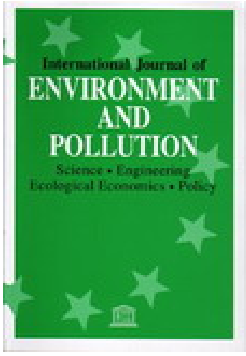

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Dynamic process mechanism of empowering carbon peak and carbon neutrality in architectural interior design based on digital technology

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Dynamic process mechanism of empowering carbon peak and carbon neutrality in architectural interior design based on digital technology

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Abstract: Traditional building design methods suffer from issues such as insufficient application of technology, low data utilisation, disconnect between design and operation, lack of systemisation, and weak innovation capabilities, making them ineffective in supporting the goals of carbon peak and carbon neutrality. This paper explores how digital technologies such as the Internet of Things (IoT) and smart control systems can enhance building interior design, contributing to achieving carbon peak and carbon neutrality, and analyses their dynamic operational mechanisms. This research utilises building information modelling (BIM) software to create and optimise building models, employs virtual reality (VR) technology for virtual simulation and user experience evaluation, uses an IoT sensor network for real-time monitoring, and integrates a smart control system for automatic adjustment of lighting and air conditioning. The experimental results show that energy consumption in buildings was reduced by approximately 36%, and carbon emissions were reduced by 32.5%.

Keywords: digital technology; BIM; building information modelling; IoT; Internet of Things; carbon neutrality; sustainable architecture.

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1 Introduction

As global climate challenges intensify, the pursuit of carbon peaking and neutrality has emerged as a critical priority for international governance and sustainable development. The construction sector represents a pivotal focus for decarbonisation efforts as a significant contributor to global energy consumption and greenhouse gas emissions (Shu et al., 2021). Conventional architectural practices, however, demonstrate substantial limitations in three key dimensions: technological innovation adoption, data-driven decision-making, and integration between planning stages and operational requirements, ultimately leading to suboptimal energy performance and poorly regulated carbon outputs (Zhang, 2023). This technological gap has accelerated the demand for innovative solutions in sustainable building design.

Digital transformation, encompassing artificial intelligence, Internet of Things (IoT) networks, predictive analytics, distributed cloud systems, and blockchain architectures, is driving paradigm shifts across industries by enhancing operational precision and enabling intelligent resource management (Spiteri and Rundgren, 2020; Ting et al., 2020). When strategically applied to spatial design processes, these technologies demonstrate multi-faceted potential – from streamlining workflow efficiency to enabling real-time environmental simulations. By integrating smart material optimisation algorithms and energy modelling platforms, digital tools empower designers to minimise resource waste while maintaining functional requirements, thereby directly contributing to emission reduction targets. This technological shift not only addresses current inefficiencies in technological integration but also establishes a framework for continuous environmental performance improvement throughout a building's lifecycle.

This paper gives a systematic and comprehensive solution to achieve the goal of building interior design empowering carbon peak and carbon neutrality by using tools such as BIM, IoT, smart control systems, and renewable energy devices. BIM technology is used to realise the digital management of the whole process of building design, construction, and operation, real-time monitoring of the building environment and energy consumption data with the help of IoT technology, the adoption of intelligent control systems to optimise the efficiency of energy use, and the combination of renewable energy equipment to reduce the dependence on traditional energy sources. The research results show that this method can significantly improve the level of building energy efficiency management, achieve dynamic monitoring and optimisation adjustment of carbon emissions, and help the building industry achieve the goal of carbon peak and carbon neutrality. Through case studies and experimental verification, the method proposed in this paper not only has high prediction accuracy and reliability but also has good prospects for popularisation and application, providing important theoretical and practical references for the development of intelligent buildings.

2 Related work

A large number of researches have been focused on the application of digital technology in addressing the high energy consumption and carbon emission problems in the construction industry. To address the limitations of traditional design methods, Liu and Ning (2019) proposed an optimal design method based on building information modelling (BIM), which improves design accuracy and energy efficiency through a refined building model. This study shows that BIM technology can effectively integrate data and information from all stages of a building to achieve energy efficiency management throughout the building's life cycle. Ghosh et al. (2021) explored the application of IoT technology in the built environment and demonstrated the idea of real-time monitoring and dynamic adjustment of energy consumption using sensor networks. Verma et al. (2019) explored the application of intelligent control systems in buildings and found that intelligent control systems can adjust the operating parameters of lighting, air-conditioning, and other equipment according to the actual use of the situation, optimise the use of energy efficiency to reduce energy consumption. Bashabsheh et al. (2019) investigated the application of virtual reality (VR) technology in architectural design, using virtual roaming to improve the evaluation and optimisation of design solutions. VR technology can not only improve the intuition and visualisation of design solutions but also further optimise the design solutions through user feedback. Husin and Zaki (2021) proposed the integration of renewable energy devices in buildings to increase building energy self-sufficiency and reduce carbon emissions. Their study showed that by integrating renewable energy devices such as solar and wind energy in buildings, the dependence on conventional energy sources can be effectively reduced and a significant reduction in carbon emissions can be realised. Although these studies have achieved remarkable results, they still suffer from insufficient data integration, insufficient systematicity, and lack of innovation, and have failed to comprehensively achieve the goals of building energy efficiency and carbon emission reduction.

