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Real-time simulation and control of indoor air exchange volume based on Digital Twin Platform

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Abstract: Building Information Modeling (BIM) technology has been widely adopted in the construction industry. However, a challenge encountered in the operational phase is that building object data cannot be updated in real time. The concept of Digital Twin is to digitally simulate objects, environments, and processes in the real world, employing real-time monitoring, simulation, and prediction to achieve dynamic integration between the virtual and the real. This research considers an example related to indoor air quality for realizing the concept of Digital Twin and solving the problem that the digital twin platform cannot be updated in real time. In indoor air quality monitoring, the ventilation rate and the presence of occupants significantly affects carbon dioxide concentration. This study uses the indoor carbon dioxide concentration recommended by the Taiwan Environmental Protection Agency as a reference standard for air quality measurement, providing a solution to the aforementioned challenges. The research develops a digital twin platform using Unity, which seamlessly integrates BIM and IoT technology to realize and synchronize virtual and real environments. Deep learning techniques are applied to process camera images and real-time monitoring data from IoT sensors. The camera images are utilized to detect the entry and exit of individuals indoors, while monitoring data to understand environmental conditions. These data serve as a basis for calculating carbon dioxide concentration and determining the optimal indoor air exchange volume. This platform not only simulates the air quality of the environment but also aids space managers in decision-making to optimize indoor environments. It enables real-time monitoring and contributes to energy conservation.

Keywords: Building Information Modeling, Digital Twin, Deep Learning, Internet of Things, Indoor Air Exchange Volume

1. INTRODUCTION

In the last 11 years, the correlation between Building Information Modeling (BIM) and Facility Management (FM) has gained considerable attention. Initially employed predominantly in the design and construction phases of buildings, BIM technology has proven its value beyond these realms. Recent years have witnessed the expansion of BIM application into the operational management phase, signifying a notable developmental trend. Particularly in the last two years, the COVID-19 pandemic has underscored the significance of BIM-FM in managing aspects such as indoor people flow, ventilation, and air quality—crucial elements for ensuring public safety and health. In such scenarios, BIM can offer vital support, aiding managers in more effective planning and execution [1]. Nonetheless, the current BIM framework can only furnish static information within the model and lacks the capability to automatically update real-time data. To address these limitations, the concept of Digital Twin (DT) has emerged. DT involves using data and models to construct virtual entities that replicate reality, facilitating a better understanding and management of objects or systems in the real world. DT finds application in various fields, including industry, construction, transportation, and medicine, among others. In the construction industry, DT serves diverse purposes such as design, planning, facilities management, and environmental monitoring [2,3]. In the realm of facility management and environmental monitoring, DT can integrate with the Internet of Things (IoT) to enable BIM models to gather real-time data about building elements, encompassing physical, chemical, and biological properties, among others [4,5].

As technology advances, deep learning technology is rapidly expanding its scope of applications. Deep learning methods significantly enhance identification accuracy while reducing the need for manual feature extraction. Furthermore, they excel at processing extensive image datasets, resulting in more precise outcomes [6,7].

In urban environments where people spend the majority of their time indoors, the quality of the indoor environment significantly affects health and comfort. Seppänen (1999) demonstrated that a ventilation rate below 10 l/s per person negatively impacts health and perceived air quality in any building. This underscores the importance of maintaining safe indoor carbon dioxide (CO_2) levels [8]. Apte (2000) further emphasized that proper ventilation is crucial for this purpose. When indoor CO_2 concentrations rise due to human occupancy, increasing the influx of fresh outdoor air becomes essential to reduce these levels and maintain a healthy indoor environment [9]. To address the aforementioned issues, this research aims to develop a digital twin platform that integrates virtual and physical elements for real-time simulation and adjustment of indoor air exchange, with the goal of enhancing air quality. Guided by the CO_2 concentration standards set by Taiwan's Environmental Protection Agency, the project aims to ensure optimal indoor air quality. Utilizing Unity as the development tool and employing deep learning for monitoring indoor human movement, the research combines BIM and IoT technologies to collect real-time environmental data, including CO_2 levels and people flow. This comprehensive approach assists managers in comprehending and adapting to changes in the indoor environment. The ultimate objective is to facilitate informed decision-making for optimizing indoor conditions, effectively managing air exchange, achieving energy conservation, and improving building operation efficiency, thereby fostering healthier, more comfortable, and energy-efficient indoor environments.

