in a work order). Clues that would be needed by operators are various and could include the HVAC component static (e.g., location, connectivity) and dynamic (e.g., manual mode/automated mode, % open, status) parameters, the history log for work orders reported for the same space, the maintenance history of components and the space related factors (e.g., existence of curtain walls, multiple windows in a space, existence of heat generating equipment). A detailed list of such clues are discussed in a previous work (Yang 2014). Virtual models can provide these clues to facility operators as they walk in virtual worlds and operators can better plan for their field trip to the spaces where problems are reported.

For sensor and equipment status monitoring, facility operators need to get a situational awareness about what the sensors are reading vs. what they are really telling to the operators given the context under which they provide that information. For instance, they need to understand if the sensor reading would require an action if a temperature sensor is close to a roof vent which is left open in a winter day or if a humidity sensor is reading a high value due to recently watered area in a greenhouse facility or requires a corrective action. Virtual models can provide the information to facility operators with the spatial context surrounding the sensors and monitored equipment without the need for operators to check the facility physically.

Virtual models of sections from two different buildings were generated using their BIMs. These two buildings were selected as the authors had access to documentation and sensor data to generate the material for virtual models and user studies. Table 1 provides an overview of the modeled sections of the facilities. The first facility was a section of a campus building and included an air handling unit with three variable air volume (VAV) boxes for conditioning three office spaces. Various building automation parameters, such as temperature and humidity of spaces, supply/return air flow rates, temperature as well as fan, coil, damper statuses were monitored. This facility was used for defining Scenario A, as described in the next subsection. For Scenario A, three zones were controlled by the AHU and utilized in the user tests.

The second facility was a greenhouse facility with 5 zones monitored as detailed in Yang & Ergan 2014. This facility included a set of upper and lower level temperature and humidity sensors for each zone due to its high ceiling (60 feet), where it would not be accurate to measure temperature and humidity at a single location and altitude only. In addition to the upper and lower sensors, various roof vent motors and fin tubes were used to cool and heat the zones, respectively. This facility corresponds to Scenario B in the study as detailed next.

**Table 1** An overview of the modeled portions of the case study facilities

| Facility type | Type of HVAC | Type of sensors | Number of zones monitored |
|---|---|---|---|
| **Campus building (Scenario A)** | Air handling unit with VAV boxes | Temperature, humidity, supply/return air flow rates, supply/return air temperature, fan, damper positions | 3 |
| **Greenhouse (Scenario B)** | Natural ventilation, passive cooling with roof vents, heating with fin tubes | Temperature, humidity | 5 |

### 3.2 An overview of the user studies and scenarios generated from real-life settings

Two scenarios, namely Scenario A and B, were generated for this research study. Scenario A was used in measuring the performance improvement of HVAC mechanics while troubleshooting HVAC related problems using the virtual models, compared with the current practice of looking at the data from drawings and building automation system interfaces. For this scenario, the campus building described in Table 1 was used. The main reason to use virtual models was to understand how the facility operators' performance at the field could be improved by providing the necessary information about the work order in a virtual facility where they could navigate and freely interact with components (e.g., a fan) and get specific information about them (e.g., fan's status).

In Scenario A, each participant was given a virtual work order at the start of the user test (Figure 1 left image) stating that the rooms were too cold and were asked to diagnose the problem and complete the work order. Each participant solved a similar scoped issue using the virtual world and the current interfaces they use. They were free to check the components, component properties, walk in spaces (or check the drawings and BASs that replicated the current interfaces) until they were ready to make a decision. The authors tracked each information item the participants checked and recorded the time they spent until a decision point.

Scenario B was used to assess the performance of facility operators in getting prompt and accurate situational awareness about the temperature and humidity sensor reading and equipment statuses. For this scenario, the greenhouse building that is described in Table 1 was used. In this scenario, each participant was asked to find the set of faulty sensor readings given that the greenhouse was operated in a winter day with an outside temperature specified as 45 °F, with certain roof vent motors being open and certain zones in the green house being watered, as marked in the interfaces provided. Two sensor readings were abnormally altered and the participants were expected to find them and decide on an action (i.e., ignore the readings, alter the status of controlled equipment) given the context the sensors and equipment operate. The details of this scenario is provided in Yang & Ergan 2014. The study reported in this paper takes the previous study one step ahead and reports the performance of the participants when virtual models are used and when they are used in immersive settings. The idea with the assigned task was to evaluate how the participants took into account the spatial context under which the sensors provide the data. For instance, they were expected to ignore the out of threshold humidity readings around the recently watered zones, and temperature readings that are around open roof vent motors in a day where the outside air temperature is around 45 °F.

