Journal of Sustainable Build Environment

https://doi.org/10.70731/8sk2aa87

The Application of Digital Twin for Indoor Air Quality Management: a Case Study in Hong Kong

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KEYWORDS

Indoor Air Quality (IAQ) Control,
Sustainable Building,
Building Management,
Digital Twin,
Case Study

ABSTRACT

With the advocacy of the development of smart cities, buildings are also evolving to become smarter and more user-friendly. Employing cyber-physical technologies, such as the Internet of Things (IoT), Digital Twin (DT) and Building Information Modeling (BIM), can effectively monitor and control the built environment. DT is an emerging tool that connects the building to its digital replica so that the building's situation can be monitored and presented to users effectively. This paper proposes a DT framework for building management to discover the applications of DT for indoor environment monitoring and control. A case study of a DT-driven indoor air quality (IAQ) system is completed to demonstrate the implementation of DT in the built environment. The system demonstrated the key features of DT, including monitoring, simulation, control and prediction, and showed their roles and functions in IAQ management. Finally, the difficulties and limitations, i.e. sensor selection and installation, of implementing the DT system in the built environment are presented after the case study.

1. Introduction

In the digital age, smart cities and buildings are highly pursued to improve living quality and environmental sustainability. To be a modern and smart building, the situations inside the building should be measured, monitored and displayed remotely, and then the data can be used to prognosis and enhance the building's performance in the future [1, 2]. However, the environmental and indoor conditions are difficult to present accurately and in real-time to users due to the communication delay between far distances and rapid change of conditions. The appearance of digital twins (DT) fills the technical gap between the physical environment and its digital model in that the data of the real environment can be instantly shown in the digital replica through the computer or mobile devices, i.e. smartphone and tablet. DT can be an immense technology for building management, maintenance planning, and improving decision-making in equipment selection for building design or repair [3-5].

The concept of DT was initially proposed by M. Grieves in 2002, using data to link up the physical

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Received 23 December 2024; Received in revised form 4 January 2025; Accepted 12 January 2025; Available online 31 January 2025.

and virtual space for product lifecycle management [6]. NASA first used “Digital Twin” in 2010 on their technology area roadmap report [7]. Then, DT is universally accepted to represent the twinning technology between the physical object and its digital model. DT is widely applied in manufacturing and aerospace for process monitoring, failure prediction and supporting decision-making [5, 6]. DT-related research has been pursued in recent years, and its application has been extended to different areas. Building and construction are among the leading areas in DT study [8]. DT and other enabling technologies, e.g. Building Information Modeling (BIM), Cloud Computing and Artificial Intelligence (AI), can drive the whole building lifecycle to be visible, predictable and controllable [2, 9, 10]. As the construction industry continues to evolve, companies should embrace these technologies to remain competitive, meet the demands of a rapidly changing market and construct more efficiently with higher quality [11].

Monitoring and control are the common applications of DT in building management. To achieve a more user-friendly and smart building environment, different types of sensors can be installed to collect the environmental data, e.g. temperature, humidity and concentration of different pollutants in the indoor area, and use those data to analyse and predict the maintenance plan. Nowadays, people spend 90% of their time indoors, i.e., in schools, offices, factories, and residences [12]. Indoor Air Quality (IAQ) is one of the important environmental factors in indoor environment management that directly affects the user’s comfort, decreasing operating performance and causing different health problems, i.e. sick building syndrome (SBS) and building-related illness (BRI) [13, 14]. According to data from the World Health Organization in 2014, about 4.3 million people die annually from household air pollutants, including stroke, ischaemic, heart disease and chronic obstructive pulmonary disease [15]. Also, poor air quality and ventilation will raise the chances of death from COVID-19 infection [16]. Therefore, an integrated and smart IAQ monitoring and control system should be developed in modern buildings to monitor indoor pollutant levels [13], maintain air quality, warn users, and predict maintenance plans and schedules.

This paper presents the DT-based IAQ monitoring and control system in the Hong Kong Insitute of Vocation Education (IVE) and discusses the DT application in IAQ management. The rest of this paper is organised as follows: Section 2. presents the framework of DT in Smart Buildings for built environment management. Section 3. presents the DT-based IQA monitoring and control system in IVE. Section 4 discusses DT’s limitations and potential applications in IAQ control or building management. Section 5. concludes the outcomes of this study.

2. Digital Twin Framework for Building Management

Digital Twin has three main elements: a physical object, a virtual model, and the connection that binds these two together [10], so developing a DT in a smart building is a huge-scope project. Therefore, the DT implementation in smart buildings can be divided into four levels, as shown in Figure 1. The product-level DT can represent the real-time situation of household products, e.g. Fan, Light and Air Conditioning. The data can be used to monitor the equipment’s health, control it and predict maintenance [4]. The unit-level DT represents the connection between the physical world and its digital replica of a single room or unit. The unit’s systems, environment, room conditions and equipment are considered and controlled. The building-level DT is integrated with all the unit DTs to represent the overall building’s performance or system, e.g. power system, water supply system and ecosystem [17]. The co-relationship and interference between the units can be monitored, controlled and predicted the improvements that can more effectively manage the overall performance of the building. The city-level DT is the ultimate goal of developing a smart city that involves not only the building DTs in the city but also the product DTs, i.e., the traffic system, city power system, and urban planning [18]. The scope of work is very large, and the government or some leading enterprises usually initiate it. Therefore, most DT projects are constructed under product level, e.g. equipment DT [19], unit level, e.g. factory shop floor DT [20], and building level, e.g. Cambridge Campus DT [9].

