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Green Building Performance Prediction and Evaluation System under BIM - based Digital Construction Technology

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ABSTRACT

Traditional green building performance evaluation methods usually rely on static design data and a single evaluation indicator, and lack dynamic monitoring and multi-dimensional data integration, which makes it difficult to connect data at different stages, resulting in a large gap between prediction and actual performance. This paper applies digital construction technology to construct a green building performance prediction and evaluation system that integrates data across stages and dynamically, thereby improving the accuracy and reliability of the evaluation. First, according to Building Information Modeling (BIM) technology, a digital building model containing data such as energy efficiency, environmental impact, and resource utilization is constructed. By deploying Internet of Things (IoT) sensors, energy consumption, temperature, humidity, and air quality in the building are monitored in real-time. The data is transmitted to the cloud platform for centralized processing and visualization, and compared with the design data in the BIM model to provide timely feedback on performance differences. Using big data analysis, support vector machine (SVM), and particle swarm optimization (PSO), data from the full life cycle are analyzed to predict building performance and optimize it. Finally, the LCA (Life Cycle Assessment) method is utilized to comprehensively consider the environmental impacts of buildings such as carbon footprint and resource consumption, and combined with multi-objective decision analysis tools to optimize the green building design and operation plan. The experiment shows that the energy efficiency comparison difference of green buildings is within 10kWh/m^2, and all indicators are accurately predicted, providing a scientific basis for the design and operation of green buildings.

Keywords: Green Building Performance Evaluation, Building Information Modeling, Internet of Things Technology, Big Data Analysis, Life Cycle Assessment

1. Introduction

With the increasingly severe global climate change and the aggravation of resource shortage problems, green building construction innovation has become the focus of attention. Green building construction

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innovation refers to the comprehensive application of advanced technology and innovative methods in the process of building construction, with the goal of minimizing environmental loads, reducing pollutant emissions and resource consumption, and realizing the sustainable development of the green building construction process [1]. The core idea of green building construction innovation is to use environmentally friendly and resource-saving methods in the construction process to optimize the construction process and reduce the impact on the natural environment and resources [2-4]. The application of digital technology in green building construction has been widely explored, through which more accurate design and construction processes can be achieved, energy efficiency can be improved, and carbon emissions can be reduced [5-6].

In today's rapidly developing digital era, all industries are seeking digital transformation and upgrading, and the engineering construction industry is no exception [7]. Engineering construction is a complex process that involves multiple links such as design, construction, management and maintenance [8]. In the past, these links usually rely on manual labor, which is not only inefficient but also prone to errors [9-10]. With the introduction of digital technology, the engineering and construction industry has begun to undergo a comprehensive digital transformation to achieve accurate management and real-time monitoring of engineering projects through the use of advanced technologies such as building information modeling (BIM), drones, and sensors [11-15]. This can not only improve the quality and efficiency of engineering projects, but also effectively reduce costs and enhance the competitiveness of enterprises [16-17]. In addition, the introduction of digital technology is precisely one of the important ways to realize the goal of green construction [18]. The realization of green construction needs to rely on advanced technical support to reduce the impact on the environment and realize the sustainable development of engineering construction through the fine management of engineering projects [19-21]. How to integrate digital technology into green construction, improve construction efficiency and reduce environmental pollution has become an urgent problem to be solved at present.

Drone and sensor technologies are widely used in the field of construction, which effectively improve construction safety and quality through real-time monitoring and data analysis. By taking high-definition pictures and videos, drones can realize real-time monitoring of the construction site, discover and deal with hidden dangers in a timely manner, and improve the level of construction safety. Waqar, A. et al. elaborated on the outstanding contribution of drones in the field of construction, where AI-driven unmanned aerial systems can effectively address many challenges in construction projects such as safety issues, quality management, and can also play an important role in promoting public health and protecting the environment [22]. Khan, O. et al. used a drone thermal imaging program to measure the wear and tear thermal resistance in the building envelope and analyzed the collected data with the help of an artificial intelligence algorithmic model in order to correctly estimate the building envelope variance and provide an efficient and inexpensive way of evaluating the development of green buildings [23]. Manan, M. S. A. et al. emphasized that thermal efficiency analysis of building materials and structures plays an important role in improving building sustainability, and for this reason, proposed UAS integrating thermal imaging, visuospatial data, and 3D modeling technologies that have significant potential for design applications in green buildings [24]. Sensor technology realizes real-time monitoring of the quality of the project by collecting various data from the construction site, such as temperature, humidity, vibration, etc., to ensure that the quality of the project is qualified.Tushar, W. et al. investigated the method of designing a management system for high-rise buildings based on IoT sensors to provide feasible ideas for reducing building energy consumption in a convenient and inexpensive way [25]. Kumar, A. et al. described numerous monitoring functions of sensor-actuator hardware devices in smart buildings, which in combination with intelligent algorithms at the software level can effectively improve building performance and energy efficiency [26]. Ren, X. et al. proposed a multi-information fusion-based intelligent detection technique for electrical fires, which is applied to the low-voltage distribution system of a green building, and can be used in a low-cost way for green building electrical fire prevention [27].

