A BIM-IoT Based Digital Twin Framework for Real-Time Indoor Environmental Quality Optimization in Educational Buildings

Yashvi Rajendrakumar Unadkat[1], Varun Kumar Reja[1], Arnab Jana[1]

[1]Department of Civil Engineering, Indian Institute of Technology Bombay, India
yashviunadkat13786@gmail.com, varunreja@iitb.ac.in, arnab.jana@iitb.ac.in

Abstract –

Digital Twin (DT) is an emerging technology that can be used for Indoor Environmental Quality (IEQ) optimization. However, its application in educational buildings, especially in the Indian context, is limited. Students spend a significant amount of their total time indoors in educational buildings, making effective IEQ management critical for their health, comfort, performance, and productivity. This study proposes a bi-directional Digital Twin framework that integrates BIM models, IoT sensors, and actuators to enable real-time monitoring, analysis, and control of the indoor environment. The framework uses real-time data on temperature, humidity, air velocity, and CO_2, which are analyzed using Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD), ensuring compliance with ASHRAE 55 and ASHRAE 62.1. To validate the proposed framework, it was implemented in a shared office space at IIT Bombay. Results show stable system performance, reliable real-time data synchronization, visualization, and standards-based IEQ assessment. The monitoring and analytical components were experimentally validated, while the actuation and control layer was established at the framework level for future deployment.

Keywords –

Indoor Environmental Quality, Thermal Comfort, Indoor Air Quality, Digital Twin, Building Information Modeling, Internet of Things, BIM-IoT Integration, IEQ Optimization

1 Introduction

IEQ plays a crucial role in ensuring the health, cognitive performance, and thermal comfort of occupants. People spend 80-90% of their time indoors, and students spend a large portion of this time in educational buildings. Hence, maintaining optimal IEQ in educational buildings plays a critical role in reducing long-term health risks and increasing quality performance [1]. IEQ consists of four parameters: Thermal comfort, Acoustic comfort, Indoor Air Quality (IAQ), and Lighting comfort [2]. Out of these, thermal comfort and IAQ are considered for this study. Currently, people use conventional methods for IEQ optimization that are often manual, inaccurate, inconsistent, and lack seamless information exchange between the physical and digital environments. Therefore, there is a need to enable accurate, efficient, and bi-directional data exchange, which is where DT serves the purpose.

DT is “a digital representation of a physical asset, updated with real-time data, collected using a network of IoT sensors” [2]. In the IEQ monitoring context, DT helps us set up a seamless exchange of real-time information between the physical and digital environments and control the facility. In this way, implementing DT in educational buildings will provide a better indoor environment for students, increasing their productivity, performance, and reducing the health risks.

To develop a DT, BIM-IoT integration plays a foundational role [5]. The primary role of BIM in developing a DT is to produce a virtual extension of a real-world item [6]. On the other hand, the IoT devices help sync the physical and virtual states by enabling real-time data measurement, which supports IEQ optimization in real-time [7], and forms the base of the DT. But the framework for the implementation of DT to optimize IEQ in developing countries is still limited, especially for educational buildings.

To tackle this limitation, this study proposes a framework for the deployment of a DT to monitor, analyze, and control IEQ in an educational building unit. DT enables enhanced dynamic spatial and temporal data visualization and monitoring, which is achieved using a DT software called Autodesk Tandem in this study. The real-time analysis of the sensor data helps the system to make decisions as per standard guidelines. The thermal comfort analysis utilizes two indices: Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD), and the ASHRAE 55 standard. On the other hand, IAQ analysis is done as per ASHRAE 62.1 standard compliance. The decisions made as per the analysis are used to control the physical environment using suggested actuators like the IR Blaster. The results of this study provide a unified framework for DT, serving as a bridge between monitoring, analysis, and control to achieve a healthier environment.

The paper is broadly divided into five sections: in Section 1, we introduce the problem statement, Section 2 reviews current approaches for IEQ monitoring, DT implementation, and identifies some research gaps. In Section 3, we will examine the proposed methodology and case study for deploying a DT for IEQ monitoring. In the last two sections, we will move on to the results, draw some conclusions, discuss future work, and summarize the study.