The unit-level DT is the focus of this paper. A completed unit-level DT should include the related product DTs, e.g. air-conditioning, lighting and ventilation, that can affect the surrounding environment directly or indirectly. The unit environment DT and product DT should interact so the unit condition can instantly trigger the product reaction. In modern buildings, building service equipment is important in controlling the indoor environment, affecting users’ comfort and improving resource management. The equipment’s per-

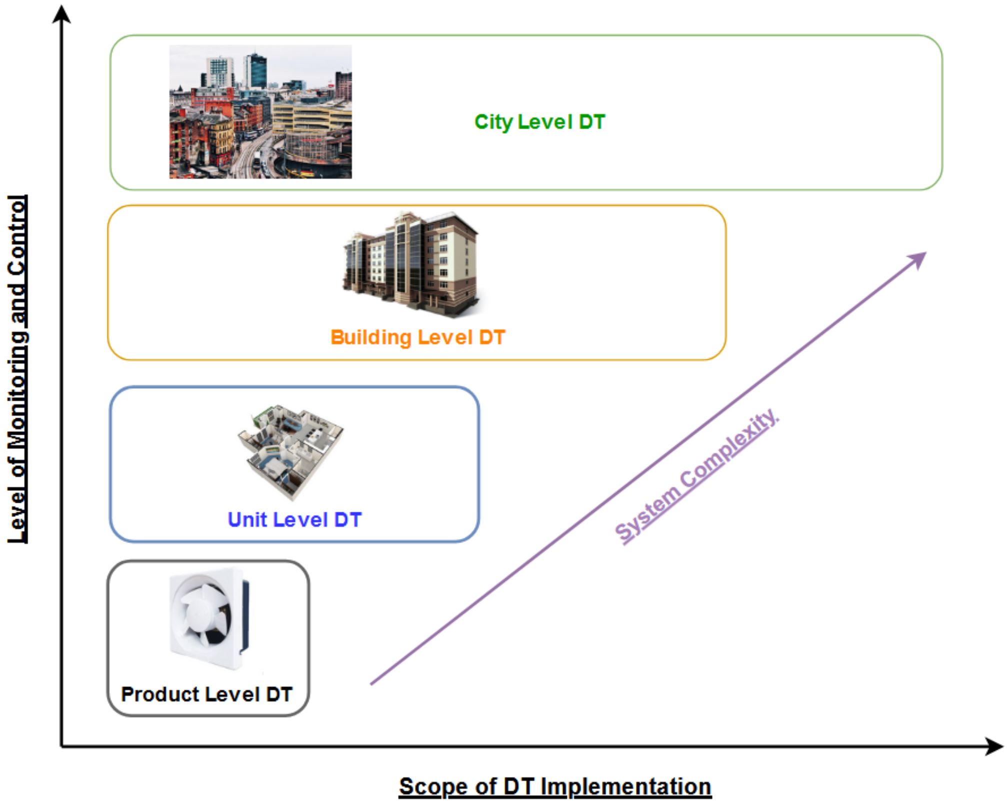

Figure 1 I DT Implementation Level in Smart Buildings

formance can be optimised, and sustainability can be improved by accurate real-time control and effective management [21]. Figure 2 shows the conceptual interaction framework between room DT and product DT. The product and the room's indoor environment interact in the physical world; for example, the air conditioning will operate to cool down the room, and it will be turned off if the environment is cool enough. The sensors installed in the environment and embedded in the product can measure the environment data, e.g. temperature, humidity and the number of users, and the product data, e.g. real-time status and operation schedule, and sync to the server. The virtual replicas of the room and products receive the measured data from the physical world and represent them in the virtual mode immediately. The data can be analysed and simulated in the digital model, and the results can be shared with the physical world and users. The results can support decision-making and control the products to provide corresponding reactions, e.g. turning off the fans and switching the A/C. All data, i.e. measurements, simulations and user actions, can be backed up on the cloud or local database and be used to support the decision-making and scheduling by machine learning, e.g. daily schedule of lighting on/off, predicting maintenance plan. Those data can be critical to achieving indoor environmental quality (IEQ) control, which can manage air quality, thermal environment, sound, and light and their effects on comfort and well-being [22].

The DT-based smart building has four main stages: monitoring, analysis, control and prediction. As shown in Figure 3, the physical environment and virtual replica contribute to each stage and interact. The physical environment is monitored, and the environmental data is recorded. Different sensors in the physical world also measure the product status and user actions. Those data would be analysed in the virtual replica to get the simulation and building information analysis results [21], e.g. energy consumption [23] and airflow analysis. Then, the server can use those results and data to make a suitable decision and action, e.g. send a signal to turn on the fans. The decisions made by data analysis, machine learning, and artificial intelligence in the digital world can give feedback on products and the physical environment. The products can be operated automatically to control the environment and give users feedback via apps or product features, e.g., Buzzer, LED or Vibration Motor. The users can also manually control the products or adjust the control parameters to suit specific needs or preferences. All data, information, and