In addition, the application of cloud computing and big data plays an important role in the field of modern building construction. Cloud computing provides a powerful computing platform, which allows construction companies to obtain the required computing resources through the network, without the need to invest in huge hardware equipment, reducing costs. Singh, A. et al. used IoT and cloud architecture to help green buildings to be intelligently constructed, designed, and operated, allowing buildings to exploit natural resources on a large scale and reduce the harmful effects of construction projects on human health and the environment [28]. Li, X. J. et al. created a green building performance index based on expert evaluation and a standard cloud scale in a comprehensive cloud model, and used it to construct a green building performance evaluation method based on cloud modeling, which provides green building managers with a reflection and basis for sustainable construction and operation [29]. Dahiya, N. et al. established a building management cloud platform for green buildings to realize O&M management among green buildings with the help of data storage, computing and hosting provided by cloud servers [30]. Big data, on the other hand, analyzes a large amount of data to provide a scientific basis for decision-making in engineering projects and optimize engineering design, construction and management, etc. Gao, X. Simulation and analysis of the energy consumption of green buildings by using data mining technology can calculate the carbon emissions in all stages of its operation, which is conducive to the improvement of the modern design of green buildings [31]. Lu, W. et al. explored the demolition method for minimizing construction waste in green buildings from scientific and empirical perspectives, respectively, by triangulating the acquired quantitative data over the qualitative data to provide a brand new path for fostering sustainability in the built environment [32]. Daissaoui, A. et al. analyzed the role of big data analytics technology in the intelligent transformation of buildings, which is conducive to improving building comfort while saving building energy consumption, which is of great significance in the field of sustainable building development [33].

However, the above construction techniques cannot avoid the common problems of design changes and engineering rework in engineering, which often result in lower quality and efficiency of engineering projects. For this reason, BIM technology with 3D visualization function is proposed, which can reduce the cost of the project by collaborating the engineering design, construction and management, while effectively avoiding the common problems of traditional engineering, and has high practical value in green building construction.

First, a digital building performance model is constructed based on BIM technology, and green building performance data such as energy efficiency and environmental impact are embedded in it. Second, IoT technology is used to realize real-time data collection in the building operation stage, and a dynamic monitoring and feedback mechanism is established. Third, big data analysis and machine learning algorithms are combined to analyze various data throughout the building life cycle, predict the future performance of the building, and optimize it. Finally, the life cycle assessment method is utilized to comprehensively consider the environmental impacts of the building such as carbon footprint and resource consumption, and combined with AHP and TOPSIS to provide an optimization solution for the design and operation of green buildings. The method proposed in this paper not only improves the accuracy of green building performance evaluation through the integration of digital construction technology, but also enhances the real-time and operability of the evaluation system, providing a scientific basis for the design and operation of green buildings.

2. Methods

2.1. Green Building Data Modeling Based on BIM

In the green buildings' design stage, accurate performance prediction and evaluation are essential. To ensure the comprehensiveness and accuracy of the evaluation results, this paper uses building information modeling (BIM) technology, combined with energy efficiency analysis and environmental impact assessment, to establish a detailed 3D digital model for green buildings. Through the BIM model, the geometric form, spatial layout, material selection, and other information of the building design can be fully modeled. The model not only covers the building appearance data, but also incorporates the performance indicators of green buildings (energy efficiency, environmental impact, resource utilization, etc.).

2.1.1. BIM Model Construction and Energy Efficiency Embedding.In the design stage of green buildings, firstly, three-dimensional modeling is carried out through the BIM modeling software Navisworks to precisely describe the building's appearance, structure, and installation location of equipment. Each building element (wall, window, roof, floor, etc.) is carefully defined and associated with the building materials (thermal conductivity, lighting performance, etc.). These geometric information are the subsequent energy efficiency analysis data. Then, the energy efficiency data of the building is embedded in the BIM model, covering heat conduction, window lighting efficiency, facade heat island effect, and other contents. To achieve this goal, this paper adopts energy efficiency analysis tools such as EnergyPlus and DesignBuilder to transmit and integrate data through the interface with the BIM model. These energy efficiency data reflect the energy efficiency level of the building design in real-time, providing a scientific basis for subsequent evaluation. The modeling process is depicted in Figure 1:

