Research on Energy-saving Design and Application of High-rise Buildings Based on BIM Technology: A Case Study of Building 9 in Shaolin Third Community, Shaolin Street, Dengfeng City

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Abstract. With the rapid increase in the number of high-rise buildings, the issue of energy consumption has become increasingly prominent, making the application of BIM technology in the field of building energy conservation more and more important. This paper aims to explore the application and potential of BIM technology in the energy conservation design of high-rise buildings. The article first analyzes the energy consumption characteristics of high-rise buildings, clarifies the principles and goals of energy conservation design, and introduces in detail the energy conservation design process and technical measures based on BIM technology, including site environment analysis and energy system design. The actual case of Building 9 in the Third Community of Shaolin Street, Dengfeng City, demonstrates the specific application of BIM technology in daylighting simulation, thermal and solar radiation analysis, energy system optimization, and renewable energy utilization planning. The research results show that BIM technology plays a key role in the energy conservation design of high-rise buildings, but there are still problems such as insufficient simulation accuracy and difficulty in data sharing. In the future, the integration of BIM technology with emerging technologies will bring broad prospects to the construction industry. It is recommended to increase investment in this field to fully tap its potential and promote building energy conservation and sustainable development.

Keywords: BIM technology; high-rise buildings; energy-saving design; energy consumption Sustainable development.

1. Introduction

In the rapid development of modern cities, the number of high-rise buildings has seen explosive growth, and the energy consumption problem that follows has become increasingly prominent. The high-intensity use of electricity, significant heat loss, and waste of water resources have reached a level that cannot be ignored. With the development of the times, a series of policies and regulations aimed at regulating energy conservation in buildings have been successively introduced. For instance, relevant policies propose that a sustainable energy development strategy of "energy conservation first, structure optimization, and environmental friendliness" should be implemented, suggesting that resource conservation be elevated to the status of a basic national policy and that buildings and transportation be identified as key areas for energy conservation to reverse the long-term lagging situation in building energy conservation [1]. Against this backdrop, the application of Building Information Modeling (BIM) technology in the construction field has gradually emerged, demonstrating outstanding potential for efficiency improvement in multiple aspects such as design, construction, and operation and maintenance.

At present, the application of BIM technology in the energy-saving design of high-rise buildings is still in a stage of continuous development and improvement. Although some advanced regions and projects have successfully introduced BIM technology, its overall popularity still needs to be enhanced. On the one hand, the proficiency of most architectural design teams in BIM technology varies, which leads to its failure to fully leverage its advantages in practical applications. On the other hand, there is a certain gap between the functions of BIM software and actual demands, which restricts its wide application.

This study focuses on the integrated application of energy-saving design in high-rise buildings and BIM technology, taking Building 9 of Shaolin Third Community in Shaolin Street, Dengfeng City as a case for analysis, and delves into the specific goals of achieving energy-saving design through the application of BIM technology in this project. By analyzing the research results of Wu Yiming, Zhou Qi, Zhao Lijun, Li Xingang and others on energy-saving design in super high-rise buildings, the methods applicable to this paper are extracted to provide a basis for concluding [2]. This study clarifies the research scope and potential limitations, laying a foundation for the smooth progress of subsequent research. On this basis, it explores effective ways to integrate building energy conservation and technological innovation, striving to provide a reference example and reliable technical support for addressing energy challenges.