For the purpose of understanding the behavior change by facility operators in the above described tasks, the authors compared the behavior of facility operators when they do these tasks in their existing work processes and when they do these tasks using virtual models developed using BIMs and gaming engines. In both scenarios, the participants were asked to perform the same tasks both using virtual models and the current way of solving these tasks. The authors used 2D drawings, BAS data with the interfaces and sketches used in the FM departments that manage the case buildings used in this study to replicate the current practice.

### 3.3 Description of the developed virtual models and current interfaces

BIMs of both facilities were generated from construction as-built drawings and photos taken from facilities and were converted to formats that would be recognized by the selected gaming engine. Additional scripts have been written in the gaming engine to enable collision free walkthroughs, interactions with components in the virtual model, and accessing properties and their corresponding attribute values for the scenarios. The virtual environments were developed using an open source game engine with 3D models exported from a commercial building information model development tool. Virtual models and example set of information embedded in the models are provided in Figure 1, 2 and 3 for Scenarios A and B, respectively.

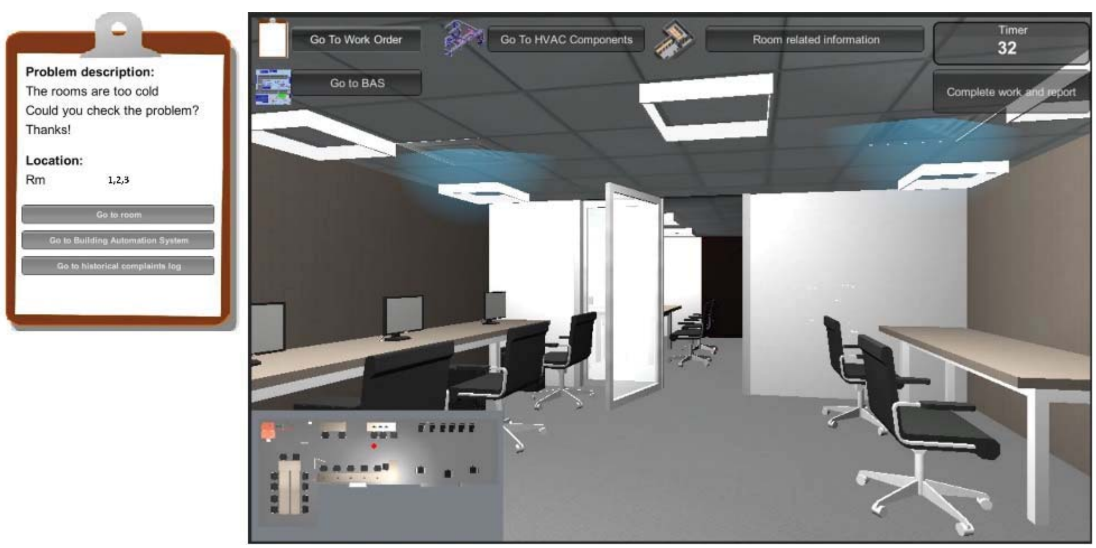


**Figure 1** Snapshots from the virtual model used for Scenario A (Left: problem description given in the virtual model; Right: A scene from the virtual space

As shown in Figure 1, in Scenario A, the virtual model included various HVAC component and component specific static and dynamic properties (e.g., the location of a damper, the status of a damper), history of work orders in the examined spaces, history about components (e.g., failure frequency), and space related characteristics (e.g., the design occupancy, the existence of additional heat generating equipment, the size of windows).

Users could perform their inspections of the spaces and the HVAC systems as they do in real world, such as checking the set point of a thermostat, and checking to see if a component works properly, until the right cause is identified. Every time a component and component information is checked, their color changed in the virtual model to track the items checked (Figure 2). They would complete the work and report the cause (s) of the problem when they are ready to do so.

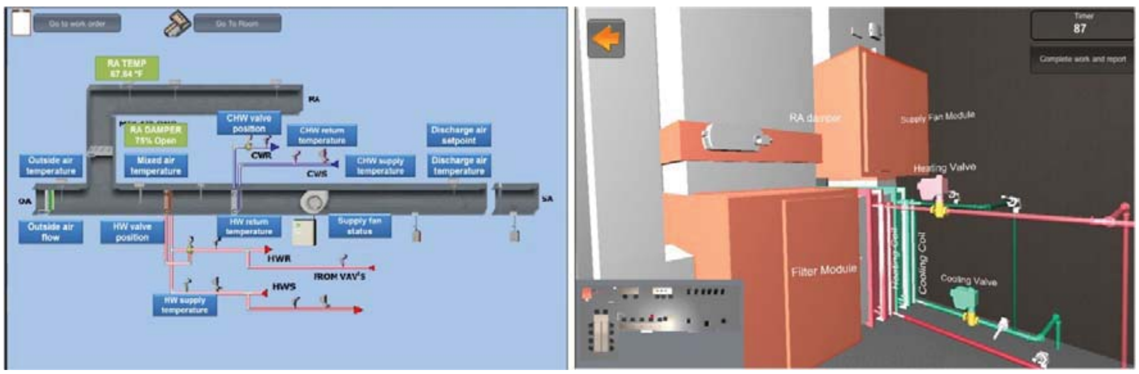


**Figure 2** Two snapshots from building automation system and air handling unit in the virtual model. Any information checked by an HVAC operator changes color

