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A BIM-Based Digital Twin Framework for Indoor Environmental Quality Monitoring and Energy Optimization in Building Operations

Xiaoqiang Hu*, and Xiangxiang Li

School of Engineering, Sanda University, Shanghai, 201209, China

Abstract. This paper proposes a building information modeling (BIM)-sensor-integrated digital twin framework to enable real-time indoor environmental quality (IEQ) assessment and occupancy-adaptive energy optimization. A multi-layer architecture is adopted to connect physical sensing devices, data management infrastructure, and a BIM-based virtual model through a sensor-space-component mapping mechanism and a Dynamo-connected bidirectional data interface. Based on national standards, a compliance-based IEQ assessment scheme is developed to evaluate thermal comfort, air quality, lighting, and acoustic performance. Operational energy consumption and carbon emissions are quantified using energy use intensity and grid emission factors. A case study conducted in a university office building is used to demonstrate the feasibility of the proposed framework. Real-time environmental parameters are synchronized with BIM and automatically classified into compliant, marginal, or non-compliant states using color-coded visualization. Human presence perception and rule-based operational settings enable occupancy-adaptive control of air-conditioning and lighting systems. The results demonstrate that energy usage can be decreased from 3.29 to 2.54 kWh/m²/day, resulting in approximately 23% energy savings and a daily carbon emission reduction of 12.04 kgCO_2e while maintaining a compliant indoor environment. The proposed framework provides a scalable and practical solution for integrating BIM and digital twin technologies in building operation and asset management.

1 Introduction

Smart and low-carbon buildings are rapidly developing and require intelligent operational strategies to enhance indoor environmental quality (IEQ) and to minimize building energy consumption. While greater thermal comfort, air quality, lighting, and acoustic conditions will enable occupant comfort and productivity, these improvements often come at the cost of increased energy consumption, which leads to a long-term operational performance trade-off. Building information modeling (BIM) has been widely considered as a powerful tool for managing the geometric, semantic, and life-cycle information of buildings [1]. However, its applications during the operational stage remain limited due to insufficient integration with real-time data. In parallel, sensor networks and Internet of Things (IoT) technologies offer continuous and fine-grained monitoring of indoor environmental parameters, allowing unprecedented opportunities for data-driven building management [2]. Digital twins have emerged as a promising concept for combining physical assets and virtual models with real-time data synchronization, predictive simulation, and decision support [3]. Although BIM has great potential to improve the efficiency of building operation and maintenance, BIM-sensor integration, reliable model updating, and multi-objective performance evaluation are still challenging.

Significant efforts have been devoted to using BIM, sensor networks, and digital twin technology in building operations, however, there are still a number of shortcomings in the current works. First, the integration of BIM platforms with IoT sensing is limited to data visualization. Through this integration, such systems cannot be coupled by a cyber-physical connection that allows for stable model update and evaluation [4,5]. Second, most digital twin implementations only consider energy system management, while the combined assessment of indoor environmental comfort and energy performance is often neglected, even though they are inherently complementary in practice [6,7]. Third, existing system architectures do not explicitly define BIM-based information extensions and spatio-temporal data mapping mechanisms, which makes it difficult to transfer existing solutions across different building types and operational environments [8,9]. Table 1 summarizes several limitations of the existing research.

In this study, our objective is to design and demonstrate a BIM-sensor-integrated digital twin solution for real-time indoor environmental monitoring and performance-based building operation. By tightly coupling physical sensing systems with virtual building

* Corresponding author: xhu@sandau.edu.cn

models, our solution can assist in simultaneous assessment of occupant comfort and energy efficiency, and support data-driven operational decision-making in real buildings.

Table 1. Comparison of this study with existing research.