2. Principles and Methods of Energy Conservation Design for High-rise Buildings

2.1. Characteristics and Influencing Factors of Energy Consumption in High-rise Buildings

During the operation of high-rise buildings, there are various types of energy consumption. Electricity consumption is particularly significant, covering elevator operation, lighting, air conditioning, and office appliances, etc. As Zeng Xudong and Zhao Ang pointed out, the energy consumption of elevators in high-rise buildings cannot be ignored. Their operation mode is complex and energy consumption is high [3]. Elevators consume a lot of energy due to frequent starts and stops and long-term operation; the electricity consumption for lighting depends on the type, duration and power of the lamps in the building; air conditioning is the main energy consumer, and it operates continuously for cooling in summer and heating in winter, resulting in high energy consumption. Thermal energy consumption is reflected in winter heating and the supply of domestic hot water in buildings, which is transported to each room through centralized heating pipelines. Water consumption is distributed in daily life and air conditioning cooling water, etc. Comprehensive high-rise buildings consume a large amount of water due to large personnel flow and high water demand. There are many key factors affecting the energy consumption of high-rise buildings. The orientation and layout of the building have a significant impact on energy consumption. A reasonable orientation can make full use of natural lighting and ventilation, reducing the reliance on artificial lighting and air conditioning. As Lin Fenglan mentioned, the orientation of the building should be comprehensively considered in terms of sunlight and ventilation, etc., to achieve energy conservation [4].

The design of the building's shape is also crucial. Complex shapes or large areas of glass curtain walls will increase the building's surface area, increasing the energy consumption for cooling in summer and heating in winter. The internal functional zoning and the distribution of personnel density in the building are also closely related to energy consumption. Office areas have high demands for electricity and air conditioning during the day on working days, while residential areas have concentrated electricity and water consumption in the morning and evening. Areas with high personnel density have relatively high energy consumption intensity due to frequent activities and concentrated use of equipment.

2.2. Basic Principles and Objectives of Energy Conservation Design for High-rise Buildings

2.2.1 Basic Principles

To achieve the energy conservation goals of high-rise buildings, the following principles and methods should be followed:

(1) Prioritize Passive Energy Conservation

Make full use of natural environmental energy resources and achieve energy conservation through the building's design and structure. For example, optimize the building's shape coefficient to make it more compact and reduce the heat dissipation area of the facade; use insulating wall materials and energy-efficient windows to reduce heat transfer; rationally arrange building openings, utilize wind pressure and thermal pressure for ventilation, and introduce natural light through light wells to reduce the power consumption of artificial lighting.

(2) Optimize Active Energy Conservation

Pay attention to the selection of high-efficiency energy-saving products and optimize the configuration of active energy equipment systems. In air conditioning systems, use energy-efficient refrigeration units, high-efficiency heat exchangers, and intelligent control systems, and adjust the operation mode and parameters based on indoor and outdoor environmental parameters to improve the efficiency of cooling and heating. In lighting systems, use energy-saving lamps such as LED lamps combined with intelligent control systems to automatically adjust the brightness according to lighting needs and human activities to achieve energy conservation.

(3) Comprehensive Energy Utilization

Encourage the comprehensive development and utilization of various energy forms. High-rise buildings can be combined with solar photovoltaic power generation systems to convert solar energy into electricity to meet part of the power demand; utilize ground source heat pump technology to utilize shallow underground geothermal resources for heating and cooling, enhancing the stability and efficiency of energy utilization; recover the residual heat and pressure within the building, such as using the heat from air conditioning condensers to preheat domestic hot water, achieving energy cascade utilization and improving the comprehensive utilization efficiency.

2.2.2 Quantitative Objectives

Under the premise of ensuring building functions and comfort, energy conservation design for high-rise buildings has clear quantitative objectives. Regarding power consumption, the efficiency of the selected small and medium-sized motors, whether in the rated output power state or at 75% of the rated output power state, must not be lower than the energy efficiency limit values stipulated in the current national standards. In terms of water consumption, except in areas with scarce solar resources, for residential buildings of 12 floors or less, solar water heating systems should be installed, and the number of households using such systems should account for more than 80% of the total number of households. If a centralized solar water heating system is used to preheat domestic hot water, the heat provided by the solar water heating system should account for more than 40% of the hot water energy consumption. Regarding heat consumption, living spaces should have conditions for natural ventilation. In hot summer and warm winter regions and hot summer and cold winter regions, the ventilation opening area should not be less than 8% of the floor area of the room, while in other regions, it should not be less than 5%.