To address the above problems, many studies have proposed specific technical solutions and verified their effectiveness in practice. Xia (2020) added a dynamic monitoring module based on BIM to optimise the design solution through real-time data feedback, which significantly improved the energy efficiency of the building. The dynamic monitoring module captures energy consumption data in real-time during building operations and feeds back into the design system for optimisation, leading to more efficient energy management. Bedi et al. (2020) showed that the application of IoT sensor networks can accurately monitor building energy consumption and achieve energy optimisation through data analysis. By installing a large number of sensors in the building, collecting energy consumption data from each area in real-time, and using big data analysis technology for energy efficiency optimisation, the overall energy consumption of the building was significantly reduced. Zhao et al. (2020) utilised an intelligent control system to automatically adjust lighting and air conditioning equipment to reduce operational energy consumption. Kim et al. (2020) conducted virtual roaming and user experience evaluation of the design scheme through VR technology, which enhanced the practical application of the design. They used VR technology to construct a virtual building model, allowing users to experience and evaluate design solutions in a virtual environment and optimise them based on user feedback, significantly improving the practicality and user satisfaction of the design solutions. Zhang et al. (2023) proposed a multi-energy complementary virtual power plant optimisation scheduling strategy around the goal of ‘carbon peak and carbon neutrality’, and constructed a multi-energy complementary optimisation scheduling model with a low-carbon economy as the goal. By coordinating and scheduling various types of devices, the consumption of renewable energy can be promoted. Digital technology has a good application effect in empowering carbon peaking and carbon neutrality research in interior design, and many studies have obtained a lot of results from it, but the depth and breadth of research are still slightly lacking.

3 Digital technology in interior design of buildings

3.1 Optimisation design of building information model

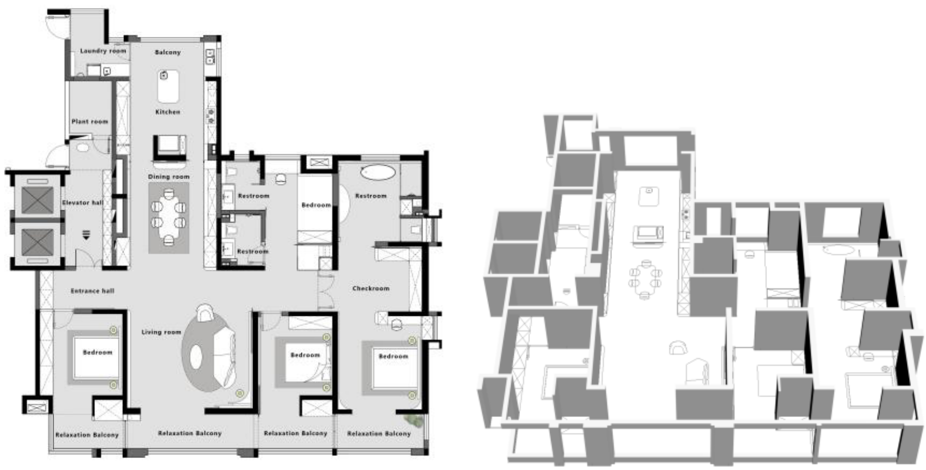
In contemporary interior design practice, BIM platforms enable the creation and refinement of intelligent digital twins through parametric 3D modelling. This technology facilitates precise quantification of material requirements during the design phase, minimising resource waste while enhancing spatial configuration accuracy. Integrated energy performance simulation modules within BIM ecosystems allow designers to conduct lifecycle energy flow analysis, optimising heating, ventilation and air conditioning (HVAC) efficiency and daylight utilisation to align with carbon neutrality objectives. The systematic integration of these capabilities – from material optimisation algorithms to real-time energy consumption forecasting – establishes a data-driven framework that simultaneously elevates design precision and operational sustainability, directly contributing to achieving carbon-peaking strategic targets.

Detailed interior space models including walls, floors, ceilings, doors, and windows, as well as furniture and decorations, are constructed using Autodesk Revit software (Ramadhan and Maulana, 2020). Through 3D modelling, the layout of the interior space was refined, and the position and size of each functional area were adjusted to ensure the rationality and efficient use of each area. By adjusting the location of the bedroom, living room, and kitchen areas, the utilisation rate of the interior space is improved to ensure the reasonable configuration of each functional area and to enhance the comfort and work efficiency of the users. The material statistics function in Revit can be used to generate a detailed list of materials required for interior decoration and optimise the use of materials through parametric design to reduce unnecessary material waste. The interior design model can be imported into Green Building Studio to set the usage conditions of the indoor environment, such as lighting, air conditioning, heating, and other parameters (Rehman, 2023). This paper conducts energy consumption simulation and analyses the energy consumption performance under different design schemes. It can simulate and analyse the energy consumption of the lighting system, adjust the type and layout of lighting fixtures, optimise lighting design, and reduce unnecessary energy consumption. Figure 1 shows the model design of interior design.

Figure 1(A) shows the 2D plan design of the interior design, while Figure 1(B) shows its corresponding 3D model structure, which includes 4 bedrooms, 5 balconies, 1 kitchen, 1 dining room, 1 checkroom, 3 restrooms, and 1 living room. The parameters of the room correspond to real data so that the decoration configuration on the simulation model can provide accurate reference for real interior design, and play a very good role in empowering carbon peak and carbon neutrality. In digital simulation design software, walls and furniture can be freely added, and intelligent management modules can be added to simulate the daily energy consumption of residents. Digital technology can be used to simulate actual rooms, simplifying the design process and providing environmental tools for empowering carbon peaking and carbon neutrality in the future.

Revit's collision detection capabilities enable systematic identification of spatial conflicts between interior subsystems, particularly in mechanical-electrical coordination and pipeline routing. Through automated clash analysis within multi-disciplinary models, designers can resolve interface mismatches, such as ductwork interference with suspended ceiling structures – during the virtual design phase. This proactive clash resolution workflow prevents on-site rework by optimising component layouts through parametric adjustments, thereby minimising material waste and labour redundancies during construction.

Figure 1 Interior design structure: (A) 2D structure and (B) 3D structure



(A) (B)

The platform's integrated documentation tools further enhance project execution through intelligent view management. Automated generation of coordinated 2D construction drawings – including annotated floor plans, elevation schematics, and critical node details – ensures dimensional fidelity between 3D models and technical documentation. Such precision in construction annotation reduces interpretation errors during fieldwork while maintaining alignment with carbon-reduction objectives through optimised material specifications and waste prevention. This digital-physical synchronisation streamlines construction workflows, elevating both operational efficiency and quality assurance across project phases.