As shown in Figure 3, Scenario B included the virtual model for the greenhouse analyzed. The virtual model showed upper and lower level temperature and humidity sensors' dynamic and static information (e.g., sensor location, ID, type, readings), the controlled equipment location and statuses (e.g., roof vent motor ID, location, open/close, automated control or manual) as participants walked in the immersive environment. The immersive equipment provided the flexibility to the users to automatically update the scenes based on the movement of the users (e.g., changing the view synchronously as the person looks up and down).

The current interfaces included (a) 2D layouts of the facility with thermal zones and IDs and locations of sensors and controlled equipment in each zone, (b) desktop displays of the current building automation system that shows color coded textual displays for the parameters and equipment monitored.

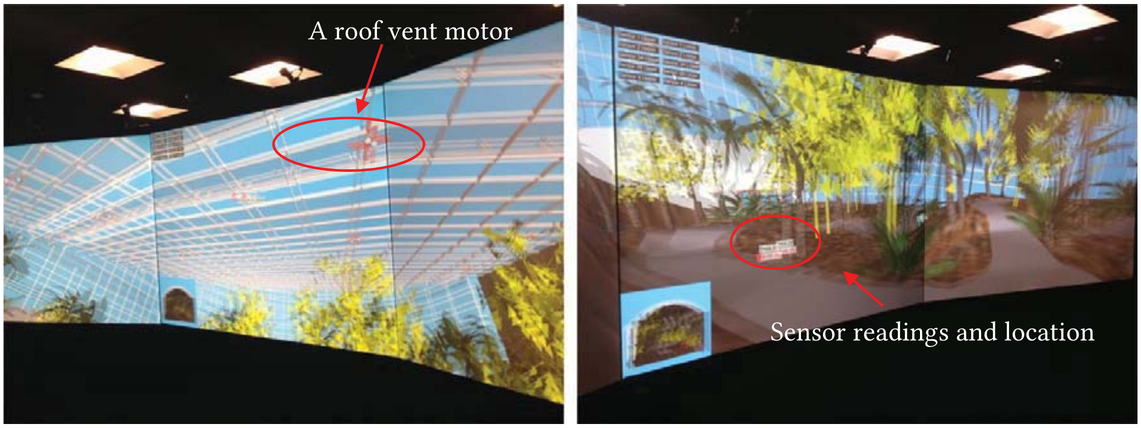


**Figure 3** Photos from the CAVE immersive visualization equipment displaying the virtual model for Scenario B (greenhouse facility)

### 3.4 An overview of the participants of the study

For evaluation of the value of virtual models on improvement of HVAC mechanics' performance (i.e., time to complete the assigned task and accuracy of their decision) on HVAC troubleshooting, so far six facility operators, who are experienced in HVAC troubleshooting, have participated in the research study. To evaluate the accuracy and efficiency of FM operators' decisions on situational awareness for sensor monitoring within their spatial context, four FM operators participated in the study so far. Table 2 provides an overview of the participating groups in both scenarios. Average age of Group 1 participants whose performances were evaluated for HVAC troubleshooting was 23 years, with minimum 10 and maximum 38 years. Group 2's average experience level was 15 years in facilities management and their performance was evaluated for sensor monitoring for getting prompt situational awareness on sensor readings given the spatial context they are embedded in. Both groups were experts in their fields. Each participant belonged to a single group and did not participate in the other group.

**Table 2** An overview of the participants of the study

| Groups | Scenarios participated | Experience in FM (years) | Expertise |
|---|---|---|---|
| **Group 1** | Scenario A | 10,10,20,28,30,38 | HVAC maintenance |
| **Group 2** | Scenario B | 10, 10, 20,30 | HVAC monitoring |

The results of the user studies with the participating groups are discussed in the next section.