2 Literature Review

This section reviews existing studies on IEQ optimization techniques, their drawbacks, and how the application of DT, BIM, and IoT can serve the purpose. The review identifies technical research gaps and limitations that form the basis for the proposed framework.

2.1 IEQ Monitoring Techniques

IEQ has gained attention over the past few years, particularly in educational buildings, due to its direct impact on students' cognitive performance [8]. Especially in developing countries like India, the deteriorating outdoor environment quality significantly affects the indoor air quality, which is one of the 10 leading causes of illness [1]. Hence, monitoring and improving IEQ in buildings is a widely studied topic. Several studies have focused on assessing IAQ and thermal comfort in educational buildings, highlighting inadequate ventilation, high CO2 concentrations, and thermal discomfort, particularly in the Indian context [1]. IEQ monitoring studies generally follow two approaches: objective and subjective. Objective methods include field measurements, and subjective methods are based on personal judgment surveys [9]. Many of the studies rely on survey-based assessment and hence provide limited insight into the dynamic behaviour of the indoor environment.

Poor IAQ is reported as the second major health threat in India, after poor water quality and hygiene [1]. And thermal comfort directly affects user performance, which is why these two are included in this study. Thermal comfort depends on indoor environmental conditions as well as the subjective factors of occupants, like clothing and metabolic rate [2]. If we look into objective methods to measure IEQ, the technologies used to measure thermal comfort are directed towards data-driven models based on networks of connected sensors. [10]. Similarly, methods used to monitor IAQ include Wireless Sensor Networks (WSN) and IoT. But few parameters revealed that the performance of these systems is low compared to real-time and dynamic monitoring IoT systems [11]. Hence, integration of real-time IoT data acquisition with building models is important to monitor IEQ.

2.2 BIM, IoT, and Digital Twin for IEQ Optimization

BIM is an important component for information management, focusing on data interchange between different stakeholders, and has wide applications. BIM-based approaches improve spatial context but are generally disconnected from real-time data streams and control strategies. Therefore, IoT-based systems are being used to collect real-time data. IoT has made buildings go from ordinary to smart buildings by integrating everyday objects with digital controllers; such improvements have made it possible to create a controllable and integrated network supporting decision-making and human well-being [11]. However, most of these systems operate using one-way communication, where data flows only from the physical environment to digital dashboards for visualization, not for control. DT technology has emerged as a bridge between this gap by enabling bi-directional communication. Other industries have been using DT for many years, but it came to attention in the Architecture, Engineering, Construction, and Operations (AECO) industry with the concept of smart buildings and smart cities [4].

Recent studies have demonstrated the potential of DTs for monitoring thermal comfort, energy consumption, and IAQ in buildings. There are three stages of DT development:

1. Digital Model, which is a static representation of the physical environment, independent of sensor data, and cannot be changed [12].
2. Digital Shadow, which has one-way data flow, i.e., the model updates automatically when any change in the physical system is detected, but not the other way around [13].
3. Digital Twin, which is "a virtual replica of a physical asset that collects and sends real-time information". It is a two-way communication loop, within which dynamic data flows and optimizes the physical environment [2]. DT effectively fills the communication gap between the physical and digital environments and creates a digital replica by integrating real-time IoT data with a BIM model. For example, a classroom with sensors sending real-time data and actuators like IR blasters controlling the devices based on the decisions made.

Data analysis serves as the core of the decision-making process, utilizing ASHRAE 55 and ASHRAE

62.1 guidelines. Nevertheless, most existing DT experimental setups are limited to residential or commercial buildings. DT application in educational buildings is very scarce, particularly in the Indian context, where educational buildings often operate under high occupancy and mixed-mode ventilation, making IEQ management more challenging under poor outdoor air quality conditions. Moreover, many studies have limited emphasis on automated actuation. Given these limitations, there is a strong need for a standardized and deployable framework to set up a DT for IEQ optimization in educational buildings. Therefore, this study aims to develop a DT by integrating a BIM model with real-time IoT data and actuators for a shared office space at IIT Bombay. The key contribution of this study includes:

1. Integration of BIM-IoT data to set up bi-directional communication.
2. Framework for the development of a deployable DT for IEQ Monitoring in educational buildings.
3. Mechanism for real-time optimization of IEQ.