During the actual construction and operation phases, an IoT sensor network is installed for real-time monitoring of the indoor environment including temperature, humidity, air quality, and other parameters. The data management platform AWS IoT is utilised to collect and store sensor data in real-time for data analysis and processing (Chakraborty and Aithal, 2023). By monitoring the indoor temperature and humidity, the operation status of air conditioners and humidifiers is adjusted in real-time to improve the management and control precision of the indoor environment, ensure a comfortable living and working environment, and realise intelligent management. Indoor lighting, air conditioning, and other equipment can be automatically adjusted through the intelligent control system KNX (Konnex) (Sapundzhi, 2020). Fuzzy logic control algorithms can be used to achieve intelligent adjustment of equipment and reduce energy waste. According to changes in indoor lighting, curtains, and lighting can be automatically adjusted to ensure appropriate indoor lighting and save energy. It can achieve intelligent control of indoor equipment, optimise energy consumption management, reduce energy consumption, and improve the comfort of living and working environments. Renewable energy equipment can be integrated into interior design, and the use of renewable energy can be monitored and managed using the energy management system SolarEdge, achieving efficient energy utilisation and scheduling (Alotaibi et al., 2020). By installing solar panels, solar power can be utilised to reduce reliance on traditional energy and achieve low-carbon environmental protection.

By following the detailed implementation steps and methods outlined above, the use of BIM in interior design not only enhances design precision and efficiency but also substantially minimises material waste and energy consumption. Additionally, it optimises the indoor environment, boosting user comfort and satisfaction. These approaches offer significant support in advancing the goals of carbon peak and carbon neutrality.

3.2 Design verification of virtual reality technology

In the process of architectural interior design, virtual reality technology is used for design verification. By creating a virtual environment, conducting virtual roaming and user experience evaluation, the design scheme is optimised and verified, and energy efficiency optimisation and sustainability are ensured.

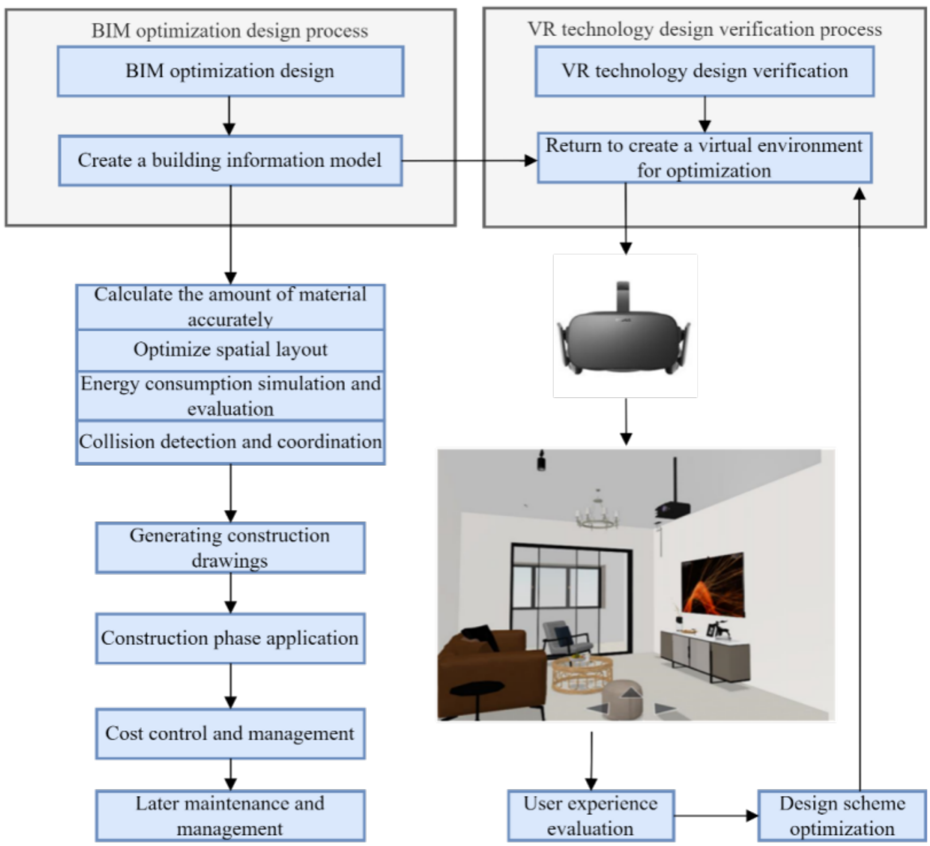
This paper utilises Unreal Engine software to import BIM models into VR platforms, creating an immersive virtual environment for interior design. The imported model can be enhanced by adding lighting, materials, and detailed decorations to ensure the virtual space accurately reflects the actual design. Interactive features are incorporated, allowing users to engage with the environment by performing actions such as toggling lights and adjusting furniture placements. By crafting highly realistic virtual environments and delivering intuitive visual effects, both designers and clients can gain a thorough understanding of the proposed design solutions.

The specific design process diagram is shown in Figure 2.

In Figure 2, it can be seen that after designing the details of the room through BIM, the model data is imported into virtual reality devices, which facilitates designers and users to observe the details of the interior design more closely, deepen the design structure, and optimise the interior design to empower the dual carbon goals. The VR headset Oculus Rift can be used to allow users to enter a virtual environment and engage in all-around virtual roaming (Jost et al., 2021; Huang et al., 2021). A predefined path can be established, allowing users to navigate through various spaces and explore design details. During the journey, users can interact with the environment, view different perspectives, and test various lighting and material effects. Virtual exploration provides users with the opportunity to experience interior design from every angle, identify potential issues, offer suggestions for improvements, refine the design plan, and ensure that the outcome meets expectations. Throughout this process, it is crucial to gather user feedback on their virtual experience, focusing on aspects such as visuals, spatial layout, functional design, and, in particular, energy efficiency and comfort. These insights serve as valuable recommendations for further optimising the design. Following the VR experience, a user questionnaire is conducted to gather subjective feedback, assess satisfaction with the design, and receive improvement suggestions, with special attention to the evaluation of energy-saving features.