2. SYSTEM FRAMEWORK

This research focuses on the development of an integrated digital twin platform that combines real-time air quality monitoring with energy-saving capabilities. Figure 1 illustrates the system architecture. The primary components of this platform are based on technologies such as BIM, IoT, and deep learning.

In the realm of BIM modeling, Autodesk Revit is utilized for modeling. After extracting geometric information and materials, the data is imported into Unity for platform development. For real-time data collection, IoT technology is employed to gather various monitoring data, including temperature, humidity, and CO_2 concentration. Additionally, the YOLO V8 image recognition technique from deep learning is applied to identify the entry and exit of individuals within indoor spaces, facilitating the calculation of air exchange rates.

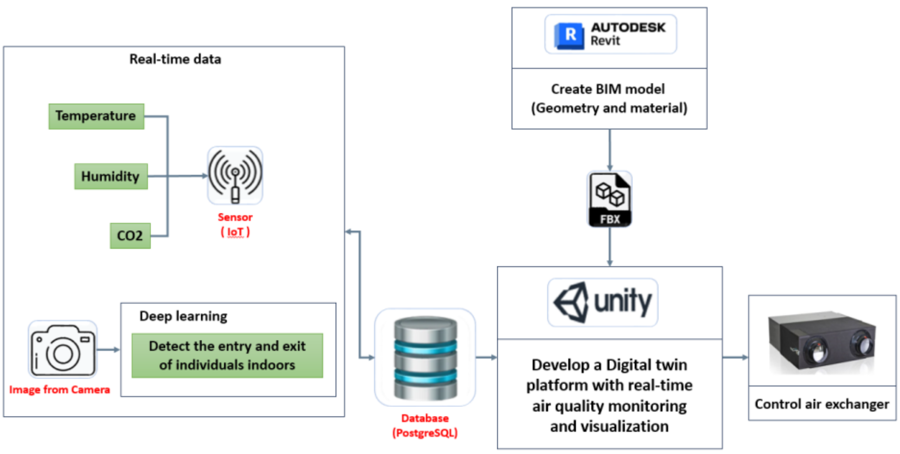


Figure 1. The Concept of the System Architecture.

2.1. BIM Model Conversion Process

In this study, an accurate model of the actual site is created using Autodesk Revit. Subsequently, for material considerations, the decision is made to convert it to an FBX file using 3ds Max. During this process, the Autodesk materials are transformed into Physical Material and rendered to ensure that material information is retained when the model is converted to an FBX file and imported into Unity. The conversion process is illustrated in Figure 2.

Figure 2. BIM Model Conversion Process.

2.2. IoT Architecture

The framework of the IoT is depicted in Figure 3, where we have established a sensor system designed for real-time monitoring of environmental conditions, including temperature, humidity, and CO_2 concentration. These sensors, connected via Wi-Fi, transmit real-time data to a Web API, where the data is processed before being further transmitted to a database. The database stores and organizes the data generated by the sensors, facilitating subsequent analysis and research. Finally, we employ visualization tools to present these data, enabling users to intuitively comprehend and analyze the trends in environmental data changes.