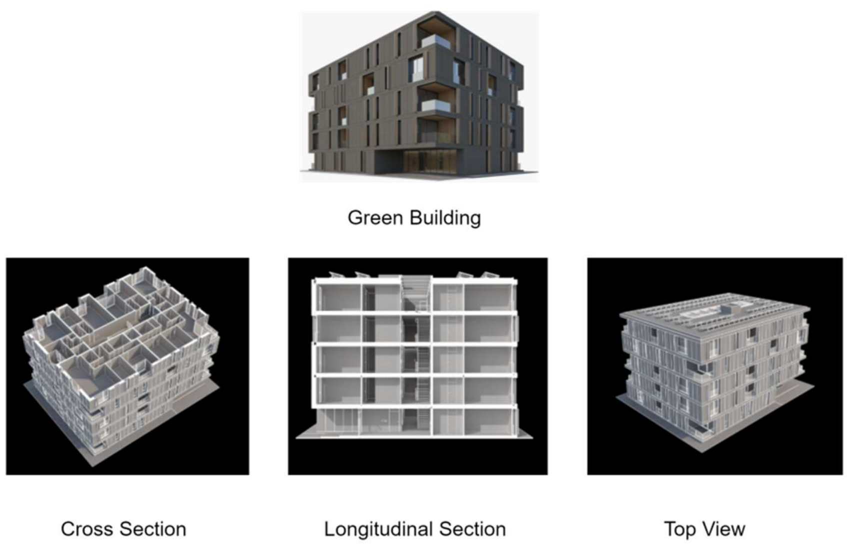

Fig. 1. 3D modeling of green buildings

By using BIM technology, energy efficiency data is closely integrated with building design information, solving the problem of disconnection between design data and performance evaluation in traditional evaluation methods. Traditional methods often rely on static data and cannot dynamically reflect the interactive effects between building elements. The BIM model systematically links green performance data with design information to form a dynamic and operational platform.

2.1.2. Associations in BIM, Environmental Impact, and Resource Utilization.In the scope of green building design, environmental impact assessment and resource utilization efficiency occupy a pivotal position. The utilization of the BIM model enables the integration of environmental impact and resource utilization data of buildings, thereby achieving a comprehensive and in-depth evaluation. The selection of building materials, as a key factor that directly affects environmental benefits such as energy efficiency, carbon emissions, and resource consumption, is deeply integrated into the BIM model. This model not only covers the geometric form and energy efficiency data of the building, but also closely combines the environmental impact data of building materials, which are mainly derived from LCA tools, providing the design team with real-time resource consumption and carbon emission analysis support.

The visualization characteristics of the BIM model enable all kinds of data in the building design process to be presented intuitively through a graphical interface. Designers can use this function to foresee the profound impact that different design schemes may have on the environment and resources in the early stages of design. By simulating the diverse combinations of building facade materials and layouts, designers can clearly understand the specific impact of these changes on building energy efficiency, resource utilization efficiency, and environmental load, so that they can make the most reasonable decisions in the early stages of design and effectively avoid major environmental and resource losses that may occur during the construction and operation stages.

2.1.3. Feedback Mechanism of BIM Integrated Optimization and Evaluation System. Traditional green building evaluation systems are usually based on static data and cannot track changes in building performance in real-time, making it difficult to provide timely feedback during the design stage. The dynamic and integrated nature of BIM technology solves this problem. During the design process, the BIM model provides designers with a real-time update and feedback mechanism, allowing designers to view changes in building performance at any time and adjust design plans based on real-time data. When modifying the size or material of building components, the BIM model automatically updates the relevant energy efficiency data and environmental impact data, helping designers to instantly understand the impact of these changes on building performance.

BIM technology is deeply integrated with EnergyPlus energy efficiency analysis tools and LCA tools to jointly build a comprehensive building performance evaluation system that covers a wide range of key green building evaluation indicators such as energy efficiency, resource use, and carbon emissions. This comprehensive green building evaluation solution significantly enhances the design process efficiency, and effectively reduces the time and cost required for subsequent design adjustments and performance evaluations. Within the integrated framework of BIM, the energy efficiency evaluation process is simplified and can be efficiently calculated using Formula 1:

$$E = \sum_{i=1}^{n} (P_i \times T_i) \tag{1}$$

Among them, P_i is the power consumption of the i-th energy (electricity, natural gas, etc.) (kW); T_i is the time of the corresponding energy consumption (hours). Through the dynamic update of the BIM model, designers can adjust various parameters in real-time to optimize the building's energy efficiency. In the BIM integrated life cycle assessment, carbon emissions are calculated using Formula 2:

$$C = \sum_{j=1}^{m} (E_j \times F_j) \tag{2}$$

2.2. Dynamic Data Monitoring and Real-time Feedback

2.2.1. IoT Sensor Deployment and Data Collection.During the building operation, the environmental performance of the building and the comfort of the residents are deeply restricted by core factors such as energy consumption, indoor temperature and humidity regulation, and air quality. In response to this, this study deploys a series of IoT sensing elements such as temperature and humidity sensors, CO_2 concentration sensors, and energy consumption monitoring equipment in several important parts of the building. These sensors are precisely configured in core links such as air conditioning systems, lighting systems, and ventilation facilities, and comprehensively collect various key data of building operations in real-time or timing mode.

Temperature and humidity sensors are responsible for monitoring indoor temperature and humidity conditions, aiming to maintain a suitable living experience and reduce unnecessary energy consumption. The CO_2 concentration sensor provides real-time feedback on indoor air quality information, providing a reliable basis for ventilation control. The energy consumption monitoring equipment focuses on collecting energy consumption data of various subsystems of the building to evaluate the economic performance and efficiency level of equipment operation. With low-power wide area network technology, the sensor transmits the collected data to the cloud platform wirelessly to ensure instant synchronization and high accuracy of the data. The application of this technology has greatly improved the monitoring efficiency and effectively reduced the cost pressure brought by traditional wiring methods.

2.2.2. Cloud Platform Data Processing and Visual Feedback.The data collected by the sensor is transmitted to the cloud platform AWS IoT (Amazon Web Services Internet of Things) in real-time through the wireless network for centralized storage and processing. The cloud platform processes and analyzes the raw data and presents the results to the operations team in a visual form. Through the tools Node-RED and Grafana, real-time data is mapped to a visual dashboard to display key indicators such as energy consumption, air quality, temperature, and humidity.