In the 'IKEA Digital Showroom', digital space can be used instead of physical space to create more design possibilities, as well as through computers and VR devices, the space and furniture materials can be replaced, lighting can be tested, and real-time identification of products and price tags can be identified.

Figure 2 Overall simulation design flow chart (see online version for colours)



Through user experience evaluation, it can comprehensively understand the advantages and disadvantages of the design scheme. Optimisation and adjustment can be made based on user feedback to ensure that the design scheme has high efficiency and comfort in practical applications while maximising energy efficiency and supporting carbon peak and carbon neutrality goals. Based on user feedback and behaviour analysis results, the design scheme can be adjusted and optimised, especially for improving energy efficiency optimisation design and modifying relevant content in the BIM model, adjusting the spatial layout, optimising lighting design, improving furniture configuration, etc. (Al-Ashmori et al., 2020). The optimised model can be re-imported into the VR platform, the virtual environment can be updated, re-validated, and evaluated to ensure that the optimisation solution meets the requirements. Through multiple iterations of optimisation and verification, the rationality and efficiency of the design scheme can be ensured, maximising user experience and satisfaction, and avoiding design changes and rework after actual construction. At the same time, continuous optimisation of design can improve energy utilisation efficiency, reduce energy consumption, achieve energy conservation and emission reduction, and achieve carbon peak and carbon neutrality goals.

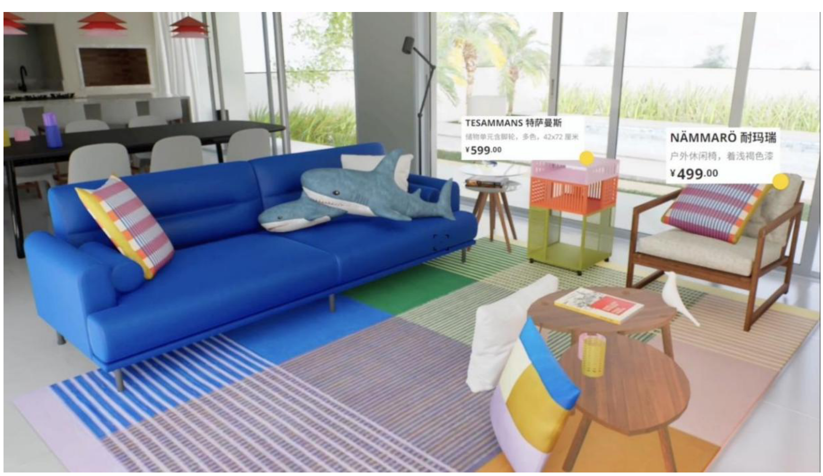
Through the specific implementation steps and methods mentioned above, virtual reality is beneficial for improving the accuracy, efficiency, user engagement, and satisfaction of design verification, thereby optimising the design scheme and ensuring that the final effect meets expectations.

3.3 Real-time monitoring of the IoT

In the process of architectural interior design, IoT technology can be used for real-time monitoring. By installing sensor networks, data transmission, and management platforms, precise monitoring and management of the indoor environment can be achieved, ensuring energy efficiency optimisation and achieving carbon peak and carbon neutrality goals.

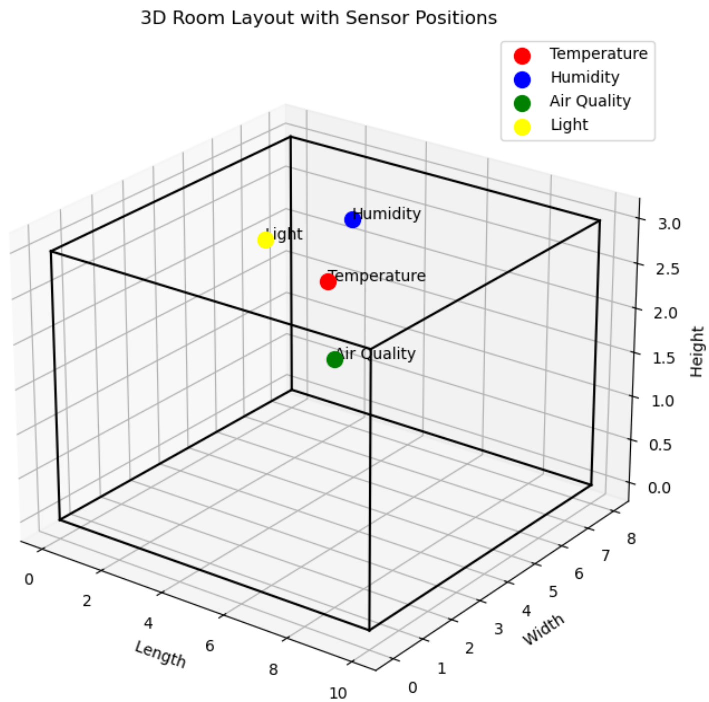
Sensors for temperature, humidity, brightness, and air quality can be strategically placed in key areas to ensure comprehensive coverage of the indoor environment. Installing sensors near the ceiling allows for accurate collection of environmental data. These sensors can be positioned in spaces like the living room, bedroom, and kitchen to monitor temperature, humidity, and air quality in real time. By utilising a network of sensors across the entire indoor space, real-time environmental data can be gathered, providing essential data for future energy efficiency management and optimisation. The message queuing telemetry transport (MQTT) protocol can be used to achieve real-time transmission of sensor data, and the collected environmental data can be sent to the data management platform (Arbab-Zavar et al., 2021; Pham and Hoang, 2021). The connection between configurable sensors and gateways ensures the stability and real-time performance of data transmission. Each sensor sends data at regular intervals, such as once every minute, to ensure real-time and accurate data. Stable and real-time data transmission ensures that environmental data can be transmitted to the management platform promptly, providing data support for real-time monitoring and adjustment. The conceptual diagram of the sensor position in the indoor 3D structure is shown in Figure 3.