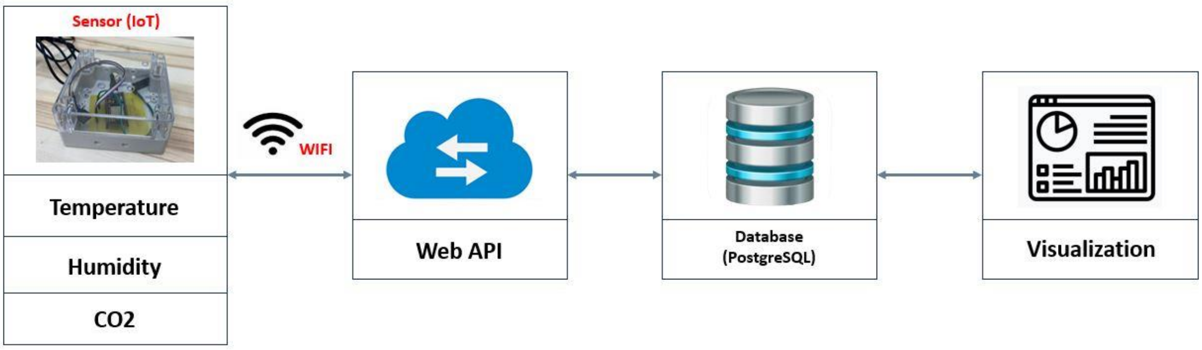


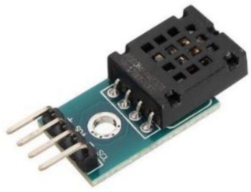
Figure 3. IoT Architecture.

2.3. Sensor Modules and Configuration

This study utilizes the NodeMCU-ESP32-S Internet of Things development board for system development. In terms of sensors, we employ the AM2320 digital temperature and humidity sensor module and the DS-CO2-20 carbon dioxide sensor module, responsible for detecting temperature and humidity, and carbon dioxide concentration, respectively. The configurations of these sensor modules are designed to collect information related to air exchange rates, as outlined in Table 1.

Table 1. Main Components of the Sensor Modules.

Sensor Module	Photo	Description
NodeMCU-ESP32-S		- Internet of Things development board - WiFi, Bluetooth 4.2, BLE network transmission capabilities - Dual-core CPU, programmable using Lua language for development

AM2320		- Digital temperature and humidity sensor module - High accuracy and stability
DS-CO2-20		- Carbon dioxide sensor module - Suitable for various applications, including indoor air quality monitoring and building energy management

2.4. Recommended Values for Air Exchange Rate

When the CO_2 concentration indoors reaches a certain level, outdoor air must be introduced to reduce the indoor concentration and alleviate discomfort for occupants. This study adopts the Taiwan indoor environment carbon dioxide standard of 1000 ppm as a reference. The calculation of the exchange rate between indoor and outdoor carbon dioxide is based on the formula proposed by Coley and Bei Steiner [10], as illustrated in Equation 1. The corresponding parameters are detailed in Table 2.

$$\boldsymbol{C_{(t)}} = \boldsymbol{C_{ex}} + \frac{\boldsymbol{G}}{\boldsymbol{Q}} + \left(\boldsymbol{C_{in}} - \boldsymbol{C_{ex}} - \frac{\boldsymbol{G}}{\boldsymbol{Q}}\right) \times \boldsymbol{e}^{-\left(\frac{Q}{V}\right)t} \tag{1}$$

Table 2. Sources of Air Exchange Rate Parameters [10].

Symbol	Description
$C_{(t)}$	Indoor carbon dioxide concentration over time (ppm)
C_{ex}	External carbon dioxide concentration (ppm)
G	Rate of carbon dioxide generation in the space (cm³/s)
Q	Indoor-outdoor air exchange rate (m³/s)
V	Volume of the space (m³)
C_{in}	Initial carbon dioxide concentration
T	Time unit

In the context of practical applications, this study incorporates a conditional statement into its formula to determine whether the previously calculated indoor CO_2 concentration is less than or equal to the target concentration $C_{(t)}$. Specifically, if the indoor CO_2 concentration exceeds the target concentration $C_{(t)}$, air exchange must be initiated with a volume of 50 units each time. Conversely, if the indoor CO_2 concentration is less than or equal to the target concentration $C_{(t)}$, no additional air exchange is deemed necessary.

2.5. Image Recognition System

An integrated model of physical and virtual elements is established using a camera to detect the entry and exit of individuals within indoor spaces. Object detection is a crucial and rapidly advancing field in computer vision technology, and the YOLO (You Only Look Once) framework stands out as one of the most popular object detection frameworks. YOLO demonstrates rapid recognition and tracking of objects such as vehicles, pedestrians, and bicycles in autonomous vehicle systems [11].

This study employs the YOLO V8 model as a platform for human detection and counting entries and exits. YOLO can predict the positions of object bounding boxes directly from real-time surveillance footage. In this study, we differentiate whether a person is entering or exiting the environment using two boundary lines. When a person touches the blue line and then the red line, the system registers an entry to the space. Conversely, if the order is reversed, it is counted as an exit, as illustrated in Figure 4. Through this mechanism, the system counts the number of people entering and leaving.