Node-RED captures sensor data streams in real-time and converts them into visual information, helping managers quickly evaluate building performance. The dashboard provided by Grafana presents the historical trends, real-time data, and alarm information of various building performance indicators, making it easier for the team to quickly detect anomalies and adjust strategies. When the CO_2 concentration exceeds the standard, the system issues an alarm to remind managers to take ventilation measures; when energy consumption is too high, the system makes energy-saving suggestions to help the operations team optimize energy management. This real-time feedback mechanism ensures the continuous optimization of building performance and reduces energy waste and environmental quality issues by dynamically adjusting operation strategies.

2.2.3. Data Comparison and Optimization Adjustment.To ensure that building operations always comply with green building performance requirements, real-time monitoring data is compared and analyzed with the design data in the BIM model. The BIM model contains the design parameters of the building and the expected energy efficiency data, while the real-time data collected through the IoT reflects the actual operation status of the building. By comparing these two types of data, the system identifies the deviations of the building in terms of energy use, air quality, and equipment efficiency, thereby providing an optimization basis for the operation team.

When the air-conditioning system's energy consumption is monitored to exceed the predetermined value, the system automatically compares the actual energy consumption with the design data in the BIM model and prompts possible efficiency problems. Based on the comparison results, the system may recommend equipment maintenance, adjustment of settings, or optimization of system operation mode. This mechanism can not only detect problems in real time, but also propose specific optimization measures based on data comparison.

During the building operation stage, after comparing the real-time energy consumption data with the design data in the BIM model, the energy efficiency deviation is calculated, and energy efficiency correction is made accordingly. Assuming that the energy efficiency (E_{eff}) of a building is determined by multiple influencing factors (air conditioning, power system, etc.), Formula 3 is utilized to calculate the energy consumption deviation and the corrected energy efficiency:

$$\Delta E_{eff} = \sum_{i=1}^{n} (E_{actual,i} - E_{design,i}) \times w_i \tag{3}$$

Among them, ΔE_{eff} is the total energy efficiency deviation; $E_{actual,i}$ is the actual energy consumption of the i -th type of equipment (air conditioning, lighting, etc.); $E_{design,i}$ is the corresponding design stage energy consumption; w_i is the energy consumption weight of the i-th type of equipment (reflecting the importance of the equipment in the overall energy efficiency). Based on this energy efficiency deviation, the system calculates the corrected energy efficiency calculation formula as Formula 4:

$$E_{eff,adjusted} = E_{eff} + \Delta E_{eff} \tag{4}$$

Among them, E_{eff} is the energy efficiency value of the preliminary evaluation.

In addition, the system also supports data comparison and analysis between multiple buildings. If multiple buildings have similar energy efficiency problems, the system provides a centralized optimization solution to help the building group improve energy efficiency and reduce environmental impact as a whole.

Figure 2 illustrates the comparison of design and actual energy efficiency of 10 buildings. The design energy efficiency of building E is 60 kWh/m², and the actual energy efficiency is 62 kWh/m², which is a slight increase; the design energy efficiency of building C is 52 kWh/m², and the actual energy efficiency is 50 kWh/m², which is a slight decrease. The design energy efficiency of building A is 50 kWh/m², and the actual energy efficiency is 55 kWh/m², with a large gap, which may be related to equipment aging or improper management. Overall, the actual energy efficiency of most buildings deviates from the design value, suggesting that the operation strategy needs to be optimized to enhance green buildings' energy efficiency.

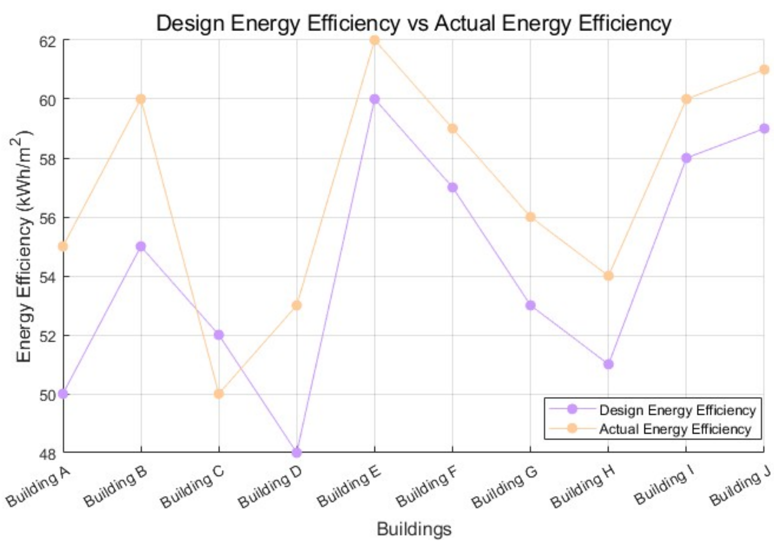

Fig. 2. Comparison of design and actual energy efficiency of ten buildings

In short, dynamic data monitoring and real-time feedback mechanism provide strong technical support for the operation and management of green buildings. Through data collection of IoT sensors, processing and visualization of cloud platforms, and comparative analysis of BIM model data, the system monitors building performance in real-time, timely discovers potential problems based on the comparison of real-time data and design data, and makes effective optimization adjustments. This process effectively improves the energy efficiency and environmental quality of the building and ensures the realization of green building design goals.