3. Energy-saving Design and Technical Measures for High-Rise Buildings Based on BIM Technology

3.1. Framework of Energy-saving Design Process for High-Rise Buildings Based on BIM Technology

In the process of building construction, BIM technology encompasses the stages of early project planning, conceptual design, scheme design, and detailed design. During the early planning stage, BIM is employed to collect and analyze climatic and environmental data. Through models, the sunlight exposure and wind direction of the site are understood, and the impact on energy consumption is evaluated to determine the energy-efficient orientation and layout planning of the building. In the conceptual design stage, in combination with the BIM model, the building shape and energy consumption characteristics are analyzed, and the functional zoning is defined. In the scheme design stage, the details of the structure and functional zoning are optimized, and the design parameters are adjusted based on the energy consumption simulation data to enhance the overall energy-saving performance. In the detailed design stage, the information and parameters of the energy system equipment are inputted into the comprehensive BIM model. Simulation analysis is carried out to achieve optimal configuration. Equipment models are added to simulate the operation and analyze the energy consumption, followed by optimizing the selection and layout to ensure the efficient operation of the energy system. The description of the functions of the Ecotect Analysis software by Wang Wentao and Zhao Jikun is consistent. This software can provide multi-faceted simulation analysis support for building energy-saving designs. Simultaneously, the software can generate visual analysis diagrams, significantly improving the readability of the simulation analysis results and providing strong support for subsequent research [5].

3.2. Application Analysis of Energy-saving Design for the Case Based on BIM Technology

3.2.1 Site Environment and Solar Radiation Analysis and Optimization of Building Layout

For the selected building, a BIM finite element model is constructed to profoundly explore the intrinsic relationship between architectural design parameters and building energy consumption, and to analyze various factors influencing building energy consumption. The three-dimensional modeling design interface it offers can conduct simulation analyses on multiple aspects of the building, such as solar radiation, daylighting, sunlight exposure, shading, and thermal performance, comprehensively covering seven key domains of the building's physical environment: thermal environment, wind environment, light environment, sound environment, economic efficiency of sunlight exposure, environmental impact, and visibility. Concurrently, the software can generate visual analysis diagrams, significantly enhancing the readability of the simulation analysis results and providing robust support for subsequent research.

3.2.2 Energy System Design and Simulation Analysis

In the early stage of the energy system design based on the BIM model, the energy supply scheme needs to be determined following the specific functional requirements and energy consumption characteristics of the building. Subsequently, the detailed information on various energy equipment, including equipment model specifications, power magnitude, and operational efficiency, is precisely inputted into the BIM model, laying a solid data foundation for subsequent simulation analysis. Next, professional energy simulation software is integrated with the BIM model. Through this integration, the actual operational status of the energy system under different operational strategies can be precisely simulated. During this process, the software can fully utilize the detailed equipment information in the BIM model to simulate the operational performance of the energy system under different strategies. Through the aforementioned simulation analysis and optimization measures, the operational effect of the energy system has been improved. By adjusting the operational strategy of the equipment, the building's energy consumption has been significantly reduced, effectively achieving the building's energy-saving goals and significantly reducing the operating costs throughout the building's life cycle, thereby enhancing the economic and environmental benefits of the building.

4. Application Analysis of Energy-saving Design in the Case Based on BIM Technology

4.1. Overview of the Building

The research case selected in this paper is located at the northeast corner of Shaolin Avenue and Fuyuan 2nd Road in Shaolin Community, the Third Community, Building 9, Shaolin Sub-district Office, Dengfeng City. The BIM model is shown in Figure 1. Dengfeng City, a prefecture-level city in Henan Province, is located in the central part of China and has considerable reference value for project analysis. The project site is surrounded by relatively rich resources and has certain development potential. It is located in a convenient transportation area of Dengfeng City, close to important urban traffic nodes, making travel convenient. The surrounding facilities are relatively complete, with small commercial facilities to meet the daily shopping needs of residents, a kindergarten, and a community health service station providing basic medical services. The internal greenery of the community is of a certain scale, but the greenery design and plant species are relatively simple. In terms of transportation, there are bus routes nearby, and it is close to a subway station. The internal roads of the community can meet the daily travel needs of residents, with sufficient parking spaces and fire lanes. The roads are wide and in good condition. Such a regional environment provides many conveniences for the use of the building and the lives of residents.