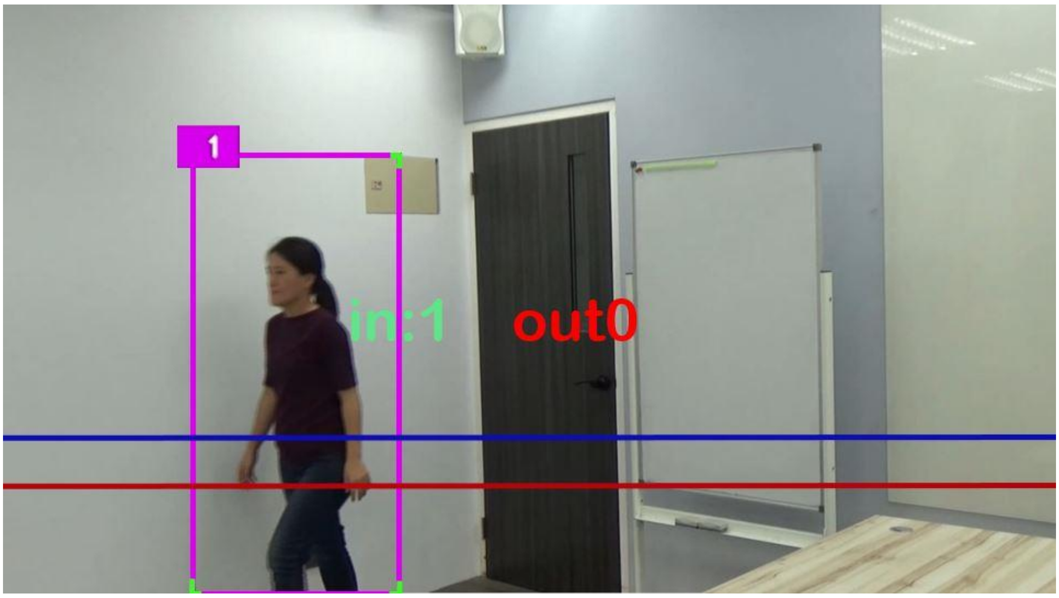
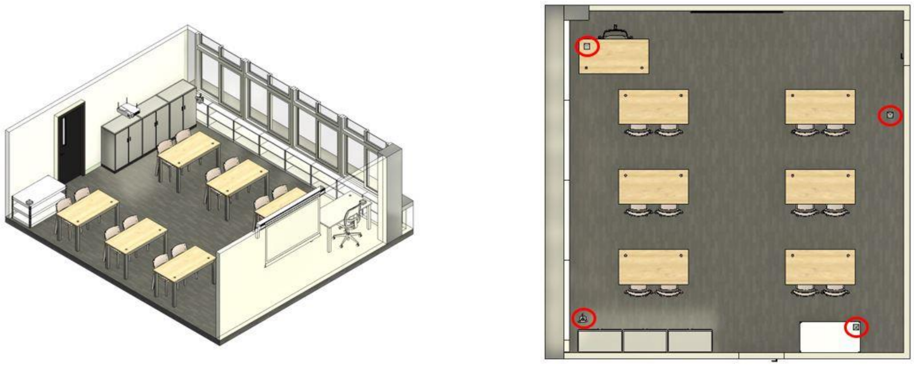


Figure 4. Personnel Recognition Entry and Exit System.

3. DEMONSTRATION

A multipurpose classroom within the BIM research center was selected as the experimental site, spanning an area of approximately 45.62 m^2. Four sensors were installed in this space for comprehensive data collection. The BIM model and sensor layout are depicted in Figure 5.