2.3. Big Data and Artificial Intelligence Optimization

In the design, construction and operation stages of green buildings, various types of data carry a lot of valuable information and reveal the potential for optimizing building performance. To extract useful insights from massive data, this paper uses big data analysis and artificial intelligence technology to process the design, construction, and operation data during the life cycle of the building, so as to find the key factors affecting the green performance of the building. Performance prediction and optimization design are carried out based on these factors.

2.3.1. Big Data Collection and Processing. Green buildings involve a wide variety of data, including building geometry, material selection, and energy efficiency data in the design stage; time cost and construction quality data in the construction stage; energy consumption, air quality, and equipment operation data in the operation stage. These data are not only massive, heterogeneous, and time-series, but also face challenges in storage and processing. To this end, this paper uses big data platforms such as Hadoop and Spark to process these data.

Hadoop provides distributed storage and computing support, stores data at different stages of the building through HDFS (Hadoop Distributed File System), and uses MapReduce for parallel processing. Spark is used for efficient real-time data processing and supports large-scale data analysis and prediction. Through these platforms, the system realizes data storage, cleaning, preprocessing, and efficient analysis. In the process of data preprocessing, data cleaning technology is utilized to ensure the accuracy and consistency of the data, including denoising, missing value filling and standardization, which provides high-quality input data for subsequent machine learning model training.

2.3.2. Machine Learning and Performance Prediction. To optimize building performance, this paper uses machine learning methods such as SVM to model and predict historical data to help identify potential problems and provide optimization solutions. Through feature engineering, characteristic variables that have a significant impact on building performance, such as heat load, ventilation efficiency, and environmental friendliness of building materials, are extracted from design, construction, and operation data. Based on these features, the SVM model is trained to predict indicators such as future energy efficiency, carbon emissions, and environmental impact of buildings.

SVM has strong nonlinear processing capabilities, processes high-dimensional data, and avoids the overfitting problem of traditional regression models. Through this model, the system predicts the performance of the building in different usage scenarios based on historical data, provides precise predictions of energy efficiency, air quality, etc., for building operations, and helps managers identify potential risks in advance and take preventive measures. The goal of SVM regression is to minimize the following objective function:

$$\min_{w,b}\frac{1}{2}\|w\|^2 + C\sum_{i=1}^{N}\xi_i \tag{5}$$

In Formula 5, C is a regularization parameter that controls the model's tolerance to errors; ξ_i is the slack variable for each training sample, which is used to tolerate certain errors; N is the number of samples. In addition, to ensure that the regression results are as smooth as possible, SVM also uses the following constraints to ensure that the prediction results do not exceed the preset tolerance $\in$:

$$|f(x_i) - y_i| \leq \in + \xi_i \quad for\ i = 1, 2, \ldots, N \tag{6}$$

In Formula 6, y_i is the actual actual energy efficiency or carbon emissions, and $\in$ is the error tolerance.

2.3.3. Optimization Algorithm and Building Design and Operation Adjustment.Based on performance prediction, this paper applies the PSO algorithm to further optimize the building design scheme and operation strategy. The PSO algorithm simulates the movement of particles in the search space and finds the optimal solution through global search. It is particularly suitable for complex nonlinear and multi-objective optimization problems. In the building design stage, the PSO algorithm optimizes the design variables of the building's facade materials, window layout, insulation layer, etc., to help evaluate the energy efficiency, carbon emissions, and comfort of different schemes. The algorithm automatically adjusts these variables and searches for the best design scheme to realize the optimization of the building's green performance. In the operation stage, the PSO algorithm is applied to the optimization of building equipment scheduling. In the energy efficiency optimization of the air-conditioning system, the PSO algorithm automatically adjusts the equipment operation strategy according to the real-time energy consumption data, optimizes the indoor temperature control, reduces energy consumption, and maintains a comfortable indoor environment. In addition, the combination of PSO and SVM model further improves the long-term operation efficiency of the building and ensures that the building achieves the best green performance during actual operation.

Figure 3 shows the impact of window size and insulation thickness on the green performance of the building. As the window area increases, energy efficiency decreases, and carbon emissions increase, but the increase gradually slows down, showing that the impact of larger windows on energy efficiency and carbon emissions gradually weakens. The thickness of the insulation layer is positively correlated with energy efficiency. Increasing the thickness can improve energy efficiency, but the improvement is small; at the same time, carbon emissions are negatively correlated with the thickness of the insulation layer, and increasing the thickness can significantly reduce carbon emissions. These data show that reasonable design variable adjustment can effectively optimize the green performance of the building.