The overall situation of the case project is as follows: The total construction area of the project is 14,949.42 square meters, including 12,955.17 square meters above ground and 1,994.25 square meters underground (basement area), with a base area of 1,363.08 square meters. In terms of scale indicators, the project grade is level two, the building category is residential, the design reasonable service life is 50 years, the building fire classification is class two residential building, the number of households is 78, the number of floors is 13 above ground and 2 underground, the fire resistance rating is level two above ground and level one underground, the seismic fortification intensity is 7 degrees, the structural seismic grade is level three, the residential floor height is 3.0 meters, the basement floor height is 3.00 meters, the roof waterproofing grade is grade II, the basement waterproofing grade is grade II, and the building height is 39.30 meters.

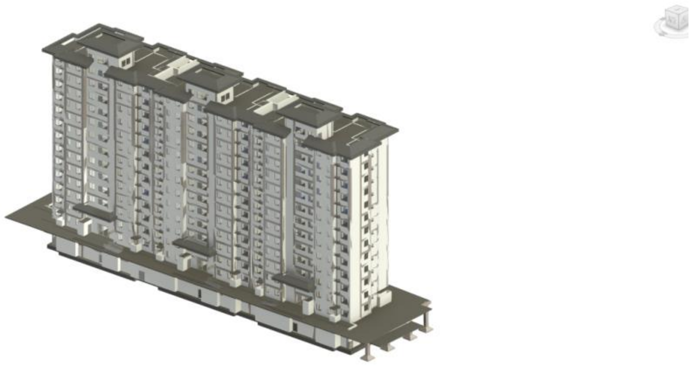

Fig. 1 Building No. 9, Third Community, Shaolin Community, Shaolin Sub-district Office, Dengfeng City

4.2. Application Practice of Energy-saving Design for a High-rise Office Building Based on BIM Technology

4.2.1 Application of BIM Technology in Daylight Simulation

When conducting energy-saving design for green buildings, natural light from the outside can be introduced into the interior through reasonable design strategies, which not only reduces energy consumption but also creates a better visual experience.

The scientific utilization of natural light plays a crucial role in the early stage of project preparation, where BIM technology is key. It can simulate the lighting conditions inside the building and precisely analyze whether the lighting in each room is balanced. Through the software, the incident angle and intensity changes of sunlight in rooms facing different directions at different times of the day can be simulated, visually presenting situations such as insufficient or excessive lighting in certain rooms due to architectural layout, such as internal partitions, corridor settings, or surrounding obstructions. Based on these simulation results, designers can adjust the size, position, and orientation of windows in the subsequent design process, optimize the building's spatial layout, and add auxiliary lighting facilities such as reflectors and light wells, providing important reference value for subsequent design and adjustments, and effectively ensuring the scientific and efficient utilization of natural light inside the building.

Fig. 2 Daylight Analysis of the Project Interior

With its potent simulation functionality, BIM technology can precisely and elaborately represent the lighting conditions of rooms on diverse floors and with different orientations. Rooms close to the building's edge, benefiting from broad vistas and fewer obstructions, typically enjoy superior lighting conditions; conversely, rooms in the middle of the building, due to the enclosure of surrounding structures, often have less satisfactory lighting effects. It facilitates designers to ingeniously conceive scientifically rational lighting design blueprints, such as judiciously laying out light wells by local circumstances or deliberately choosing the optimal size and position of windows. The case in this paper further conducts an in-depth analysis of the improvement effects of lighting on each floor and orientation. Please refer to Table 1 for details. From the table, it can be concluded that BIM technology can accurately locate lighting issues and formulate targeted measures. It contributes to attaining green building goals and highlights the value of BIM technology.