Figure 3 Simulation design case 'IKEA digital showroom' (see online version for colours)



In Figure 4, the spatial coordinate axis is used as a template to simulate the room and display the positions of some sensors. The spatial coordinate positions of temperature sensors, humidity sensors, air quality sensors, and light sensors are included with length as the x-axis, width as the y-axis, and height as the z-axis. Their corresponding 3D coordinates are (5,4,2.5), (3,7,2.5), (8,1,2.5), and (2,5,2.5), respectively, and their corresponding points are red, blue, green, and yellow. The relevant sensors can collect data in working conditions and cooperate with the indoor intelligent management system to achieve intelligent control of furniture and appliances, achieving the goal of energy conservation and environmental protection.

Figure 4 Sensor position distribution map (see online version for colours)



This paper leverages the AWS IoT data management platform to collect and store sensor data. Data analysis tools are then applied to examine the collected environmental data, using methods such as statistical analysis and trend analysis, to identify anomalies and opportunities for optimisation. Through systematic data management and analysis, potential issues and energy efficiency improvements in indoor environments can be detected, enabling effective management and reduced energy consumption. Based on the analysis results, the KNX intelligent control system can automatically adjust the operation of indoor environmental control systems in real-time: for example, when the temperature sensor detects a temperature rise, the air conditioning system adjusts accordingly; when the air quality sensor detects a drop in air quality, the ventilation system activates automatically. Real-time monitoring and automated adjustments ensure both comfort and health in indoor environments while promoting energy efficiency and reducing carbon emissions.

Through the specific implementation steps and methods mentioned above, IoT technology can be applied in interior design. This not only improves the accuracy and efficiency of environmental monitoring but also significantly enhances the level of energy efficiency management, ensuring the comfort and health of indoor environments, while providing strong support for achieving carbon peak and carbon neutrality goals.

3.4 Intelligent control system

In the process of interior design in buildings, intelligent control systems automatically adjust lighting, air conditioning, and other equipment to achieve energy efficiency optimisation and carbon peak and carbon neutrality goals. To achieve the goal, it is necessary to install intelligent control devices in various functional areas, while ensuring that the installation position of the devices is reasonable. By installing intelligent control devices, centralised management and control of electrical equipment in various indoor areas can be achieved, improving energy efficiency and reducing unnecessary energy consumption. In Table 1, the simulation data collected during the simulation experiment is presented.

Table 1 Simulation data table under simulation test

Timestamp	*Temperature* (°C)	*Humidity* (%)	*CO_2 concentration* (ppm)	*Illumination intensity* (lux)	*AQI*
08:00	22.5	45	400	150	50
10:00	24.0	50	420	300	60
12:00	25.5	55	450	500	70
14:00	26.0	60	500	450	80
16:00	24.5	55	430	300	60
18:00	23.0	50	410	200	50
20:00	21.5	45	400	100	45
22:00	20.0	40	380	50	40

By analysing the data in Table 1, the intelligent control system can achieve detailed management of the indoor environment. The operation status of air conditioning, fans, and lighting can be dynamically adjusted based on the data from various sensors. When the temperature rises to 25.5°C at noon, the cooling capacity of the air conditioner can be automatically increased to maintain a comfortable indoor temperature. When the temperature drops to 20.0°C at 10:00 p.m., the air conditioning temperature can be appropriately raised to avoid energy waste. When the humidity rises, the system activates the dehumidification function to maintain a suitable indoor humidity level, improve comfort, and save energy consumption. When the CO_2 concentration and air quality index (AQI) increase, the ventilation system and air purifier are automatically activated to ensure air quality while reducing the burden on the air conditioning. When the light intensity is high, some lights can be turned off and curtains can be opened to utilise natural light and reduce power consumption. On the contrary, when the lighting intensity is low, the system turns on some lights to ensure the suitability of indoor lighting. By comprehensively analysing data and periods related to temperature, humidity, CO2 concentration, light intensity, and air quality, the intelligent management system can implement various energy-saving measures.

Based on the collected data, fuzzy logic control algorithms can be applied to achieve intelligent adjustment of lighting, air conditioning, and other equipment. The operating status of the equipment can be automatically adjusted according to real-time data and control strategies (Urrea et al., 2020; Civelek, 2020). The implementation of intelligent control strategies and algorithms enables precise equipment management, enhancing energy utilisation efficiency and minimising unnecessary energy waste. This paper integrates user behaviour data to facilitate predictive control. By analysing user routines, predictive control adjusts indoor temperature and lighting in advance, ensuring optimal conditions when the user enters the room. It also automatically adjusts curtains based on natural light levels, reducing lighting energy consumption. Additionally, a feedback mechanism continuously monitors equipment performance, allowing for timely adjustments to the control strategy. Through real-time adjustments and feedback, the system ensures efficient operation, continuously improves energy efficiency, reduces consumption, and supports the achievement of carbon peaking and carbon neutrality goals.

A user-friendly control interface on a smartphone app or control panel allows users to monitor and adjust the indoor environment at any time. The control interface displays real-time data and device operating status, allowing users to manually adjust device settings to regulate room temperature and light intensity. By providing a convenient user interface, users can enhance their control experience and engagement, ensuring the flexibility and operability of intelligent control systems.