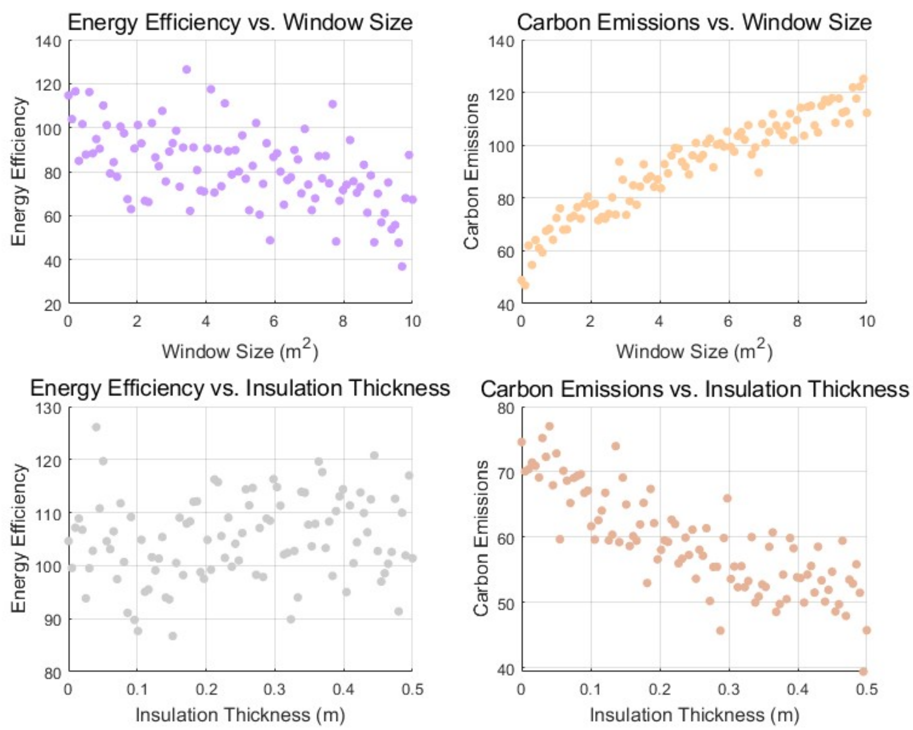

Fig. 3. The impact of design variables on energy efficiency and carbon emissions

2.3.4. System Integration and Intelligent Decision Support.This study combines big data analysis, machine learning, and optimization algorithms to build an intelligent decision support system to achieve intelligent improvement of building performance. The system covers the design, construction, and operation stages, providing optimization solutions and real-time adjustment strategies to maximize the energy efficiency and environmental adaptability of buildings. Through system integration and intelligent optimization, the performance of green buildings can be continuously improved to ensure the best green benefits throughout the life cycle.

2.4. LCA and Intelligent Decision Support

2.4.1. LCA and Environmental Impact.This paper utilizes SimaPro software to conduct LCA analysis and quantify the long-term impact of buildings on the environment, combining data on building materials, energy consumption, waste disposal, etc.

In the design stage, LCA evaluates factors such as material selection and energy consumption to help designers choose materials and processes with low environmental impact and use low-carbon cement or recycled materials. LCA analysis in the construction stage focuses on evaluating energy consumption and waste emissions to promote the implementation of energy-saving and emission reduction measures. During the operation stage, LCA helps to identify energy efficiency loss points and propose optimization strategies to ensure that the building achieves optimal energy efficiency and environmental impact during use. By comprehensively evaluating the environmental impact of the full life cycle, LCA provides quantitative decision-making support for the green development of buildings.

2.4.2. Multi-objective Decision Optimization.To make full use of LCA results to guide green building design and operation optimization, this paper combines multi-objective decision analysis methods such as AHP and TOPSIS to comprehensively evaluate and optimize different building schemes. These methods help to find the best balance between multiple conflicting goals and ensure the green optimization of building performance.

AHP: By establishing a hierarchical structure, multiple influencing factors in building design (energy efficiency, environmental impact, cost, etc.) are decomposed into different levels for weight allocation. The weights of each level are determined by expert review or historical data analysis to help select the best design solution that meets the green building goals.

TOPSIS: This method calculates the distance between each solution and the ideal solution, and finally ranks the advantages and disadvantages of different solutions according to the distance. In the design stage, the TOPSIS method helps decision-makers comprehensively consider multiple indicators such as energy efficiency, carbon emissions, and material use to select the best design solution. By combining LCA results with AHP, TOPSIS, and other methods, this paper provides comprehensive optimization suggestions for green buildings, which not only helps designers choose the best solution, but also provides long-term optimization strategies for the operation team to ensure the green performance of the building throughout its life cycle.

Table 1 shows the energy efficiency, carbon emissions, material use, construction costs, and comprehensive scores of the four building design schemes. Scheme A has an energy efficiency of 80 kWh/m², a carbon emission of 12 $kgCO_2/m^2$, and a construction cost of 500000 yuan, which has the highest comprehensive score and ranks first. Scheme B has a lower energy efficiency (75 kWh/m²) and higher carbon emissions (15 $kgCO_2/m^2$). Although the cost is lower (480000 yuan), it ranks third overall due to carbon emissions and material use. Scheme C is superior in energy efficiency (85 kWh/m²) and carbon emissions (10 $kgCO_2/m^2$), but the construction cost is higher (550000 yuan), ranking second overall. Scheme D has the worst energy efficiency (70 kWh/m²), the highest carbon emissions (20 $kgCO_2/m^2$), and the worst overall performance, ranking fourth. Overall, Scheme A is the best choice, considering the balance of various indicators.