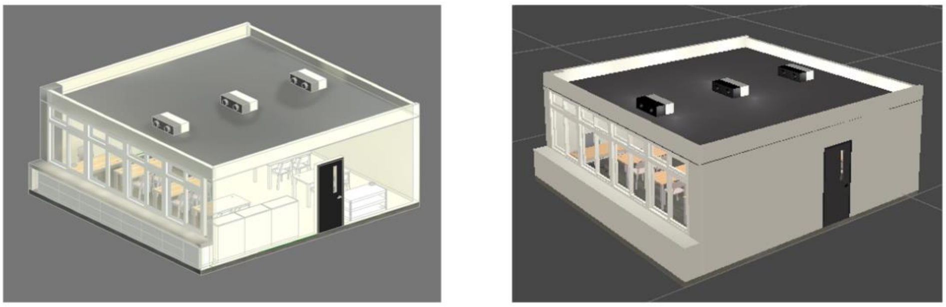


(a) (b)

Figure 5. BIM Model and Sensor Configuration Diagram. (a) BIM Model (b) Sensor Configuration.

The classroom serving as the experimental site is typically in a closed state equipped with air conditioning. After a certain duration of classes, the CO_2 concentration tends to increase, leading to symptoms such as dizziness, drowsiness, or diminished concentration among occupants. However, the existing environment lacks a real-time monitoring sensor system to promptly relay crucial information to administrators.

The DT platform was developed based on Unity and C# to offer real-time environmental monitoring and decision-making support. Spatial visualization is realized using the BIM model. Therefore, this study transforms the classroom's BIM model, initially created with Autodesk Revit, into Unity, constituting a developed digital twin platform. A visual comparison of both models is presented in Figure 6. Environmental data monitoring relies on classroom sensors, encompassing features such as an alert system for elevated CO_2 concentrations and a control function for air exchange units. This integration simplifies the management of indoor air quality. A detailed account of these features is provided below.



(a) (b)

Figure 6. Model Comparison Diagram. (a) Revit Model (b) Unity Model.

3.1. Real-time Environmental Monitoring and Data Visualization

Concerning environmental data, this study engages in real-time data collection within the space using sensors; data includes temperature, humidity, and CO_2 concentration. Managers can access this real-time environmental information by selecting the "Env. Info" button in the menu list, as illustrated in Figure 7. For data visualization, heat maps are employed to portray the comfort level in various corners of the space with respect to CO_2 concentration, as shown in Figure 8.

Figure 7. Real-time Environmental Data.

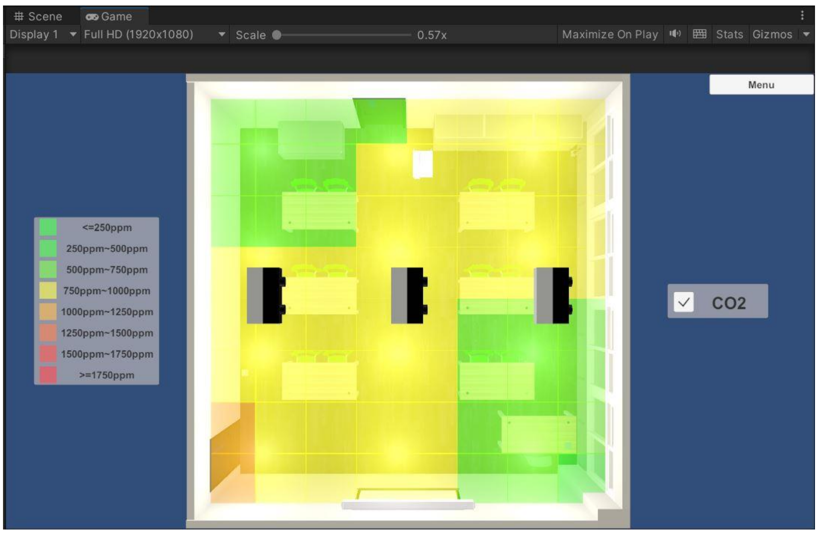


Figure 8. Carbon Dioxide Heatmap Display.

3.2. Warning system

Real-time information collected in this study is stored in a PostgreSQL database and subsequently retrieved by Unity for further development. When the platform identifies that the CO_2 concentration has surpassed 1000 ppm, it triggers an alert to notify administrators to adjust the air exchange rate, as depicted in Figure 9. This feature is designed to help users consistently maintain a comfortable indoor environment.