3 Methodology

This section presents the proposed methodology for developing a BIM-IoT integrated Digital Twin framework for real-time IEQ monitoring and optimization. It describes the workflow, system architecture, data acquisition process, analysis approach, and actuation strategy. The methodology is further tested and demonstrated till the actuation part through a case study conducted in an educational building unit at IIT Bombay. The workflow of the proposed DT framework is shown in Figure 1. It illustrates the process from real-time data acquisition to BIM-based visualization, analysis, and actuation, forming a continuous loop.

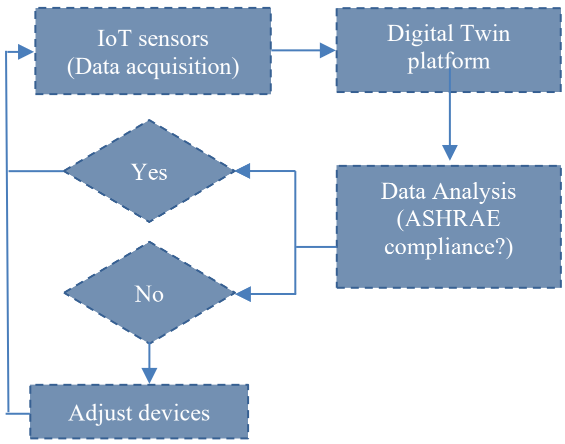


Figure 1. Proposed system workflow

3.1 DT Framework Architecture

The DT framework proposed in this study consists of five interconnected layers that collectively establish a bi-directional communication loop between the physical environment and its digital representation. These layers are described as follows:

1. Physical Layer: The physical layer comprises real-world assets like the building and IoT sensors. This layer is responsible for sensing, collecting, and providing real-time physical data for subsequent processing.
2. Data Transfer Layer: The data transfer layer enables the transmission of collected sensor data from the physical environment to the DT platform. This layer integrates real-time IoT sensor data with the BIM model on the digital twin platform, facilitating the creation of a synchronized DT.
3. Visualization Layer: The visualization layer supports real-time visualization of incoming data, allowing users to monitor system performance, observe alerts, and analyze historical trends through dashboards and charts.
4. Analysis Layer: The analysis layer plays a critical role by interpreting the received data to support informed decision-making. The outcomes of this layer form the basis for the actuation layer, as the results are translated into control commands for the actuation layer.
5. Actuation Layer: The actuation layer implements control actions based on analyzed results. Actuators, like IR Blasters, can be used to control devices like fans and ACs to maintain optimal IEQ. The integration of this layer is designed to enable closed-loop control of the system.

Together, these five layers establish a bi-directional DT system, forming a continuous feedback loop that spans real-time data acquisition, transfer, analysis, visualization, and control. The interrelation and sequence of action of all these five layers are as shown in Figure 2. These layers support some specific tasks, which are discussed below.

3.1.1 Data collection and transfer

The methodology adopts an integrated approach for developing a DT of an educational building unit to optimize Indoor Air Quality and Thermal Comfort. The framework integrates the above-mentioned five layers to enable a bi-directional DT. However, in the current stage of implementation, the focus is on real-time monitoring, visualization, and standards-based analysis, while the actuation logic is designed and planned to be deployed in upcoming stages. The data to be collected using IoT sensors must first be selected based on the requirements of the analysis. For assessing thermal comfort and IAQ,