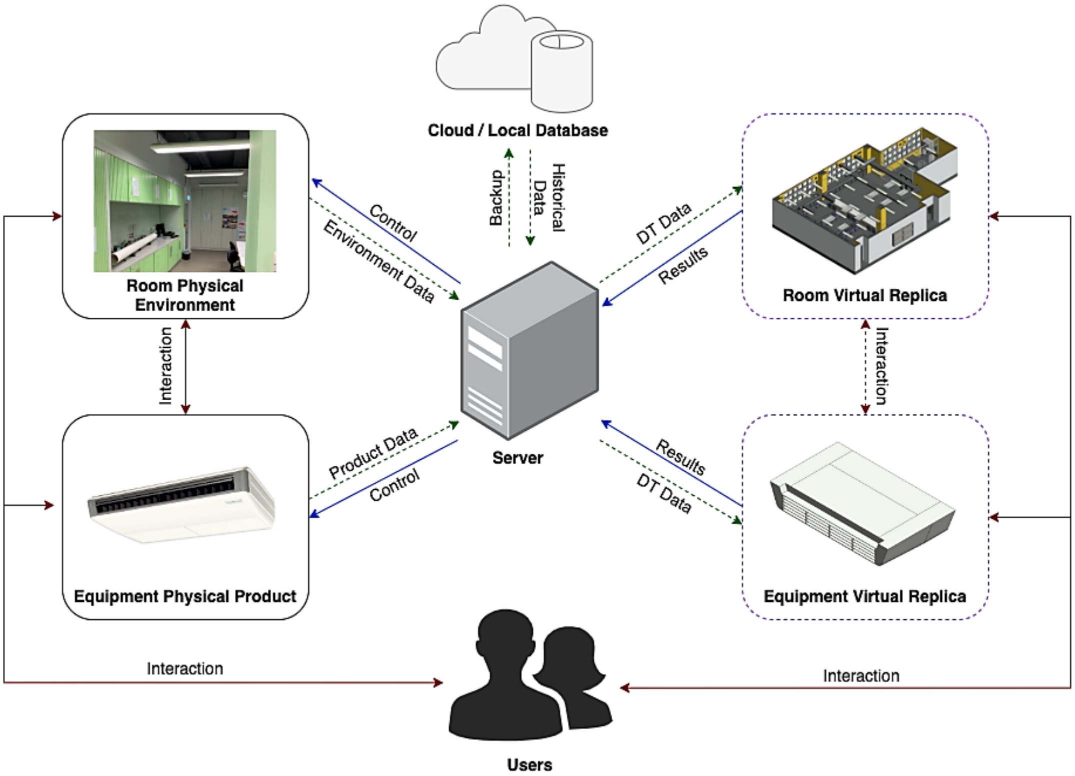

Figure 2 I The conceptual framework of DT-based unit management

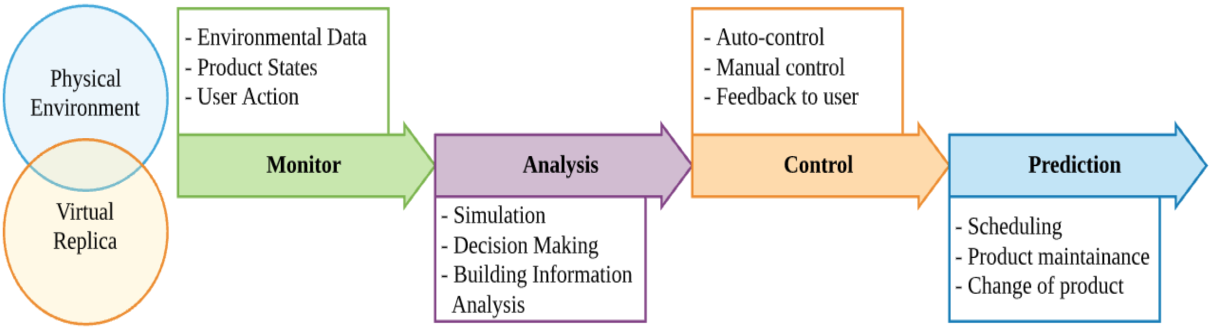

Figure 3 I Data Flow of DT system for smart building

actions performed at each stage are stored in the cloud database, creating a comprehensive record of operational history. This data can be analyzed and used to predict future situations and recommend corresponding actions, such as optimizing lighting schedules or creating proactive product maintenance plans. Additionally, the historical data is highly valuable for engineers, as it enables them to evaluate product performance over time and select the most suitable replacements for aging or outdated products. This approach not only helps optimize user satisfaction but also promotes sustainable design practices by ensuring efficient resource usage and minimizing environmental impact. The conceptual framework and flow are detailed in Figure 3.