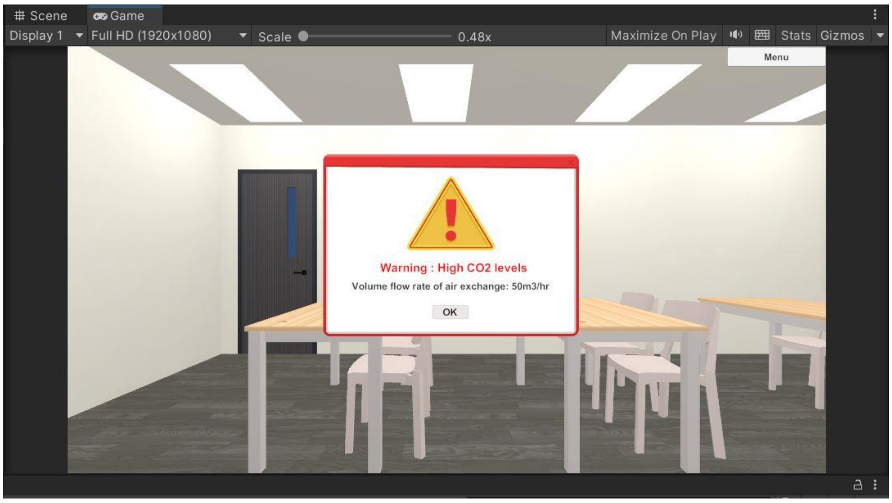


Figure 9. High Carbon Dioxide Concentration Alert.

3.3. Air Exchanger activation

Upon activation and subsequent closure of the warning system by the administrator, the platform immediately provides a prompt to assist the manager in swiftly addressing indoor air quality issues. The activation process for the air exchanger is as follows: the platform displays the air exchanger units that need activation, as illustrated in Figure 10. For an exchange volume requirement of 50, one unit is displayed; for 100, two units; and for 150, three air exchanger units are displayed.

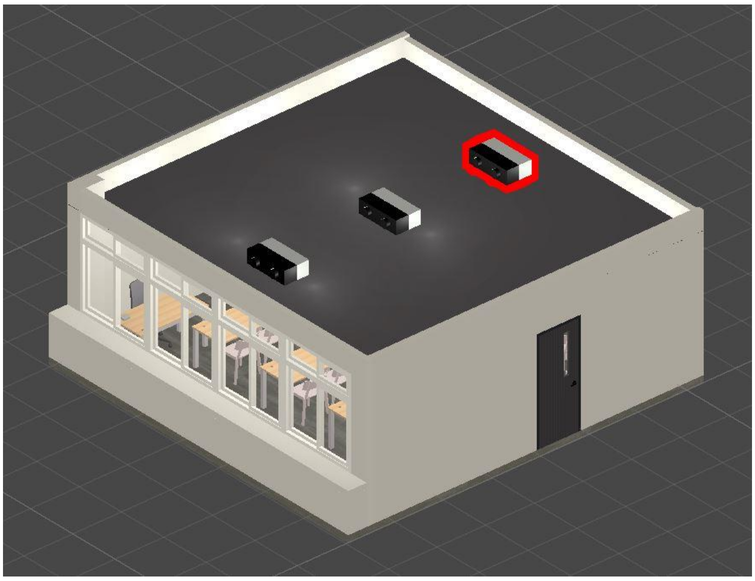


Figure 10. The platform automatically indicates the air exchanger units that need to be activated.

4. CONCLUSIONS

The primary objective of this study is to address the challenge of real-time updating of environmental information during building occupancy, presenting a solution in the form of a real-time simulation and control system for indoor air exchange rates based on a digital twin platform. By integrating BIM and

IoT technologies, the study achieves the real-time synchronization of virtual and physical environments. Additionally, the use of deep learning enables the simulation of personnel movement. The results indicate that this platform effectively monitors and controls indoor air quality, providing a more comfortable and healthier environment for occupants. These outcomes make a substantial contribution to the enhancement of energy efficiency, safety, and comfort within buildings. In the future, further exploration will be conducted to apply this system to various types of buildings and environments, ensuring its adaptability and practicality in diverse settings. This expansion will enhance the system's real-world applicability.

During the operation of the air exchanger, the platform can provide real-time information on changes in carbon dioxide concentration, enabling administrators to assess effectiveness in real-time.

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