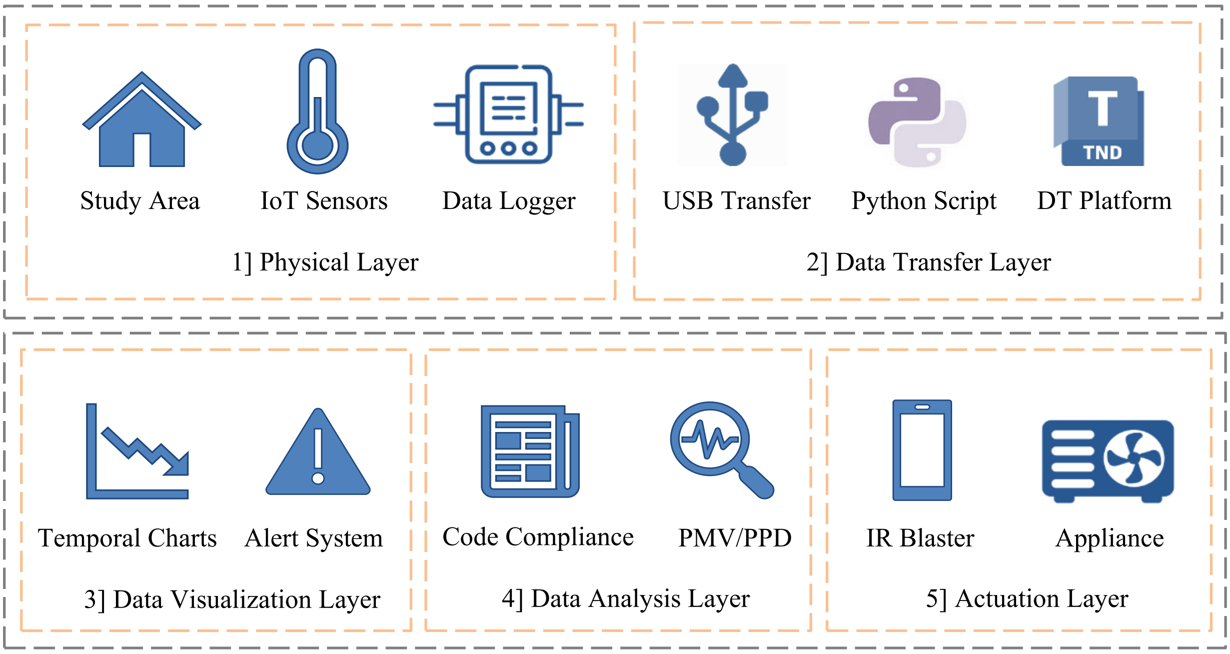


Figure 2. DT framework architecture

specific parameters should be chosen in accordance with ASHRAE standards and relevant research, as presented in Table 1 below.

Table 1. Selected parameters to assess thermal comfort and IAQ [14],[15], [16], [17]

Parameters	Description
Air Temperature (°C)	Directly impacts human perception of a hot/cold environment
Radiant Temperature (°C)	Radiative heat exchange from surfaces
Relative Humidity (% RH)	Affects Thermal comfort and sensation
Air speed (m/s)	Directly impacts the rate of convective and evaporative heat loss
CO2 (ppm)	Has an impact on cognitive performance

These parameters will be collected in real-time using IoT sensors, where thermal comfort parameters will be analyzed using indices PMV, PPD, along with checking compliance with ASHRAE 55. On the other hand, IAQ parameters will be analyzed by checking compliance with ASHRAE 62.1 standards. There are two more such parameters like: Particulate Matter (PM) and Volatile Organic Compounds (VOCs), which are responsible for IAQ, but this study utilizes only CO_2.

Real-time data acquisition is carried out using IoT sensors, where sensor selection and placement play a critical role in data accuracy and reliability. Selection criteria for IoT devices include measurement accuracy, availability, and cost-effectiveness. Sensor positioning follows ASHRAE guidelines with sensors placed near the occupant's breathing zone, working/sitting zones, and other representative points of the space. To develop a DT, the digital representation of the physical environment should be created first. A detailed BIM includes the architectural elements, furniture layout, and represents the physical environment, occupants' zones, and spatial layout. The BIM model is then to be integrated with real-time environment data collected from sensors deployed within occupant zones. These sensors continuously measure key IEQ parameters related to thermal comfort and IAQ, as mentioned in Table 1.