3. A Case Study of DT-Based IAQ Control in Hong Kong Institute of Vocation Education (IVE)

The Hong Kong Institute of Vocational Education (IVE) of the Vocational Training Council developed a Digital Twin (DT) system for a laboratory at its Tuen Mun campus. This represents a significant advancement in smart facility management and interactive learning environments. The project involved the installation of multiple types of sensors, including current probes, lumen sensors, indoor air quality (IQA) sensors, and contact sensors, to capture a wide range of environmental and operational data. These sensors continuously monitor energy consumption, lighting levels, air quality, and room occupancy status

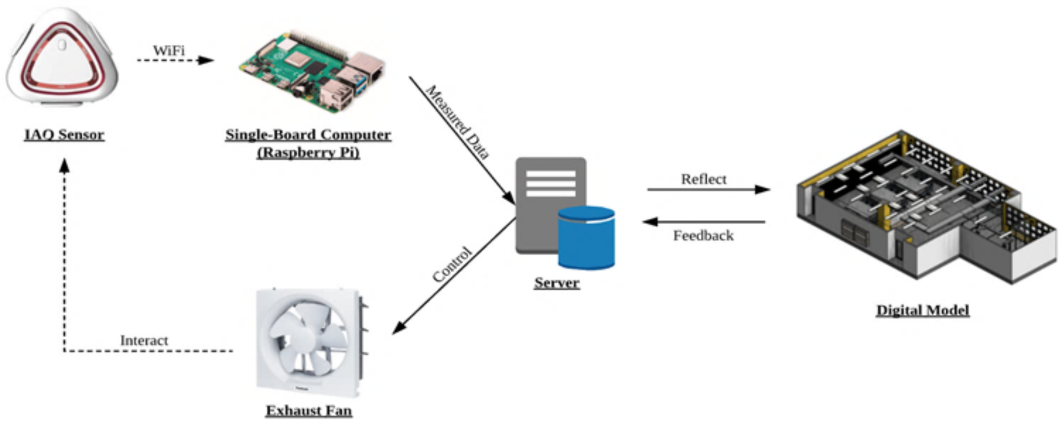

Figure 4 I Configuration of DT-based IAQ monitoring and control system

to provide a comprehensive, real-time understanding of the laboratory's conditions. The data collected from these sensors is synchronised with the laboratory's Building Information Modeling (BIM) system, creating a dynamic, virtual representation of the physical space. This sensor data integration with the BIM model allows the DT system to display real-time and historical information about the laboratory's environment and operations. The synchronised data is accessible through a web-based browser interface, enabling users to interact with the DT system through PCs, smartphones, or other smart devices.

This system supports various user groups, including students, laboratory assistants, and faculty managers, by providing instant access to the laboratory's operational data. The DT system offers students an interactive platform to learn about smart building technologies and data-driven decision-making. Laboratory assistants can utilise the system to monitor equipment usage, optimise resource management, and ensure safety compliance. Faculty managers benefit from the ability to oversee multiple laboratories remotely, analyse energy usage patterns, and identify areas for operational improvement.

This case study focuses on DT-based IAQ monitoring and control, and other possible applications are discussed in Figure 4. The configuration of the DT-based IAQ monitoring and control system is shown in Figure 4. The IAQ sensors measure the air pollutant level in the room, and the data will be sent to a single-board computer via WiFi. The measured data are synced to the server and reflected on the digital model. The digital model can present the data clearly to the user, and they can control the exhaust fan on the system. The system will analyse the measured data and feedback to the server, then automatically control the exhaust fans. When the exhaust fans are on, indoor air pollutants can be exhausted out of the areas. The operation of exhaust fans can interact with the sensors and develop a closed-loop monitoring and control system.

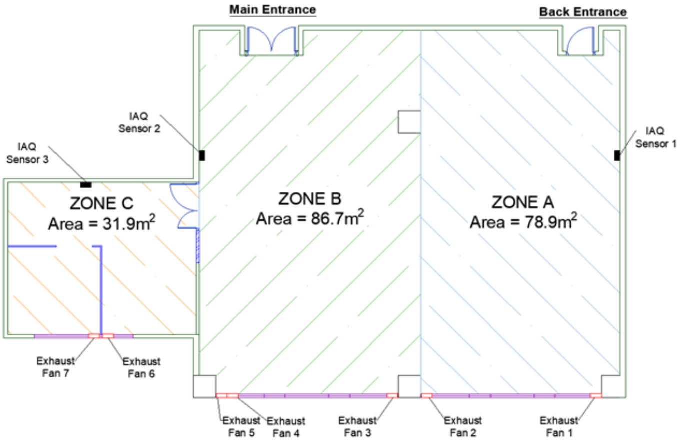

Figure 5 I Arrangement of IAQ sensors and exhaust fans

The laboratory can be divided into three main areas, and the location of the IAQ sensors and exhaust fans are shown in Figure 5. The IAQ sensor 1 is decided to monitor the IAQ in Zone A and control exhaust fan operations 1 and 2. And then sensor 2 is located in Zone B and controls exhaust fans 3, 4 and 5. Finally, sensor 3, located in Zone C, controls exhaust fans 6 and 7. The mechanism and operation of the system will be monitored in the next section.