Study	BIM–IoT Integration	Cyber-physical Coupling	Automatic Data Mapping Mechanism
[4]	√	X	X
[5]	√	X	X
[6]	√	Partial	Limited
[7]	√	Partial	Limited
[8]	√	Partial	Moderate
[9]	√	Partial	Moderate
This study	√	√	High

2 BIM-sensor-integrated digital twin framework

The proposed BIM-sensor-integrated digital twin framework (see Fig. 1) is structured as a multi-layer architecture designed to enable seamless interaction between the physical building environment and its virtual counterpart. The building entities and distributed sensor networks form the real-world baseline of the system in which environmental conditions, such as temperature, relative humidity, formaldehyde (HCHO) concentration, particulate matter (PM2.5), illuminance, and noise levels, are continuously monitored within the building environment. The data layer is responsible for acquiring raw sensor streams through communication gateways, performing preprocessing procedures including noise filtering, missing-data handling, and outlier detection, and storing both real-time and historical information in time-series databases to support subsequent analysis. The model layer is responsible for the BIM representation of the building, describing geometric shapes, system layouts, and semantic properties of components. Based on this static information backbone, the twin layer maintains a cyber-physical link by acquiring incoming sensor information, mapping to corresponding BIM entities, synchronizing operational states, and updating BIM model parameters in real time rather than geometric configurations to describe current building conditions. The application layer uses the synchronized digital twin to provide real-time performance visualizations, anomaly detection and alerts, scenario simulation, and multi-objective operational optimization to achieve indoor environmental comfort and energy efficiency.

The proposed digital twin does not change the BIM model's geometry. Instead, it updates attribute parameters (such as temperature, relative humidity, and occupancy status) in real time for the relevant BIM components. This keeps the model stable while still reflecting current operating conditions.

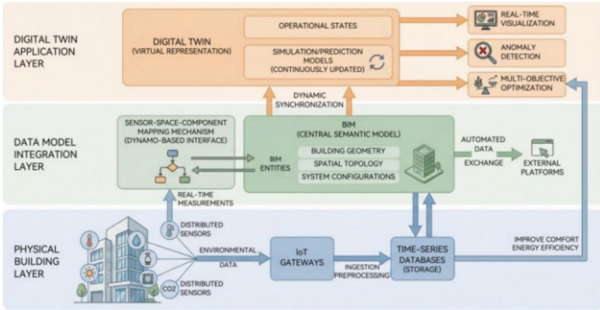

Fig. 1. BIM-sensor-integrated digital twin framework.

3 Performance evaluation indicators

To achieve the standardized and objective evaluation of IEQ, we use the relevant criteria of Chinese national standards, including GB/T 18883-2022 (Indoor Air Quality Standard), GB 50118-2010 (Code for Design of Sound Insulation of Civil Buildings), and GB/T 50034-2024 (Standard for Lighting Design of Buildings). We measure the indoor environmental parameters acquired by the sensor network and compare them with the standard limits. Specifically, thermal and air quality are assessed by the limits of temperature, relative humidity, HCHO and PM2.5 as defined in GB/T 18883-2022. Acoustic comfort is measured by whether indoor noise levels meet the acceptable limits specified in GB 50118-2010. Visual comfort is evaluated according to the illuminance requirements in GB/T 50034-2024. Based on these standards, we develop a compliance-based assessment index, which splits each environmental parameter into compliant, marginal or non-compliant states (as shown in Table 2).

Table 2. Compliance-based classification of indoor environmental parameters (summer conditions).

Standard No.	Parameter (Unit)	State		
		Compliant	Marginal	Non-compliant
GB/T 18883-2022	Temperature (℃)	22 - 28	20 - 22 or 28 - 30	< 20 or > 30
	Relative humidity (%)	40 - 80	30 - 40 or 80 - 85	< 30 or > 85
	PM2.5 (ug/m3)	≤ 50	50 - 75	> 75
	HCHO (mg/m3)	≤ 0.08	0.08 - 0.10	> 0.10
GB/T 50034-2024	Illuminance (lx)	≥ 300	200 - 300	< 200
GB 50118-2010	Noise (dB)	≤ 45	45 - 55	> 55

Energy and carbon performance are measured by both operational electricity consumption and officially published emission factors from the National Greenhouse Gas Emission Factor Database of China. Energy use is quantified by major subsystems, such as air-conditioning and lighting, and normalized using the Energy Use Intensity (EUI) for comparison across different operating times and spatial scales. The EUI is calculated and reported in Equation (1), accounting for variations in operating time and building area. Carbon emissions are calculated by multiplying the current electricity consumption (activity data, kWh) by the corresponding regional grid emission factor (kgCO2e/kWh) as provided by the National Greenhouse Gas Emission Factor Database, as shown in Equation (2).

$$EUI = \frac{E_{actual}}{A} \tag{1}$$

Where: EUI = Energy use intensity (kWh/m²); E_{actual} = Actual measured energy consumption (kWh); A = Building area (m²).

$$C_{actual} = E_{actual} \times EF \tag{2}$$

Where: C_{actual} = Actual carbon emissions ($kgCO_2e$); Eactual = Actual measured energy consumption (kWh); EF = Emission coefficients from the National Greenhouse Gas Emission Factor Database ($kgCO_2e$/kWh).