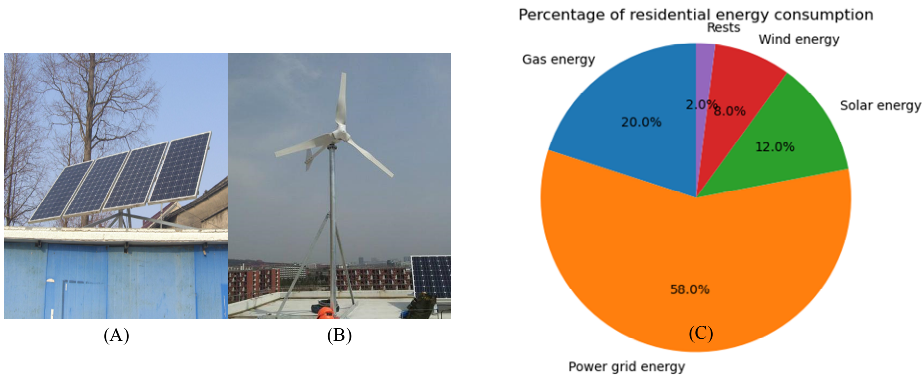
3.5 Renewable energy integration

The use of renewable energy can ensure the effective reduction of carbon emissions under normal energy demand, playing a very important role in achieving carbon peak and carbon neutrality goals.

Solar photovoltaic panels can be installed on building balconies, using high-efficiency photovoltaic modules to ensure maximum capture of solar energy. The direct current generated by photovoltaic panels can be converted into alternating current through inverters for internal use in buildings. The photovoltaic system can be integrated into the building's power system to ensure priority use of photovoltaic power when there is sufficient sunlight, reducing reliance on grid power. By installing solar photovoltaic systems, renewable energy can be utilised to provide partial electricity demand, reduce consumption of traditional energy, and lower carbon emissions. In a suitable geographical environment, small wind turbines can be installed at appropriate locations in buildings (indoor ventilation openings). Low noise and high-efficiency wind power generation equipment can be selected to ensure normal operation under different wind speed conditions. The electricity generated by wind turbines can be converted into AC (alternating current) power through inverters and connected to the building power system to supplement the shortcomings of photovoltaic systems. By installing small wind turbines and utilising wind energy as a supplementary source of electricity, a stable renewable energy supply can be ensured even under insufficient sunlight, further reducing the use of traditional energy.

Figure 5(A) and (B) respectively show images of photovoltaic panels and wind turbine blades, while Figure 5(C) shows the energy consumption pie chart of a resident in a certain area within a week. In Figure 5(C), it can be observed that even with the addition of solar and wind energy, grid electricity remains the main energy source for this resident, accounting for approximately 58%. Wind and solar energy together account for about 20% of the total, because their power generation efficiency is easily affected by the environment, and their power generation is very unstable. However, they still effectively alleviate the high demand for electricity among residents in daily life, while playing an environmental role and meeting the goal of carbon peak and carbon neutrality.

Figure 5 The proportion of solar and wind energy in the daily energy consumption of residents: (A) solar generator and (B) wind turbine generator and (C) energy consumption pie chart (see online version for colours)



An energy management system, such as Enphase Energy, can be deployed to monitor the real-time performance and status of solar and wind energy systems. By analysing the data, energy distribution and scheduling can be optimised to ensure efficient energy use throughout different periods. During peak electricity demand times, priority can be given to utilising photovoltaic and wind energy to reduce the strain on the grid. Additionally, integrated energy storage systems can be implemented to store surplus renewable energy, which can then be used when energy demand is low or generation is insufficient. By integrating energy management systems, the efficient use and distribution of renewable energy can be achieved, ensuring a continuous and optimal energy supply while minimising energy waste.

It can regularly monitor the operating status of solar photovoltaic systems and wind turbines, utilise sensors and data acquisition systems to obtain real-time data on the operation of the equipment, and carry out regular maintenance and inspections to ensure the efficient operation and safety of the equipment. The surface of photovoltaic panels can be regularly cleaned and the mechanical components of wind turbines are checked to ensure their proper operation. Regular monitoring and maintenance ensures the long-lasting operation and efficient power generation of renewable energy equipment to avoid energy loss caused by equipment failure.

This paper collects user feedback on integrated renewable energy systems, and through questionnaire surveys and data analysis, understands user experience and needs. Based on user feedback and system operation data, equipment configuration and control strategies can be optimised to improve system efficiency and user satisfaction. Through user feedback and optimisation, the integrated renewable energy system can be continuously improved to ensure its efficient operation and high user satisfaction, further promoting the achievement of energy conservation and emission reduction goals. The application of renewable energy integration in the interior design of buildings is conducive to improving energy utilisation efficiency, reducing the use of traditional energy and carbon emissions, and providing solid technical support for achieving carbon peak and carbon neutrality goals.

4 Experimental evaluation

4.1 Experimental environment and tools

In order to complete the various optimisation designs and validation methods mentioned in this study, the selection of experimental environments and tools is crucial. These tools and environments support different stages of design, monitoring, and evaluation to ensure the accuracy of data and the reliability of results. The following are the tools and environments collected based on the content of the paper, detailed in Table 2.

Table 2 Environment configuration and tool selection table

Serial number	*Category*	*Name*
1	Energy consumption monitoring system	Building energy management system (BEMS)
2	Baseline model of energy consumption	Integrated performance measurement and verification protocol (IPMVP) – Option C
3	Carbon emission calculation	Greenhouse gas (GHG) protocol
4	Carbon footprint tool	Carbon trust footprint calculator
5	Economic analysis tool	Life cycle cost analysis (LCCA) tool
6	Satisfaction survey	Likert scale questionnaire
7	VR design tools	Unity
8	Modelling software	Autodesk Revit
9	Energy consumption simulation tool	Green Building Studio
10	Intelligent control system	KNX
11	Data management platform	AWS IoT
12	Energy management system	Enphase energy