3.1. DT-Based IAQ Monitor and Control

IAQ is an important factor in indoor environment quality as it can cause building-related illness to the users, e.g. cough and chest tightness [24]. Therefore, it is necessary to develop a smart IAQ control system

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IAQ Sensor 01
496 ppm, 153.00 ppb, 16.0 μg/m³, 21.0 μg/m³, 26.7 °C, 62.0 %
IAQ Sensor 02
465 ppm, 109.00 ppb, 13.0 μg/m³, 16.0 μg/m³, 27.1 °C, 65.0 %
IAQ Sensor 03
457 ppm, 181.00 ppb, 6.0 μg/m³, 8.0 μg/m³, 25.8 °C, 73.0 %
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Real time IAQ data

Virtual replica of the environment

Figure 6 I User Interface of DT-based IAQ Monitoring and Control System

in the indoor environment, especially in schools, offices, and hospitals, which are densely populated. The case of DT-based IAQ monitoring and control systems in IVE is presented stage by stage, as mentioned in Section 2: monitoring, data analysis, control, and prediction. The IAQ sensors used in this case can measure the surrounding temperature, humidity, concentration of carbon dioxide (CO2), total volatile organic compounds (TVOC), PM10 and PM2.5, which are the common factors to indicate IAQ. According to the guideline of the IAQ certification scheme for office and public places (2019) issued by the Hong Kong Environmental Protection Department (EPD) [25] and the standard of ventilation for Acceptable Indoor Air Quality issued by ASHRAE [26], the target values of those pollutants are listed in Table 1. The selected pollutants should be controlled within the target values at any time.

3.1.1. Monitoring

The sensors monitor and record the concentration of selected pollutants, such as carbon dioxide (CO2), particulate matter (PM2.5 and PM10), humidity, and volatile organic compounds (VOCs), across different areas of the room. As shown in Figure 6, the system displays real-time indoor air quality (IAQ) data for each pollutant in every monitored space area. This detailed visualisation enables users to assess environmental conditions quickly and accurately. Numerical data values are presented alongside visual indicators, making it easier for users, such as students, faculty managers, or laboratory personnel, to understand the pollutant levels in specific areas and identify zones that require attention.

Faculty managers or health officers can remotely access the system via the internet to monitor the real-time IAQ situation at any time. This accessibility allows them to take immediate action when pollutant concentrations exceed acceptable thresholds. Actions may include scheduling air filter cleaning, enhancing

Table 1 I Target values of the selected IAQ pollutants [25] & [26]

IAQ Pollutant	Unit	Target Values
Carbon Dioxide (CO2)	ppm	<1000
Respirable Suspended Particulates (PM10)	ug/m	<100
Total Volatile Organic Compounds (TVOC)	ppb	<261

ventilation, or reducing the number of room occupants to improve air quality. Such proactive interventions ensure a healthier and safer environment for all room users. The BIM model of the room is stored securely in the cloud and integrated into a cloud-based platform using Autodesk Fusion 360. This platform allows users to access and interact with the system on various devices, such as PCs, tablets, or smartphones, ensuring a seamless and user-friendly monitoring experience.

3.1.2. Data Analysis and Simulation

The measured data can be represented in the digital model in real-time, enabling immediate analysis and visualization. This data can be utilized to simulate the physical environment, such as airflow and air change rates, using Computational Fluid Dynamics (CFD) technology to identify the causes or sources of pollutants [27, 28]. These simulations provide actionable insights for improving indoor air quality (IAQ), such as recommending the opening of specific windows to enhance ventilation. The data also supports automated decision-making processes. As shown in Figure 7, the exhaust fan control logic is programmed to turn on or off based on IAQ changes. Additionally, the simulation results are valuable for future design or renovation projects, helping to optimize the arrangement and location of equipment, such as determining the ideal height for inlet and outlet openings [28], ultimately enhancing the room's overall performance and efficiency.

3.1.3. Control

Once the decision is made, the server can send a signal to the programmable logic controller (PLC) to activate or deactivate the relay of the exhaust fans. This allows for automated control of ventilation based on real-time indoor air quality (IAQ) data. Users have the flexibility to set target pollutant values and customize the delay time for turning off the exhaust fans, ensuring efficient operation tailored to specific needs. By reviewing the data and simulated results on the virtual model, users can also manually control the exhaust fans, switching them on or off to actively reduce pollutant levels in the room as needed.

Beyond controlling the exhaust fans, the collected data can trigger a variety of automated actions within the built environment. These include turning on or off lights, adjusting curtains to optimize natural lighting, and managing other resources such as HVAC sys-