4 Case study

A real-world case study was conducted in an office environment during summer periods to demonstrate the benefits and efficiency of the proposed BIM-sensor-integrated digital twin framework. The real office is a typical university office, with normal office hours and standard interior layout. It has a floor area of 28m² for both routine academic and administrative activities. The experimental office serves as a testbed for evaluating digital twin-based occupant comfort and energy efficiency. A BIM model of the entire building was created in Autodesk Revit based on architectural drawings and on-site measurements. Subsequently, the experimental office was modeled with detailed geometric representation, semantic properties, equipment parameters, and customized families. A dedicated sensor family was developed to store real-time environmental variables and historical records, forming the digital foundation for dynamic twin construction. The overall BIM model is shown in Fig. 2.

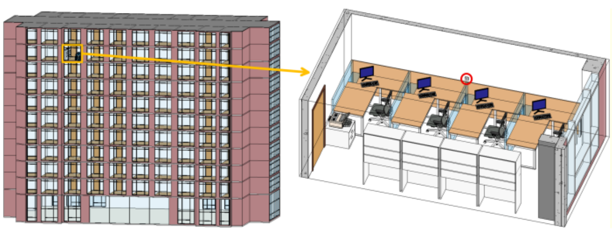

Fig. 2. The overall BIM model.

An all-in-one environmental sensor (see Fig. 3) was installed on a central interior wall, with an effective monitoring area of 30m², to ensure representative spatial coverage of the office environment. Temperature, relative humidity, PM2.5 concentration, HCHO, light, and noise were monitored by the sensor. Also, a human presence sensor (HPS) module was integrated into the sensor for human presence detection. The environmental data were collected every 5 minutes and transmitted over a Wi-Fi network using Modbus to a central server, where data quality control, such as calibration and anomaly detection, was conducted.

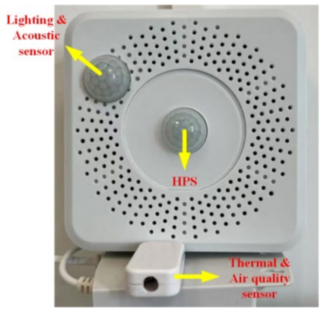

Fig. 3. A all-in-one IEQ sensor.

Dynamo was used as the core integration engine to connect real-time sensor data and BIM. Custom Dynamo scripts (see Fig. 4) were applied to automatically read sensor data and update corresponding BIM family parameters at a refresh rate of 1 second, enabling real-time synchronization between the physical office and the virtual model. Dynamo workflows (see Fig. 5) were also employed to automatically generate and store Revit schedules for long-term historical data management. By both instant parameter updating and structured schedule storage, the originally fixed BIM model was turned into a dynamic digital twin, which could reflect the instantaneous changes in the built environment.

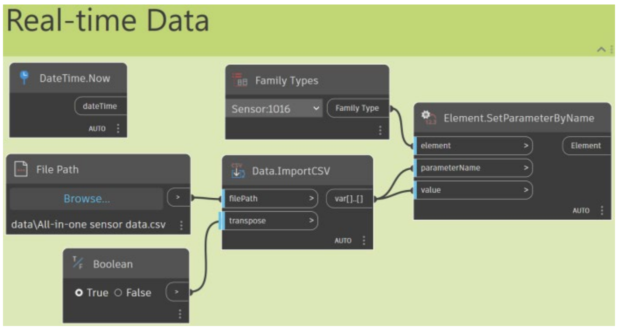

Fig. 4. Family data storage scripts.