Table 1. Comparative Table of Building Daylighting Analysis Before and After the Application of BIM Technology

Floor	Orientation	Lighting Condition (Before Simulation)	Lighting Condition (After Simulation)	Improvement Measures and Effects
Low floors (1 - 3)	East-facing	Some rooms are blocked by surrounding buildings, resulting in insufficient lighting.	By reasonably setting up light wells to increase the lighting area, the lighting has been improved.	The light well design effectively increases the lighting rate of east-facing rooms on low floors, reduces the use time of artificial lighting, and is expected to reduce power consumption by about 15%.
Middle floors (4 - 8)	South-facing	Overall lighting is good, but there is uneven light distribution in some rooms.	Adjust the size and position of windows and optimize the indoor space layout to make the light distribution more uniform.	The optimization measures improve the light uniformity of south-facing rooms on middle floors, enhance indoor comfort, and at the same time reduce the additional lighting energy consumption caused by local over-brightness or over-darkness, with an expected energy saving of 29%.

High floors (9 - 13)	West-facing	Direct sunlight in the afternoon, with excessive lighting, causing the indoor temperature to rise.	Install shading facilities such as sunshade blinds and adjust the shading angle based on lighting analysis.	The shading facilities effectively block the excessive sunlight, reduce the indoor temperature, decrease the air conditioning cooling energy consumption, and at the same time ensure appropriate indoor lighting, with an expected comprehensive energy saving of 33%.

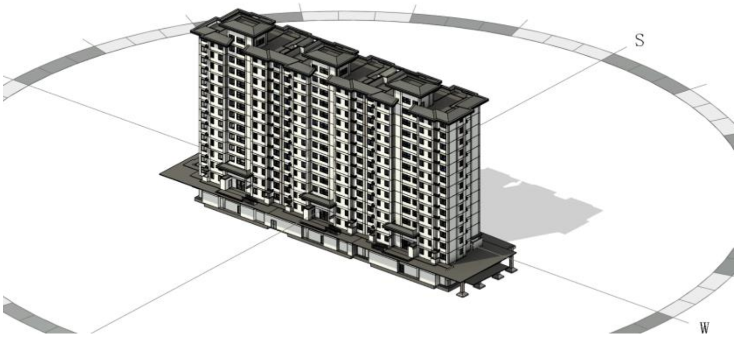

Fig. 3 Outdoor solar radiation analysis of the project

4.2.2 Application of BIM Technology in Thermal Analysis and Solar Radiation Analysis

The exterior wall envelope is of vital significance for building energy conservation. In local architectural designs, exploring energy-saving strategies with BIM technology holds considerable importance. At the outset of the design, it is requisite to take into account standard elements such as local heating and cooling loads, analyze the indoor thermal environment, encompassing heat sources and latent heat, comprehensively assess the heat variations of the envelope and air circulation, weigh the heat balance to determine the design direction and ensure the compliance of temperature data. BIM simulations reveal that in the absence of cooling or heating, a lower indoor temperature in summer and a higher indoor temperature in winter indicate superior insulation of the exterior walls. In extreme temperatures, it is crucial to enhance insulation and heat insulation and analyze the materials. When the insulation is inadequate in high summer temperatures, the influence of temperature synergy should be considered and addressed under regulations. Regarding the application of BIM in solar radiation analysis, its supporting software can simulate the radiation of the building façade, assisting designers in adjusting the shape, orientation, and windows and doors. In combination with energy consumption software, it can predict energy consumption based on radiation, providing a foundation for energy-saving designs. Table 2, as a key data carrier, demonstrates significant disparities in the efficacy of traditional and BIM-optimized designs: optimizing the thermal performance of the envelope and shading measures reduces the operating duration of air conditioners; traditional designs do not consider the utilization of solar energy, with a collection efficiency of 0. After determining the installation parameters based on BIM technology and radiation analysis, the collection efficiency reaches 15%, signifying that the rational planning of solar equipment installation has enhanced the collection efficiency of solar energy, which can supply power to some low-power facilities in the building, reduce power consumption from the grid, and achieve approximately 25% self-sufficiency in energy.