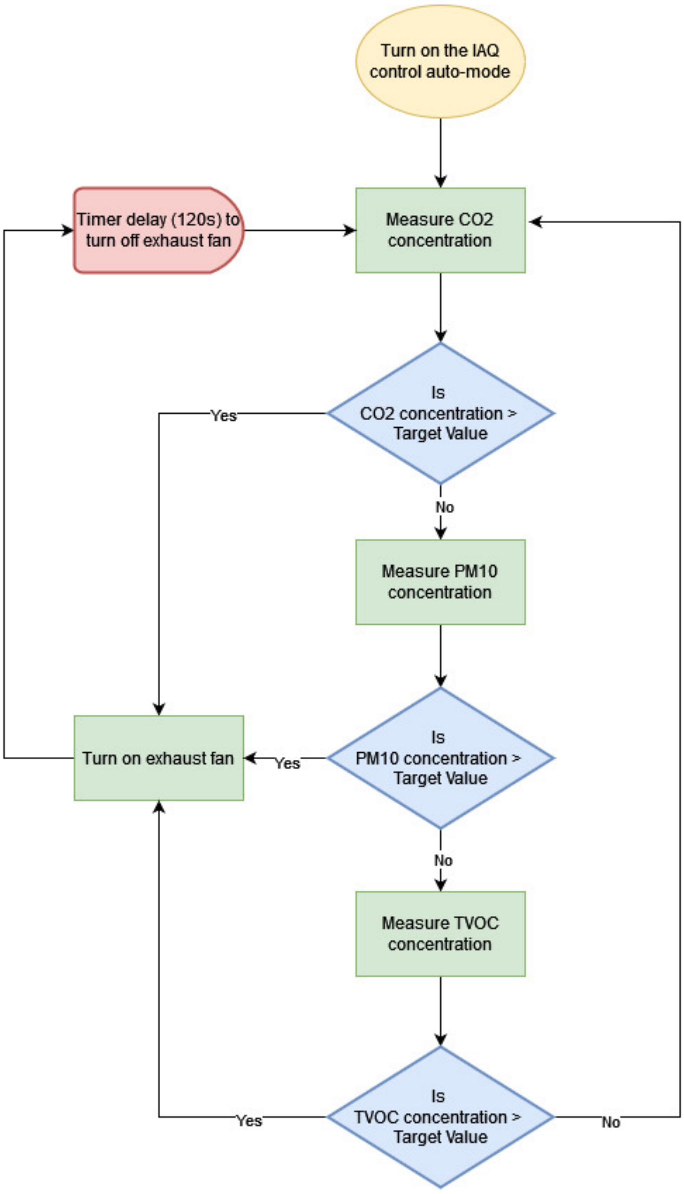
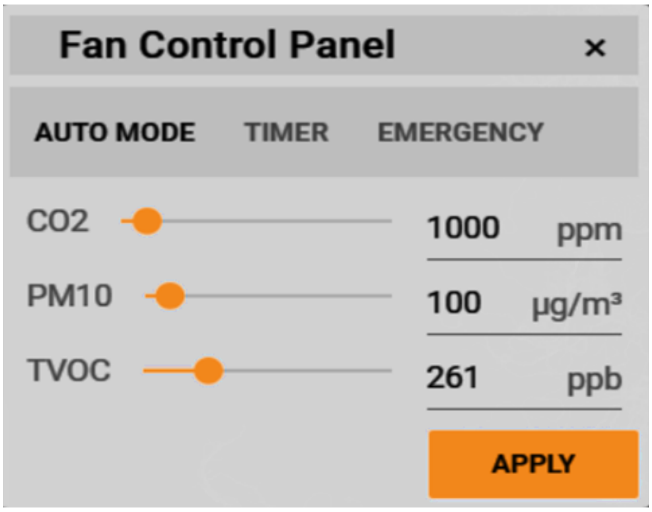