3.1.2 Data Visualization and Analysis

Real-time sensor data is transferred from the physical layer to the digital environment via the data transfer layer, enabling synchronization between the two systems. There are different software programs available to develop a DT, like Bentley iTwin, Autodesk Tandem, Ansys Twin Builder, etc. We can use any software that provides easy integration of BIM and Real-time IoT sensor data, and that offers multiple ways to visualize spatial and temporal data. For this study, we have worked on Autodesk Tandem because Tandem and Revit are released by the same software company, favoring the cross-platform compatibility and enabling Autodesk Tandem to read the Revit model correctly [6]. The incoming data is mapped to corresponding zones, Zone A and Zone B, as shown in Figure 3, to allow users to visualize IEQ conditions using temporal charts, heatmaps, and customizable dashboards. These visualization tools help us study the trends for the selected parameters, which may help in future prediction as per historic trends. Additionally, the Autodesk Tandem provides a feature that triggers an alert whenever the parameter data exceeds the assigned permissible range as per ASHRAE 55 and ASHRAE 62.1.

Later, an analysis layer processes the sensor data to assess the compliance with thermal comfort and IAQ standards. Thermal comfort is evaluated using the PMV and PPD indices in accordance with ASHRAE 55, and IAQ parameters are assessed in accordance with ASHRAE 62.1. The permissible limits of all the selected parameters are shown in Table 2. The analysis layer then determines the corrective actions based on the predefined decision rules.

Table 2. Permissible range of thermal comfort and IAQ parameters as per ASHRAE, WHO guidelines [15],[16],[17]

Parameters	Permissible limit
Average Air Speed (m/s)	< 0.20 m/s
Air Temperature (°C)	22 °C - 26 °C
Mean Radiant Temperature (°C)	+2 °C of air temperature (Ta)
Relative Humidity (%RH)	30-60 %RH
CO_2 (ppm)	≤ 1000 ppm above outdoor (~1400 ppm max.)

3.1.3 Actuation Strategy

To enable bi-directional communication, the methodology incorporates an actuation layer that transforms the analytical decisions into control signals for the physical devices. These signals are generated to be transmitted to actuators like IR Blasters, which can regulate devices such as ACs and fans in a deployed setup. IR blaster devices work just like a normal remote, but based on the signals it receives from the analysis layer. This actuation strategy closes the loops between monitoring, analysis, and control, thereby distinguishing the proposed system from conventional one-way monitoring approaches.
It also provides the basis for the future evaluation of energy consumption impacts and occupant well-being improvements. In this study, the actuation workflow was defined and validated conceptually but not physically executed.

3.2 Case Study

This case study demonstrates the proposed framework to deploy a DT in an educational building unit. The selected unit is a shared office space at the Department of Civil Engineering at Indian Institute of Technology Bombay, which is a 50-year-old building with faculty offices, classrooms, conference rooms, and laboratories.

3.2.1 The study area

The study area shown in Figure 3 is a room occupied by research scholars for an average of 6 to 8 hours on weekdays. The space has an area of 25.6 m² (8m x 3.2m x 3m). A glass partition wall divides the room into two parts, each measuring 12.2 m² and 13.4 m², occupied by the professor and students, respectively. The walls are of brick masonry with plaster finish, while the floor is tiled, and the finished ceiling contains lighting fixtures and a fan. The partition wall with a door allows partial transparency and limited air circulation between the two spaces. Both zones are equipped with wooden desks with computer systems, chairs, and storage shelves.

Figure 3. Selected study area

The Zone A (professors' seating area) has a split-type air conditioner unit, along with ceiling fans and a glass window on the wall. Zone B, occupied by research scholars, is equipped with a fan which is remote controlled. The BIM model (architecture and furniture layout) for the study area cabin was created using Autodesk Revit, as shown in Figure 4.