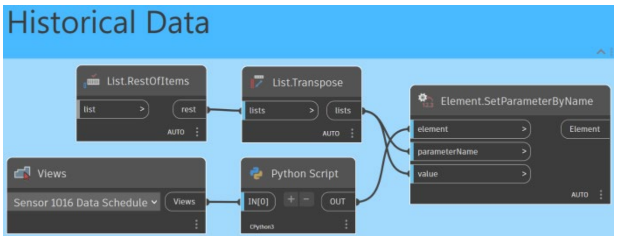

Fig. 5. Schedule data archiving scripts.

Once the data was synchronized, indoor environmental parameters were automatically checked against the reference values reported in Table 2. A rule-based compliance checking procedure in the digital twin was implemented to check each monitored parameter according to the range of classification (compliant, marginal, and non-compliant). If a specified parameter falls within the non-compliant range, the space in BIM is

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highlighted in red, and a dialog box is triggered to display the parameter name and its measured value. If no parameter is non-compliant but at least one parameter lies within the marginal range, the space is highlighted in yellow, and a warning dialog box lists the parameters and associated values. Only if all monitored parameters fall within the compliant range is the space highlighted in green, and no dialog box is generated. Fig. 6 shows the Dynamo scripts used to implement the algorithm. The parameters are checked in a stepwise manner that makes higher-risk conditions (non-compliant) priority over intermediate ones (marginal).

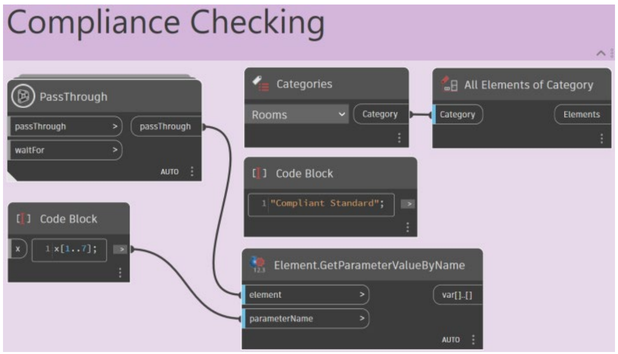


Fig. 6. Compliance checking scripts.

In addition, operational energy consumption was quantified using the EUI, which adjusts measured electricity consumption by floor area and operating time. Carbon emissions were then calculated by multiplying electricity consumption data by the officially published regional grid emission factors, thereby maintaining methodological consistency with national carbon accounting practices. We deployed an HPS module to detect occupancy in indoor spaces. Based on the detected occupancy status, we developed Dynamo scripts (see Fig. 7) to automatically trigger the corresponding evaluation workflow. If a space is unoccupied, it is highlighted in gray in the digital twin in order to distinguish it from actively occupied areas, and this situation does not trigger the compliance checking process.

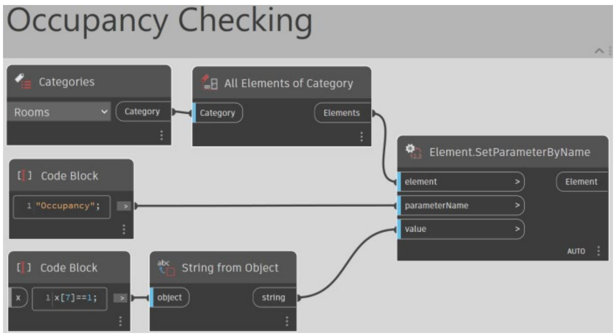
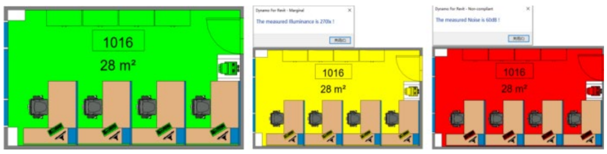


Fig. 7. Compliance checking scripts.

To better compare framework performance in measurable terms, two operating scenarios were established: (1) Baseline scenario (non-adaptive operation): equipment runs on fixed schedules, with no response to occupancy changes. (2) Digital twin-enabled scenario (occupancy-adaptive operation): equipment adjusts in real time based on detected occupancy levels. Both scenarios were tested under similar environmental and operating conditions.