Table 1. Energy efficiency, carbon emissions, material use, construction cost, and comprehensive scores of four building design solutions

Building Design Scheme	Energy Efficiency (kWh/m²)	Carbon Emissions ($kgCO_2/m^2$)	Material Usage (kg/m²)	Construction Cost (10,000 CNY)	AHP Weight	TOPSIS Distance to Ideal Solution	Rank

Scheme A	80	12	30	50	0.4	0.12	1
Scheme B	75	15	35	48	0.3	0.25	3
Scheme C	85	10	28	55	0.2	0.18	2
Scheme D	70	20	40	45	0.1	0.3	4

2.4.3. Integration and Application of Intelligent Decision Support Platform. This study combines LCA with multi-objective decision analysis technology to build an intelligent decision support platform to provide accurate decision support in the design, construction, and operation stages. In the design stage, the platform evaluates the scheme through LCA analysis and AHP and TOPSIS methods, and conducts dynamic analysis of green performance; in the construction stage, it monitors energy consumption and material use in real-time and puts forward energy-saving and emission reduction suggestions; in the operation stage, it adjusts the equipment operation strategy based on real-time data and LCA results to improve green performance. The platform is deeply integrated with BIM, IoT, and other systems to achieve data sharing, comprehensively improve the intelligent operation and green performance management of buildings, and ensure that the building meets green standards throughout its life cycle.

3. Effect Evaluation

3.1. Resource Utilization Rate during the Life Cycle of the Building

This study calculates the key resource utilization indicators during the life cycle of the building, such as material recovery rate, proportion of renewable energy use, and water consumption, to evaluate the resource utilization efficiency of the building. The relevant data of each stage are collected separately, and the trend of each indicator is calculated. The resource utilization levels at different stages are compared to evaluate the overall resource efficiency.

Table 2 shows the resource utilization of the building at different stages. The material recycling rate gradually increases from 50% in the design stage to 70% in the operation stage. The proportion of renewable energy use increases from 20% in the design stage to 40% in the operation stage. Water consumption increases year by year, but the water recycling rate increases from 10% to 25%, showing more efficient water management. In addition, the green roof area and energy recovery rate also increase with the advancement of each stage, reflecting the gradual optimization of the building in terms of sustainability.

Table 2. Resource utilization of buildings at different stages

Resource Utilization Indicator	Design Stage (%)	Construction Stage (%)	Operation Stage (%)
Material Recycling Rate	50	60	70
Renewable Energy Usage Ratio	20	30	40
Water Consumption (m3/year)	1000	1200	1500
Water Recycling Rate	10	15	25
Green Roof/Greening Rate (%)	5	10	15
Energy Recovery Rate	15	20	25

3.2. *Green Building Carbon Emissions*

The building's energy consumption data in the operation stage is collected, and then the carbon emissions of each type of energy are calculated based on the carbon emission factors of different energy types. Combining various data, the total carbon emissions of the building over its full life cycle are obtained.

Table 3 shows the annual carbon emissions of the four building design schemes. The carbon emissions of each scheme are obtained by calculating the annual energy consumption and carbon emission factors of different schemes. Among them, the annual carbon emissions of Plan A are 36 $kgCO_2/m^2$, while that of Plan D is 35 $kgCO_2/m^2$, showing the difference between the schemes. Plan A reduces emissions by 5 $kgCO_2/m^2$. These data evaluate the effectiveness of different design schemes in reducing carbon emissions and improving energy efficiency. Overall, Plan D has the lowest annual energy consumption and a higher carbon emission factor, but its overall performance makes up for this through a larger emission reduction, so it is a better carbon emission reduction scheme.

Table 3. Annual carbon emissions of four building design schemes

Building Plan	Annual Energy Consumption (kWh/m^2)	Carbon Emission Factor ($kgCO_2/kWh$)	Annual Carbon Emissions ($kgCO_2/m^2$)	Carbon Emission Reduction ($kgCO_2/m^2$)
Plan A	80	0.45	36	5
Plan B	75	0.48	36	4
Plan C	85	0.43	36.55	3.5
Plan D	70	0.5	35	6

3.3. *Energy Efficiency Evaluation*

Based on the energy efficiency simulation in the building design stage and the real-time energy consumption data in the operation stage, the energy efficiency model is utilized to evaluate the energy consumption of the building. Combined with the climate conditions, building appearance, usage functions, and other factors of Plan D, the annual energy efficiency performance of the building is predicted, and compared and corrected based on the actual energy consumption data.

The annual energy efficiency bar chart in Figure 4 shows the energy efficiency comparison between the Plan D building design stage and the actual operation stage. The energy efficiency predicted in the design stage is 40 kWh/m^2 in January, and gradually decreases to 28 kWh/m^2 in June, reflecting that the air conditioning load increases in summer and the energy consumption of air conditioning increases, resulting in a gradual decrease in the overall energy efficiency of the building. The actual energy efficiency data in Figure 4 is generally higher than the design value, and is 42 kWh/m^2 in January and 41 kWh/m^2 in December, indicating that the energy efficiency performance of the building is good in actual operation. Especially in the high-load season, the actual energy efficiency is more stable, and the difference is small, indicating that the design and actual performance are basically consistent.