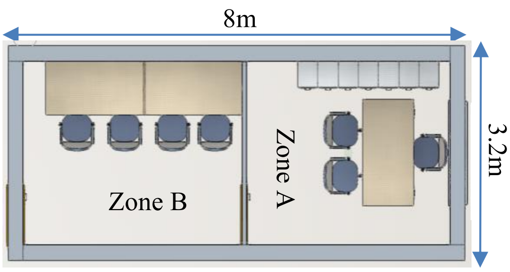


Figure 4. Study area model

3.2.2 Data Acquisition and Visualization

To capture real-time data, a Testo multi-sensor kit was used due to its high measurement accuracy, availability, and its compliance with ASHRAE standards. These sensors were deployed within the occupants' breathing zone using tripods set up as per ASHRAE 55 and ISO 7762 guidelines. The Testo multi-sensor kit, as shown in Figure 5, consists of some sensors and components as mentioned in the list below:

1. Globe Temperature sensor
2. CO_2 sensor
3. Air Velocity vein sensor
4. Air Temperature/ Humidity sensor
5. Testo 480 data display

Figure 5. Sensors used to collect data

The sensors recorded real-time data for temperature, humidity, air velocity, and CO_2 at predefined intervals of 30 seconds which were shown on Testo 480 display device. The data is then sent to the computer system on Easyclimate software via USB connection. The updated version of Easyclimate software allows users to send real-time data, but the available older version was not compatible with Autodesk Tandem. Therefore, to send real-time data, a pipeline using a Python script and Node-RED was created to transfer the average of collected data at an interval of 2.5 minutes; this frequency is selected as per ASHRAE standards. As the data arrives at the DT model, the visualization can be done in the form of heatmaps, temporal stream charts, and an alert system based on the set threshold values, as shown in Figure 5.

3.2.3 Data Analysis and Actuation

Next, the analysis layer will compute the thermal comfort indices (PMV and PPD) using ASHRAE 55, assuming a standard metabolic rate of 1.0 met (activity: sitting and typing) and clothing of 1.0 clo unit (can vary from case to case). IAQ parameters will be checked for compliance with ASHRAE 62.1 using a Python script. IAQ analysis is done based on CO_2 only. Other parameters like PM and VOCs can be used to get more accurate IAQ optimization. For thermal comfort analysis, if at any time thermal comfort indices (PMV and PPD) are going out of the permissible range, the parameters affecting thermal comfort indices will be checked, and whichever parameter is deviating will be adjusted by controlling the respective device. For example, if the temperature is going out of range, the AC temperature can be controlled. When any parameter deviates from the threshold values, the actuation layer is designed to be triggered. To enable automated control, an IR blaster has to be deployed within the study area. A Python script-generated signal can be sent to the IR Blaster via Wi-Fi network, thereby regulating thermal conditions and air quality in real-time. The actuation part is planned to be deployed. The IR blaster selected for use is the BroadLink RM4 Mini, due to its compatibility with Python and Node-RED, its widespread use in research, and its Wi-Fi-based design. This creates a bi-directional loop, as the adjusted data will be collected again through sensors on predefined intervals, and the entire procedure is designed to be repeated upon deployment.

3.2.4 Validation Strategy

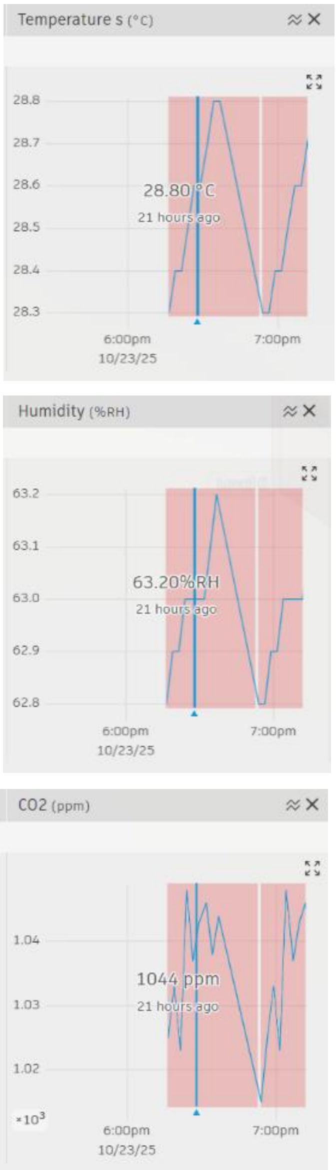
Validation strategy to evaluate system performance under real-world conditions includes:

1. Assessing improvements in IEQ indicators before and after automated control.
2. Testing the responsiveness of the control system by measuring the time lag between the detection of parameter deviation and the actuation response.
3. Comparison of manual vs automated operation modes and reduction in electricity use.