Table 2 Comparison Table Before and After Using BIM Technology for Building Thermal Performance and Solar Radiation Analysis

Analysis Items	Traditional Design (Without BIM Technology)	Optimization Based on BIM Technology	Description of Changes	Energy-saving Effect Evaluation
Exterior Wall Heat Transfer Coefficient [W/(m² · K)]	1.5	1.2 (Optimized Value)	By adjusting the materials and structure of the building envelope, the heat transfer coefficient of the exterior wall is reduced, reducing heat transfer.	Heating energy consumption in winter is expected to be reduced by about 25%, and cooling energy consumption in summer is expected to be reduced by about 20%.
Indoor Temperature Stability (During High-temperature Days in Summer)	Indoor temperature fluctuates greatly, with the maximum temperature reaching 32℃.	Indoor temperature fluctuations are reduced, and the maximum temperature is controlled at around 28℃.	Optimizing the thermal performance of the building envelope and shading measures improves indoor temperature stability.	Reduces the operating duration of air conditioning cooling equipment, saving about 18% in energy.
Solar Energy Collection Efficiency (Calculated per Unit Area)	Solar energy utilization was not considered, with a collection efficiency of 0.	After determining the installation parameters based on radiation analysis, the collection efficiency reaches 15%.	Reasonably planning the installation of solar energy equipment improves solar energy collection efficiency.	Can supply power to some low-power facilities in the building, reducing power consumption from the power grid and achieving about 25% energy self-sufficiency.

4.3. Energy-Saving Optimization Process Based on BIM Technology

In the early project stage, BIM technology is employed to simulate the interior lighting of the building. The lighting conditions of rooms on different floors and with various orientations are analyzed, such as the potential insufficient lighting in east-facing rooms on lower floors, uneven lighting in south-facing rooms on middle floors, and excessive lighting in west-facing rooms on upper floors. Based on the findings, designers make targeted adjustments to windows or incorporate additional lighting assistance facilities to enhance the scientificity of lighting and reduce lighting energy consumption.

During the design phase, factors such as local heat and cold loads are taken into consideration to analyze the indoor thermal environment. The direction is determined by comprehensively assessing the heat variations of the building envelope and air circulation to ensure compliance with temperature data. BIM is utilized to simulate the insulation of exterior walls. When there is no cooling or heating, the insulation performance is judged based on the indoor temperature, insulation is enhanced and materials are analyzed under extreme temperatures. BIM software simulates the radiation of the building façade, facilitating adjustments to the shape, orientation, and windows and doors. Combined with energy consumption software, energy consumption is predicted based on radiation. Simultaneously, the installation of solar energy equipment is optimized based on the radiation intensity and duration to improve collection efficiency and supply power to low-power facilities, reducing reliance on the power grid and achieving energy self-sufficiency, thereby comprehensively achieving energy conservation in buildings.

5. Disparities and Gaps between Traditional Energy-Saving Analysis and BIM-Based Energy-Saving Analysis

5.1. Integration and Simulation Analysis Capabilities of Design Information

Traditional energy-saving analysis typically relies on simplistic experience and calculation tools, making it challenging to achieve high-precision simulation and comprehensive analysis, particularly in aspects such as lighting, thermal performance, and solar radiation in complex buildings. In contrast, BIM technology, through 3D modeling and data integration, offers more precise analysis tools. For instance, BIM models can comprehensively simulate the lighting conditions of buildings, accurately depicting the incident angles and intensity variations of sunlight in rooms on different floors and with different orientations throughout the day. Simultaneously, it can analyze heat sources and latent heat within the indoor thermal environment, precisely determine the design direction by integrating heat changes in the building envelope and air circulation, and also assess the insulation quality of exterior walls by simulating the indoor temperature without cooling or heating, promptly strengthening insulation and optimizing materials.