Figure 7 | The logic flow of the IAQ control system



CO2 1000 ppm

PM10 100 $\mu g/m^3$

TVOC 261 ppb

Figure 8 | Fan Control Panel for target value setting of each pollutant

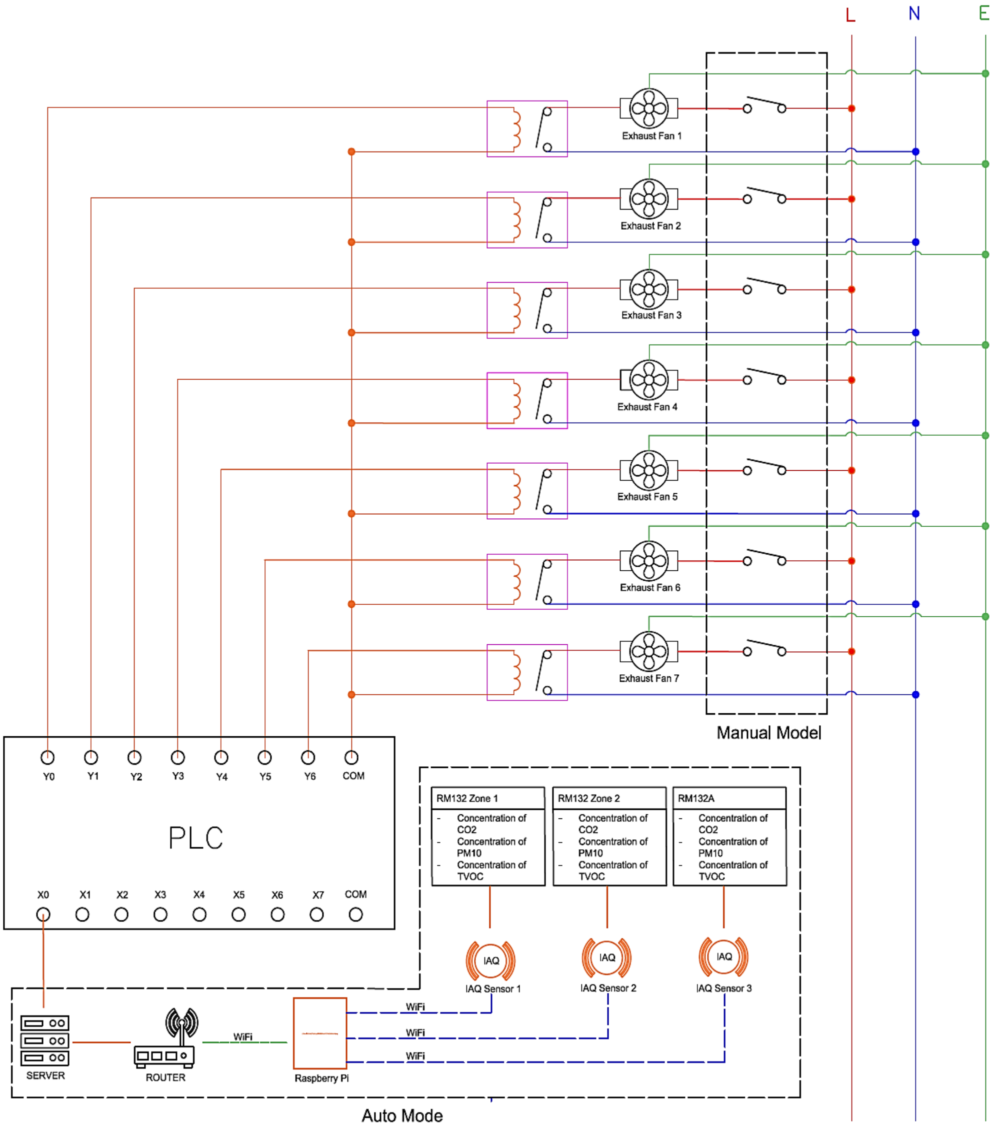


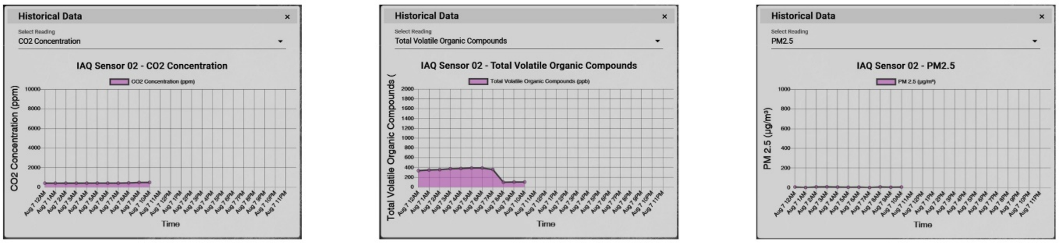
Figure 9 | Schematics of exhaust fan control

tems. By integrating these controls, the system enhances operational efficiency, optimizes resource usage, and improves occupant comfort. This approach demonstrates how Digital Twin (DT) technology can provide a comprehensive framework for automating and managing multiple systems in a smart and sustainable manner, further showcasing its value in modern building operations and environmental control.

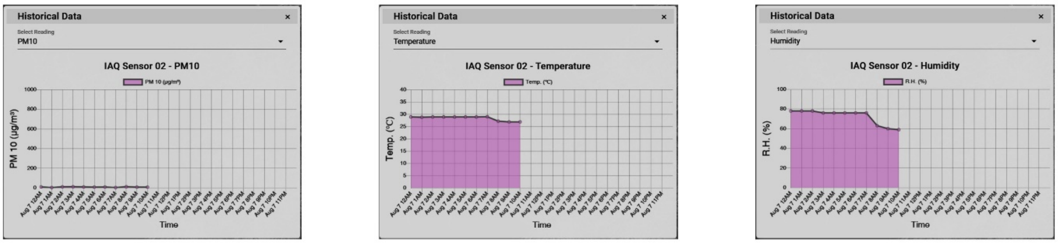
3.1.4. Prediction

Finally, all the data, room information, and user records are synced and securely stored on the server, creating a comprehensive database for analysis and decision-making. The measured data can be analyzed using AI to predict trends in indoor air quality (IAQ) changes. These predictions can improve exhaust fan operation planning by allowing proactive measures, such as turning on the fans in advance before peak hours to maintain optimal air quality. Additionally, the operational hours of each exhaust fan can be tracked to predict maintenance schedules or estimate the lifespan of the equipment [19]. This predictive approach ensures timely maintenance, reduces downtime, and extends the life of building systems.

The predictive insights not only enhance building environment optimization but also improve operational decision-making [3]. Relevant stakeholders, such as building service engineers and faculty managers, can access historical data, simulations, and analysis results to redesign or upgrade the room. These insights can guide device selection, equipment specifications, and system improvements, ensuring the room is better equipped to meet future demands. This integrated system of data-driven predictions, in-



(1) CO2 Concentration (2) TVOC Concentration (3) PM2.5 Concentration



(4) PM10 Concentration (5) Temperature (6) Humidity

Figure 10 | Historical IAQ data of the room

formed decision-making, and proactive management highlights the value of leveraging advanced technologies for sustainable and efficient building operations.

4. Discussion

The DT project in IVE demonstrated the framework of DT-based IAQ monitoring and control. The real-time data monitoring feature allows the user to understand the invisible information, e.g. pollutant concentration, on the virtual model. The measured data can further simulate the indoor situation, support decision-making, control the related equipment and predict future trends. Using those analysis results and data, the engineer can generate a more accurate room design by choosing the suitable device and location to optimise building energy efficiency [4, 23] and improve the performance of future buildings [4]. Building Information Model (BIM) is an emerging technology for building design and management that benefits engineers and developers to create virtual environment replicas and perform simulations [17, 21, 29]. Integrating DT and BIM can optimise the whole building lifecycle.