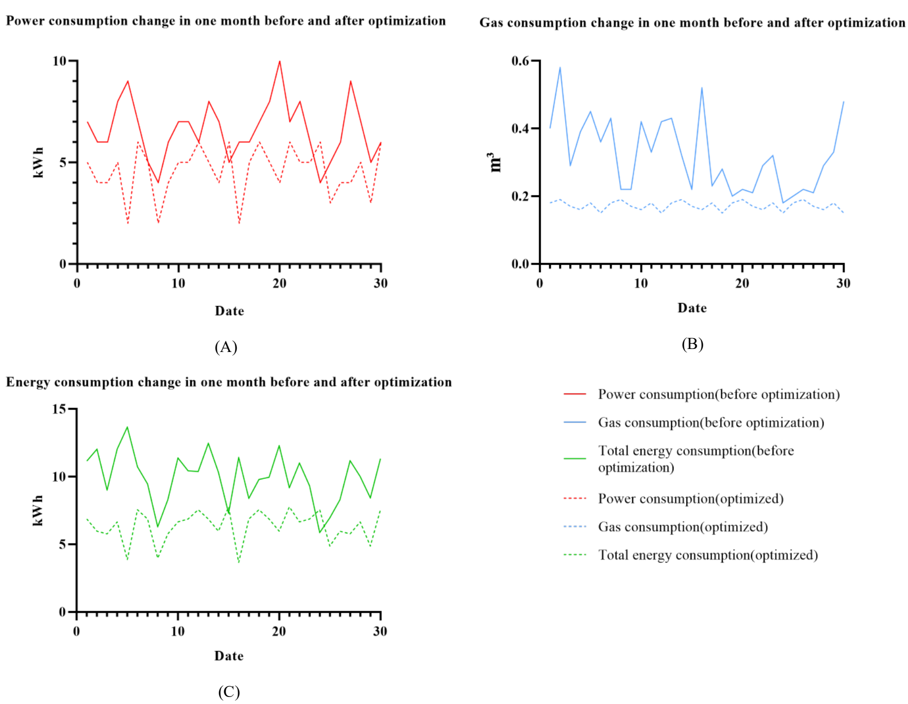
The tools and environments listed in Table 2 cover various aspects from design modelling, energy consumption simulation, real-time monitoring, and intelligent control. Specifically, the building energy management system (BEMS) is used to monitor the energy consumption of buildings, while the IPMVP Option C is used to establish energy consumption baselines and conduct evaluations. Greenhouse Gas Protocol and Carbon Trust Footprint Calculator help calculate carbon emissions, lifecycle cost analysis tools are used to evaluate the economic benefits of optimised design, and Unity software is used to create virtual reality environments for design validation. Autodesk Revit and Green Building Studio are used for creating building information models and simulating energy consumption. These tools and environments work together to ensure that the optimisation design and validation in the research can be effectively carried out.

4.2 Energy consumption reduction

In the simulation experiment, the daily energy consumption of a resident was simulated and the data were recorded for one month before and after optimisation respectively. This paper collects energy consumption data of buildings in the month before optimisation through the BEMS system and establishes detailed baseline data (Yu et al., 2021). The optimised design scheme can be applied by using the simulation tool Green Building Studio to simulate the energy consumption of buildings under the same conditions, ensuring that the simulation results are as close as possible to the actual situation. After implementing an optimised design, the BEMS system can continue to collect energy consumption data for the building for one month. This paper compares these data with baseline data and calculates the energy consumption reduction brought about by optimised design. Figure 5 shows the energy consumption changes before and after optimisation.

In Figure 6, the trend of changes in electricity, gas, and total energy consumption of residents for a month in the simulation environment is shown. It can be observed that the optimised energy consumption of residents has significantly decreased and is more stable compared to the energy consumption before optimisation. After optimisation, the daily electricity consumption decreased by about 2 kWh, and the gas consumption remained stable at around 0.2 m^3, indicating that the application of digital technology has indeed played a huge role in empowering carbon peaking and carbon neutrality. According to statistical data, the total energy consumption before optimisation was about 298.4 kWh, and the total energy consumption after optimisation was about 190.5 kWh. The total energy consumption decreased by about 108 kWh, an overall decrease of about 36%.

Figure 6 Simulates the monthly energy consumption of residents (see online version for colours)



4.3 Carbon emission reduction

The corresponding carbon emission reduction can be calculated based on energy consumption reduction, combined with energy types and carbon emission factors (provided by GHG Protocol) (Joung et al., 2020). Carbon Trust Footprint Calculator can be used for accounting (Burgui-Burgui and Chuvieco, 2020). Table 3 shows the carbon emissions of residents over 30 days under simulation experiments.

Table 3 Carbon emission data for residents

Date	*Electricity (before)*	*Natural gas (before)*	*Total (before)*	*Electricity (after)*	*Natural gas (after)*	*Total (after)*
1	4.06	0.56	4.62	2.9	0.25	3.15
2	3.48	0.81	4.29	2.32	0.27	2.59
3	3.48	0.41	3.89	2.32	0.24	2.56
4	4.64	0.55	5.19	2.9	0.22	3.12
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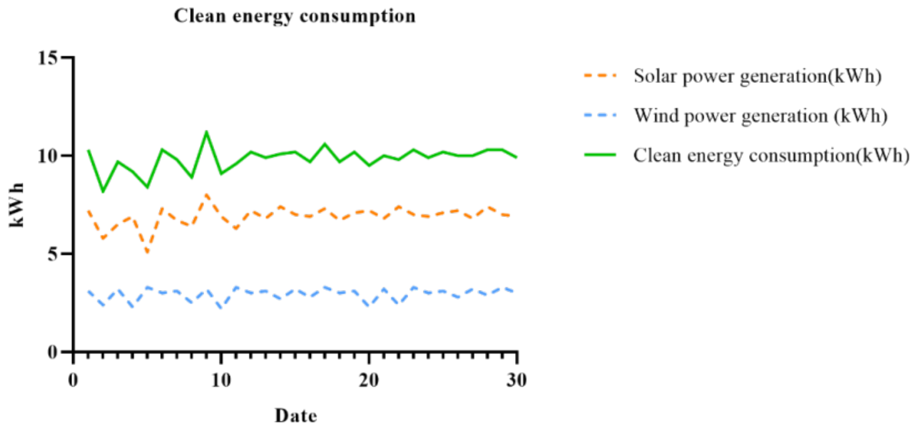
…						
…						
28	4.06	0.41	4.47	2.9	0.22	3.12
29	2.9	0.46	3.36	1.74	0.25	1.99
30	3.48	0.67	4.15	3.48	0.21	3.69