## 4 Initial Research Results

Analysis of the initial findings for Scenario A, which tasked HVAC mechanics to pinpoint the causes of a reported HVAC related work order in a space, shows that there is a 58% reduction in time (relative improvement) used by HVAC mechanics to pinpoint a cause when they use virtual models as compared to the practice of looking at the information from BAS interfaces and 2D drawings. As shown in Figure 4a, the participating HVAC mechanics reached a conclusion in median around 5 minutes, minimum in around 1 minute and maximum in around

6 minutes when they used virtual models, whereas the median was 12:30 minutes, minimum was around 10 minutes and maximum was around 14 minutes for HVAC mechanics to pinpoint similar tasks in the current practice of looking for facility information. The efficiency was observed to be high when virtual models were used to get the required facility information. The initial findings suggest that virtual models could be effective tools to use as planning tools before HVAC mechanics go to the field to check and trace the components in spaces. This could also help in planning for dispatching of resources at management levels.

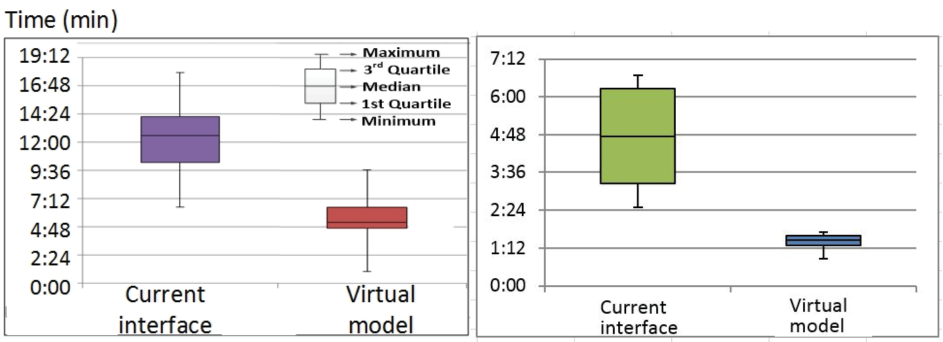


**Figure 4** Task completion times by FM operators. Left: Figure 4a. Task completion times for Scenario A; Right: Figure 4b. Task completion times for Scenario B

The results of the user studies in Scenario B were also similar. The difference between the efficiency of the FM operators when they used virtual models vs. current interfaces was large as shown in Figure 4b. As shown in Figure 4b, the participating HVAC mechanics reached a conclusion in around a minute when they used the virtual model, whereas the median was 4.5 minutes, minimum was around 2.3 minutes and maximum was around 6.5 minutes for HVAC mechanics to identify the faulty sensors in the scenario provided to them. In terms of the efficiency of facility operators finding the problematic sensor readings, their performance improved by 73% (as also summarized in Table 3).

**Table 3** Average accuracy rate of decisions for the tasks and efficiencies of facility operators using virtual models as compared to the current practice

| Scenarios | Metrics used (mean values) | Current interface | Virtual models |
|---|---|---|---|
| **Scenario A** | Efficiency | 12.13min | 5.5 min |
| **Scenario B** | Efficiency | 4.75 min | 1.5 min |
| | Accuracy | 100% | 100% |

The second metric in Scenario B was also the accuracy of decisions by FM operators. The scenario included two step decision where each participant required to find the upper level temperature sensor and the lower level humidity sensor that showed abnormally low temperature high humidity readings, respectively. Accuracy of an FM operator would be 100% if both were correctly identified and would degrade linearly if any of the sensors was incorrectly identified. The four facility operators from the greenhouse facility achieved 100% of accuracy rate for both the current interface, representing the interfaces that they currently use at the studied facilities, and the virtual model. This was attributed to the familiarity of the facility operators with the spaces monitored in Scenario B. Their familiarity with the spaces eliminated their disorientation in spaces while navigating in virtual models.

## 5 Conclusion and Future Work

One of the challenges in the FM industry is the lack of mechanisms that enable use of BIMs in facilities management with without the need to generate custom views, enable interaction with components' information and decision making. One way of addressing this challenge is to convert BIMs to 3D virtual models through gaming engines. The study aimed at evaluation of 3D virtual models, generated by bringing BIMs to gaming engines, in capturing the behaviors of facility operators. The initial research findings on facility operators' performance (i.e., accuracy of their decisions and efficiency in completing the assigned tasks) while using virtual models to access the facility information are promising. Specifically, the study showed that there is 58% time efficiency improvement when virtual models are used in pinpointing possible causes of HVAC related work orders as compared to looking at the HVAC component and space information in drawings and BAS interfaces. Similarly, the study also showed that similar efficiency improvements are observed (i.e., 73% time efficiency) to get situational awareness on sensor reading within their spatial context when virtual models are used.

Gaming engines provide opportunities to interact with BIMs and components based on the specific task requirements of FM operations, as shown in this study for HVAC troubleshooting and sensor monitoring. This study will be extended to include more facility operators from different organizations and look at their performance under these two scenarios when the operators are familiar and unfamiliar with the spaces being monitored and maintained.

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