Traditional energy-saving analysis has limited means of simulating the physical environment of buildings. Lighting analysis, largely relies on the subjective judgment of designers and simplistic sun exposure charts, making it difficult to accurately simulate the actual lighting conditions of rooms on different floors and with different orientations, and the analysis of lighting issues in complex building layouts is insufficiently accurate. In thermal performance analysis and solar radiation analysis, there is a dearth of high-precision simulation software support, unable to consider in detail the influence of factors such as heat loss in the building envelope, heat loss from air circulation, and the distribution of radiation on the building façade on energy consumption, making it arduous to achieve precise energy-saving design optimization. This is analogous to the issues mentioned by Zhao Lijun et al. regarding BIM models; the sharing of data among different specialties is not seamless, affecting collaborative design; energy-saving design standards and norms are insufficiently detailed, making it difficult to objectively evaluate the application effect of BIM [6,7]. BIM technology provides potent simulation and analysis functions. Its 3D modeling design interface can conduct comprehensive and in-depth simulation and analysis of various aspects of buildings such as solar radiation, lighting, sun exposure, shading, and thermal performance, encompassing seven key domains of the building's physical environment including the thermal environment, wind environment, light environment, sound environment, economic benefits of sun exposure, environmental impact, and visibility, and can generate visual analysis diagrams, providing detailed and accurate data support for designers, thereby more precisely uncovering energy-saving potential.

5.2. Efficiency of Optimization and Adjustment

The adjustment process in traditional energy-saving design after identifying problems is rather cumbersome. Once energy consumption issues such as inadequate lighting or suboptimal thermal performance are detected after the completion of the building design, modifying the design often entails redrawing the blueprints and recalculating relevant parameters, involving repeated communication and coordination among multiple specialties, which is time-consuming and prone to omissions. BIM technology possesses highly efficient optimization and adjustment capabilities. Based on the simulation analysis results of the BIM model, designers can expeditiously optimize and adjust the building layout, envelope structure, energy system, etc. For example, they can adjust the size and position of windows and optimize the operation strategy of the air conditioning system. Through the BIM model, the effects of the adjustments can be visually perceived, and the energy-saving benefits can be evaluated promptly, significantly augmenting the efficiency of optimization and adjustment and ensuring that the energy-saving design of buildings can rapidly attain the anticipated goals.

6. Conclusion

This study demonstrates that BIM technology plays a pivotal role in each stage of the energy-saving design process of high-rise buildings, effectively integrating information, enhancing the scientific nature of the design, and precisely controlling energy consumption. Taking a certain high-rise office building in Dengfeng City as an example, significant energy savings were achieved through BIM optimization of the building layout and energy system. Nevertheless, there are also challenges in its application, such as the limited simulation accuracy of BIM software, insufficient technical support for new energy-saving materials, poor data sharing among different specialties, which impedes collaborative design, and the lack of detailed energy-saving design standards and norms, making it difficult to objectively assess the application effect of BIM. On this basis, it is imperative to explore effective approaches for integrating building energy conservation with technological innovation, striving to provide a referential example and reliable technical support for addressing energy challenges.

The potential for the integration of BIM technology with emerging technologies is substantial. The construction industry needs to take proactive actions to tap into its potential in the energy-saving design of high-rise buildings and achieve sustainable development of buildings. In the future, it should leverage technological integration to optimize design, enhance the utilization efficiency of renewable energy, increase investment, and refine related elements, promoting the harmonious coexistence of buildings and the environment.

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