5 Results

During occupied periods, the monitored space maintained compliant indoor environmental conditions for most of the monitoring duration (see Fig. 8(a)), indicating that the existing air-conditioning and lighting systems were generally capable of meeting indoor comfort requirements. Thermal conditions demonstrated stable performance, with temperature and relative humidity remaining within recommended ranges for the majority of operating hours. Nevertheless, occasional marginal states were observed for temperature, particularly during peak occupancy periods, which can be attributed to increased internal heat gains and temporary delays in air-conditioning response. Air quality indicators consistently satisfied the compliance requirements, showing only minor fluctuations associated with occupant activities and outdoor environmental variations. In contrast, a large number of illuminance levels were within the marginal range (see Fig. 8(b)) due to fluctuations in natural light and localized workspace lighting. Acoustic performance showed the largest deviations, with noise levels occasionally classified as non-compliant (see Fig. 8(c)) due to transient human activity or external noise sources. These abnormal conditions were immediately detected by the digital twin, which provided automated visual alerts to support timely operational awareness and corrective actions such as replacing old fixtures or installing additional acoustic panels.



(a) (b) (c)

Fig. 8. Indoor environmental performance visualization.

The office is equipped with a central air conditioner, six small ceiling lights, two large ceiling lights, four desktop computers, and a printer. To get a reliable picture of energy performance, electricity use was tracked directly with sub-meters.

In a typical operating setup (baseline case), weekdays were split into occupied and unoccupied time slots based on real usage patterns. During unoccupied times, measurements showed that some systems stayed on at lower levels, leading to ongoing background energy use. Based on the measured electricity consumption data, the daily EUI of the monitored office space under the baseline condition was: EUI_{base} = 3.29 kWh/m²/day.

Using the HPS module to detect whether someone was present, the digital twin changed how the system ran based on real-time occupancy. When no one was around, non-essential equipment was either shut off or kept at very low power. Daily occupancy times varied, but based on monitoring data, spaces were typically occupied for about 7 hours a day on average. Using the actual electricity use recorded under the occupancy-adaptive control strategy, the average EUI came out to: $EUI_{adap} = 2.54$ kWh/m²/day.

The energy saving rate represents the relative reduction in energy consumption achieved under the occupancy-adaptive operation compared with the baseline operation condition. It quantifies the effectiveness of the digital twin-enabled control strategy in reducing unnecessary energy use. The energy saving rate is calculated to be 22.80%.

Following the evaluation of energy performance, carbon performance was further assessed to quantify the environmental impact associated with building operation. In this study, a grid emission factor of 0.5737 $kgCO_2e$/kWh was adopted for calculation based on the location of the building. Under the baseline operation condition, the daily electricity consumption of the monitored space was 92.12 kWh, resulting in total daily carbon emissions of 52.84 $kgCO_2e$. After implementing the occupancy-adaptive digital twin strategy, daily electricity consumption decreased to 71.12 kWh, yielding carbon emissions of 40.80 $kgCO_2e$.

Compared to the baseline, the proposed digital twin-based approach brought the EUI down from 3.29 to 2.54 kWh/m²/day, a drop of about 23%. This shows that occupancy-adaptive control works well for cutting down unnecessary energy use. Moreover, the optimized operation achieves a reduction about 12.04 $kgCO_2e$ per day.

6 Conclusions

A BIM-sensor-integrated digital twin framework for real-time indoor environmental monitoring and occupancy-adaptive energy management was developed and demonstrated in this paper. We proposed a structured sensor-space-component mapping mechanism and a Dynamo-based automatic data exchange interface to transform the static BIM model into a dynamically updated cyber-physical system that synchronizes in real time. A compliance-based IEQ assessment method, established according to national standards, was adopted to classify indoor environmental states into compliant, marginal, and non-compliant, offering visual feedback and automated warnings within the twin environment. The integration of occupancy sensing further enabled context-aware operational adjustments, effectively balancing comfort and energy performance.

In conclusion, the main contributions of this study include:

(1) A BIM-based digital twin architecture with explicit sensor-space-component mapping;

(2) A compliance-based IEQ evaluation framework integrating multiple national standards;

(3) An occupancy-adaptive control strategy demonstrated through a real-world case study.

Acknowledgments

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