The results will demonstrate the feasibility and effectiveness of deploying a bi-directional DT framework for IEQ monitoring and control in educational buildings within the Indian context.

4 Results and Discussion

This paper provides a framework for monitoring IAQ and thermal comfort in educational buildings using a DT. The results demonstrate the feasibility and effectiveness of integrating BIM and IoT systems to develop a DT for IEQ optimization. The proposed framework of DT successfully established continuous data flow between the physical environment and the digital model. Real-time sensor data collected at a defined interval was found to be sufficient to capture meaningful variations in parameters. Despite software compatibility constraints, the integrated pipeline using Python and Node-RED enabled stable data synchronization. The observed latency between physical data acquisition and digital visualization remained within acceptable limits for facility management use cases, indicating quick system responsiveness. The DT platform enabled real-time visualization of IEQ parameters using temporal stream charts, color-coded heatmaps, and an alert-based system. The BIM-integrated visualization provided enhanced spatial awareness for facility managers, as shown in Figure 6.



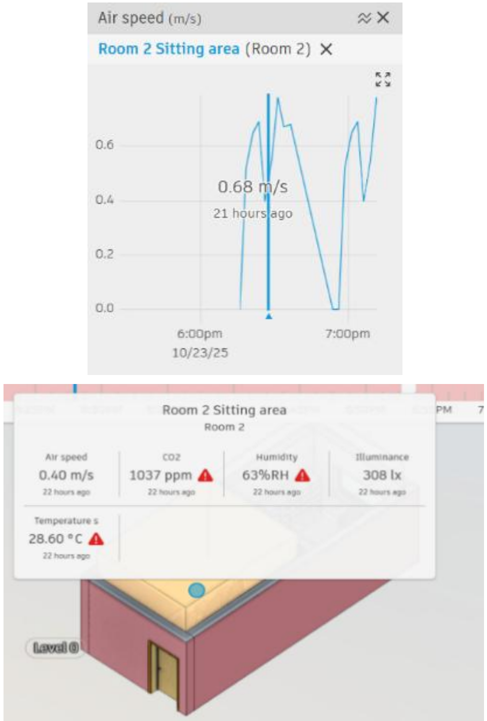


Figure 6. Visualization of real-time data on Autodesk Tandem

Despite the absence of the field-level actuation, the successful integration of monitoring, analysis, and control logic demonstrates framework readiness.

5 Conclusion and Future Work

This paper presents a bi-directional Digital Twin framework for monitoring and optimizing IEQ in educational buildings by integrating BIM, real-time IoT sensor data, analytical models, and actuation logic. The proposed approach addresses the limitations of conventional IEQ management systems by enabling continuous data exchange between the physical and digital environments and supporting standards-based decision-making in real time. The case study conducted at IIT Bombay demonstrates the feasibility of deploying the proposed framework in an educational setting. The DT enabled real-time visualization of thermal comfort and indoor air quality parameters through BIM-integrated dashboards and alert systems, with acceptable system responsiveness despite software compatibility constraints. The results confirm that real-time monitoring combined with ASHRAE 55 and ASHRAE 62.1 compliance assessment can effectively identify thermal comfort and air quality deviations. By incorporating an actuation strategy, the framework establishes the foundation for closed-loop control, distinguishing it from traditional one-way monitoring approaches. This capability has the potential to improve occupant comfort and well-being while supporting more efficient building operations and energy use. Overall, the proposed Digital Twin framework offers a scalable and practical solution for intelligent IEQ management in educational buildings.

Although the present study validates the monitoring, visualization, and standards-based decision framework, physical actuator integration remains to be implemented and tested under real world conditions. Further extensions will include quantification of energy consumption impacts resulting from automated control actions and comparative analysis between manual and automated operation modes. Additionally, IAQ parameters, such as PM and VOCs, will be incorporated to enhance IAQ assessment. Occupant feedback surveys will be integrated to correlate objective IEQ indicators with subjective comfort responses.

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