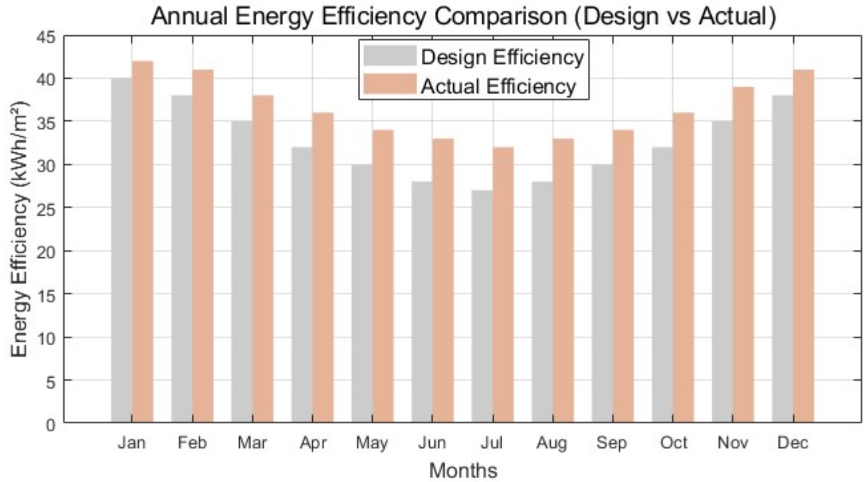

Fig. 4. Comparison of energy efficiency between the building design stage and the actual operation stage

3.4. Indoor Air Quality

The air quality inside the building is evaluated based on data such as CO_2 concentration, temperature, and humidity monitored in real-time by IoT sensors. Air quality assessment is carried out using relevant standards such as ISO 16814 to ensure the comfort and health of the building.

Figure 5 shows the changes in CO_2 concentration, temperature, and humidity within 24 hours. The CO_2 concentration reaches its highest point at 770 ppm in 24 hours, indicating that human activities keep the CO_2 concentration increasing. The temperature changes from 22°C to 25°C, maintaining a comfortable environment. The humidity fluctuates between 55% and 85%, which is closely related to the temperature change, ensuring good air quality. These data reflect the dynamic changes in the building environment and help evaluate the comfort and health of green buildings.

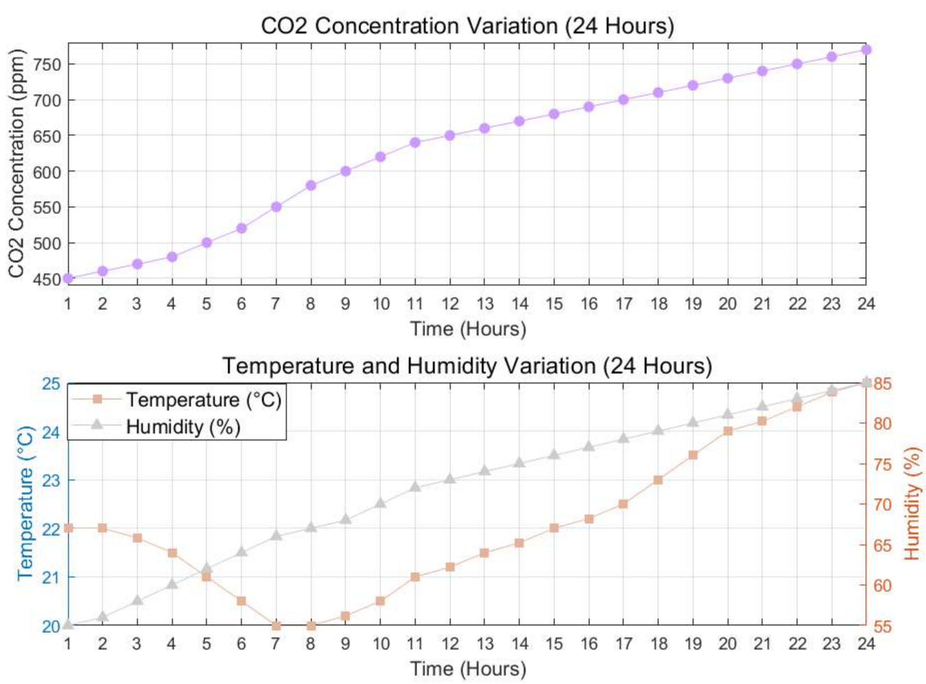

Fig. 5. Changes in CO_2 concentration, temperature, and humidity within 24 hours

4. Conclusions

This paper explores the application of big data, IoT, LCA, and intelligent decision support systems in green buildings. By integrating IoT sensors and cloud computing technology to real-time monitor key indicators such as building energy efficiency and environmental quality, and combining big data analysis and machine learning algorithms, this paper achieves dynamic prediction and optimization of building performance. In addition, LCA, AHP, and TOPSIS methods are used to provide quantitative environmental impact assessment and optimization suggestions for building design and operation. The research results of this paper provide intelligent decision-making support for the full life cycle management of green buildings, significantly enhance the energy efficiency and resource utilization of buildings, and promote the sustainable development of green buildings. However, the application effect of the current method in large-scale building groups needs further verification, and there is still room for improvement in the real-time and accuracy of data transmission and processing. Future research can further explore more efficient data processing technologies and optimization algorithms, expand the scope of application of the system, and promote the widespread application of intelligent green buildings.

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