As shown in Table 3, the 30-day carbon emission data of residents is presented. The carbon emission factor for electricity used for calculation is 0.58 kg CO_2/kWh, and the carbon emission factor for natural gas is 1.4 kg CO_2/m^3. On the first day, the carbon emissions from electricity consumption before optimisation were 4.06kg, and the carbon emissions from gas were 0.56 kg. However, after optimisation, the related carbon emissions were reduced to 2.9 kg and 0.25 kg, respectively. The total carbon emissions before optimisation were calculated to be 128.37 kg CO_2, and after optimisation, the total carbon emissions were 86.66 kg CO_2. The total carbon emissions reduction was 41.71 kg CO_2, and the optimised reduction in carbon emissions was about 32.5%. The average daily carbon emissions from electricity have decreased by about 1 kg, while those from gas have decreased by about 0.2 kg. This indicates that the environmental benefits brought by digital optimisation technology are very significant in daily energy use.

As shown in Figure 7, the power generation of solar and wind energy in the simulation environment is very stable. During one day, the solar power generation remained stable at around 7 kWh, while the wind power generation remained stable at around 3 kWh. The clean energy generated in a day can provide about 10 kWh of electricity, which can provide a good source of electricity for residents in their daily lives. According to data statistics, the total amount of clean energy generation orders accumulated in a month is 303.5 kWh, and the carbon emissions converted into electricity factors are about 176 kg. This indicates that the use of clean energy can effectively respond to carbon peak and carbon neutrality goals, and the combination of indoor optimisation design and the implementation of clean energy collection devices has good environmental benefits.

Figure 7 Total electricity generation using clean energy (see online version for colours)

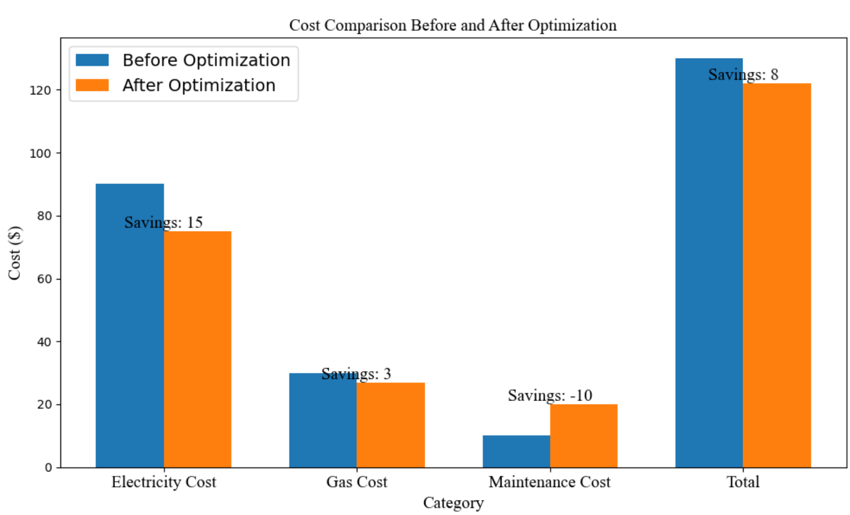


4.4 Economic benefits

Economic benefits can be evaluated by saving energy costs and equipment maintenance costs. The LCCA method can be used to calculate the total cost savings (Nikolaidis et al., 2019). Figure 7 shows the cost histogram of the simulation experiment.

Figure 8 shows the cost comparison of different categories before and after optimisation. In terms of electricity costs, the pre-optimisation cost was $90, while the post-optimisation cost was reduced to $75, saving $15. In terms of natural gas costs, the pre-optimisation cost was $30, and the post-optimisation cost was reduced to $27, saving $3. In terms of maintenance costs, the pre-optimisation cost was $10, while the post-optimisation cost increased to $20, an increase of $10. Overall, the total cost after optimisation decreased by $8 compared to before.

Figure 8 Histogram of cost comparison before and after optimisation (see online version for colours)



The use of digital technology to optimise the interior design of buildings not only effectively reduces energy consumption and carbon emissions to achieve the goal of energy conservation and emission reduction, but also brings certain economic benefits by reducing energy consumption and increasing the use of clean energy. Although maintenance costs have risen after optimisation, in the long run, this investment can help to improve the service life and operational efficiency of the equipment.

5 Conclusions

This paper examines how digital technologies, including the IoT and intelligent control systems, can optimise building interior design to support the achievement of peak carbon and carbon neutrality goals. The study utilises BIM software for the creation and optimisation of building information models, VR technology for design validation, an IoT sensor network for real-time monitoring, and an intelligent control system to automatically adjust lighting and air-conditioning systems. Experimental results demonstrate that the optimised design significantly reduces energy consumption and carbon emissions, while effectively lowering energy and maintenance costs, and improving user satisfaction. However, the study has some limitations, including the reliance on simulated data, with actual performance potentially influenced by factors like environmental conditions and user habits. Future research should focus on expanding practical application scenarios, enhancing sensor placement and control algorithms, continuously improving system intelligence and efficiency, and exploring the integration of more innovative technologies in building design to achieve larger-scale energy savings and emission reductions.

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Conflicts of interest

All authors declare that they have no conflicts of interest.

Data availability statement

No/Not applicable (this manuscript does not report data generation or analysis).

Ethical statement

Not Applicable.

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