The DT-based building monitoring and control system seems beneficial for building management, but some limitations are found when developing the project. According to the United States Environmental Protection Agency's definition [30], IAQ is affected by not only the gases (CO2 and TVOC) and particulates mentioned in the demonstration project in IVE but also other hazardous gases (e.g. Nitrogen Dioxide, Radon and Carbon Monoxide) and biological pollutants. Many kinds of pollutants can affect the IAQ, so a well-structured sensor network to detect those pollutants should be developed to measure and monitor the IAQ comprehensively. It is a great challenge to set up a complicated sensor network in the built and operating building because of the limited space and lack of appropriate locations for the sensor installation. In addition, extra effort and investments should be made in using buildings, for example, redesigning the system, creating digital models, and rearranging the room furniture and equipment. There are low incentives and efficiency in implementing and developing the DT system in the constructed and used buildings. To optimise the performance of the sensor network and DT system for indoor environment monitoring and control, IAQ, temperature, humidity and brightness should be designed and developed in the early stage of the building lifecycle. As shown in Figure 11, the difficulty of implementing DT in the building increases along with the building lifecycle due to the location restriction and interference with the other equipment and system. Implementing DT in the earliest stage of building development can gain the most benefits along the building lifecycle. DT can be implemented in the early stage of the project and integrated with other building technologies, i.e. Building Information Modeling (BIM), Internet of Things (IoT),

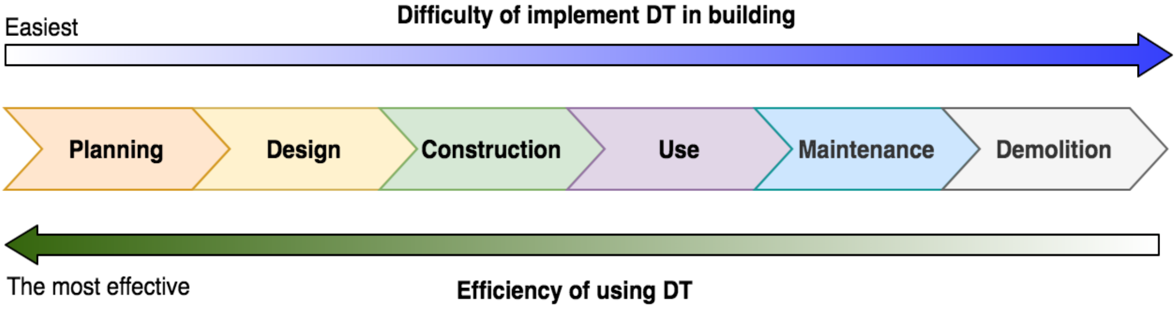


Figure 11 | Level of difficulty and efficiency to implement and use DT in the building lifecycle

and Geographical Information Systems (GIS), to maximise the use of DT [2]. Applying simulation to evaluate IAQ at the design stage can improve the IEQ, and DT can provide mass data to support the simulation. DT also has various applications in the whole building lifecycle, i.e. construction site logistic management, fault detection [10] and energy control [23]. Therefore, effectively implementing DT in the planning and design stage is an important topic for the industry.

In the future, there are some possible directions for DT in the building and construction industry. The study of implementing DT in the planning stage of the construction project can optimise the efficiency of the whole building lifecycle. The guidelines and framework for applying suitable sensors in planning and design can make DT easier to implement and maximise its usage. With the development of Modular Integrated Construction (MiC) technology, the sensors and DT system can be installed in the factory in advance so that the DT system can be used to optimise the construction processes, e.g. progress monitoring and quality control, and also be used when the building is completed. It is a fatal opportunity for the industry to merge and implement MiC, BIM and DT into future building design.

On the other hand, it is not easy to implement a comprehensive DT system at the time or by a single party. Different vendors can provide different equipment or systems in the building. Therefore, an integrated platform for connecting and coordinating different DT systems should be designed. For example, the air-conditional DT should be able to operate individually and also interact with the room DT to optimise the built environment control and management. The performance of the single DT is limited, so the integrated management platform can maximise the building's performance in the future.

5. Conclusion

The paper describes how using Digital Twin (DT) technology has significantly extended the application of Building Information Modeling (BIM) throughout the building lifecycle, encompassing planning, design, construction, and ongoing monitoring and control during building operation. DT bridges the gap between the physical and digital worlds by integrating real-time data with virtual models, enabling more efficient and effective building management. The study focuses on designing and implementing a DT control system for managing indoor air quality (IAQ) in a school laboratory in Hong Kong. It demonstrates DT's various roles and applications, including monitoring environmental conditions, analysing data patterns, simulating airflow and pollutant sources, and predicting future scenarios for proactive decision-making. The findings highlight how DT can effectively control and improve IAQ, thus enhancing building occupants' comfort, health, and performance.

The case study offers valuable insights into the broader applications of DT in the building industry, showcasing its potential to optimise building performance, streamline operations, and enhance sustainability. It also addresses the limitations and challenges of DT implementation, such as restricted installation spaces for sensors, high costs, and potential issues with system performance and data integration. The paper emphasises that the most effective way to implement DT is during the design stage of a construction project. This ensures seamless integration of DT technology, allowing for the full realisation of its benefits, such as improved energy efficiency, better resource utilisation, and more informed maintenance planning throughout the building's lifecycle.

Conflicts of Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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