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Article

Research on the Analysis of Thermal Environment and Lighting Balance Efficiency of Green Buildings Based on Optimization Calculation Methods

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Abstract: In the context of growing concerns over global warming and environmental pollution, the construction industry is facing unprecedented energy conservation burdens and environmental pressures. This paper aims to address issues related to indoor thermal environment and daylighting balance in green buildings. By employing optimization algorithms to calculate and design systems, the paper seeks to optimize building performance and explore new strategies for energy balance and daylighting balance in green building design. Using a non-dominant sorting genetic algorithm and parametric design software, an evaluation model for indoor environmental comfort in green building design is constructed, and the effectiveness of the optimized design strategy is validated. This research method begins with an application study of green technology innovations on building energy conservation and emissions reduction effects, based on actual surveys and field data collection. Not only did the optimized design control building energy consumption and indoor thermal environmental comfort, resulting in a 19.5% improvement in energy-saving indicators per unit building area and thermal comfort satisfaction in green buildings (from 70% to 85%), but it also made valuable contributions to filling gaps in the field of green building research, providing useful references and bases for the practical application of green buildings. The study demonstrates the significant potential of green buildings for energy conservation, emissions reduction, and protection of the Earth's environment.

Keywords: green buildings; thermal environment; daylighting balance; optimization calculation; parametric design

1. Introduction

1.1. Research Background and Research Approach

As China's “dual carbon” strategy continues to be implemented and the global energy crisis worsens, the task of reducing emissions in the construction industry has become increasingly challenging [1-2]. Due to the fact that architectural design places greater emphasis on the expression of building functionality and form, there is a lack of precise control over ecological performance such as thermal environment and natural lighting, resulting in high energy consumption during building operation and poor comfort levels. Green building design, which emphasizes efficient resource utilization and ecological friendliness, is increasingly becoming a key factor in achieving sustainable urban development [3-4]. Among the constituent elements of green buildings, thermal environment and daylighting performance exhibit significant coordination and are one of the key factors influencing building operational energy efficiency and occupant comfort [5]. However, these two elements often conflict during the building process; for example, enhancing daylighting can lead to increased indoor thermal loads. Therefore, how to address the increasingly conflicting and complex constraints among various building elements and achieve the optimal solution for their comprehensive performance has become one of the solutions of interest to current architects. The incorporation of optimization calculations is an effective method for resolving such multi-objective conflicts. By employing optimization calculations to establish mathematical models and utilizing intelligent algorithms for efficient iterative solutions, architects can make more scientifically sound adjustments to design variables and perform performance estimations from the outset of the design process, thereby driving the evolution of green buildings from “experience-based design” to “intelligent decision-making” [6].

This paper aims to optimize thermal environment and daylighting balance in green buildings by constructing an analytical design model based on optimization calculation methods. First, typical building energy consumption and daylighting data are obtained through surveys and simulations, and influencing indicators are identified. A dual-objective optimization model is then constructed with the objectives of minimizing energy consumption and maximizing natural daylighting, and the Non-Dominated Sorting Genetic Algorithm (NSGA-II) is used for solution. A parametric tool is developed to enable efficient scheme generation and performance evaluation, and EnergyPlus and Radiance software are utilized for integrated thermal and lighting environment simulation. The model's effectiveness is validated through case studies, providing reliable technical basis and practical solutions for green building design.

1.2. Significance of Green Building Research

Green buildings serve as a prime example of the greening and sustainability of modern architecture. The importance of optimizing their design extends beyond energy efficiency in architectural design; it directly impacts the improvement of people's health and comfort. Both architectural planners and government officials are now well aware of the numerous shortcomings in the current state of building industrialization. For example, issues such as high energy consumption and poor indoor environmental quality can largely be attributed to insufficient experience and outdated methods in architectural planning and design, as well as a lack of scientific, reasonable, and quantitative parameter support. This results in final design decisions being made solely based on experience, making it difficult to find the optimal solution under complex constraints (multi-objective problems), especially when faced with continuously increasing building energy efficiency standards. Therefore, to achieve green and sustainable development in construction and reduce the negative impact of human experience or intuition on design decisions, this paper adopts an optimization design concept based on thermal environment and daylighting balance efficiency, utilizing optimization computational technology. By fully leveraging the advantages of mathematical modeling and optimization algorithms to adjust design parameters, this approach ensures that indoor comfort meets safety and practical requirements while maximizing the sustainable development benefits of buildings.

The optimization design method proposed in this paper theoretically enriches the design theory of green buildings, particularly the integration of multi-objective optimization methods with parametric design software. This opens a new research direction for green building researchers, provides them with a reference model, and objectively advances the trend toward quantitative target optimization in green building design. The research findings of this paper establish corresponding mathematical models for building performance optimization, driving the progression of architectural design methods from intuitive to quantitative approaches, ultimately guiding design decisions toward more scientific directions. The optimization design method proposed in this paper is also highly practical. By studying and mastering the optimization design method, architects can predict the performance of buildings under various design schemes during the early stages of design and construction. Based on comprehensive evaluations, they can select more rational solutions, further improving design efficiency, ensuring the excellent environmental performance and reasonable economic viability of buildings throughout their lifecycle, and achieving the large-scale popularization of green buildings.

2. Review of Research on the Analysis of Thermal Environment and Daylighting Balance Efficiency in Green Buildings

2.1. Theoretical Basis of the Study

Building energy consumption, thermal environment, and other evaluation indicators for green buildings are the three most important and fundamental aspects of green building design. Based on research into building energy consumption, heating, cooling, lighting, and equipment operation account for the majority of a building's energy consumption throughout its entire lifecycle. Reducing building energy consumption not only lowers operational costs but, more importantly, reduces greenhouse gas emissions. The quality of a building's light environment directly impacts human physiological and psychological health, and the optimization of natural lighting design is a critical consideration for residential buildings. According to research and experimental results, window size, building orientation, and window area all influence indoor daylight levels. Reasonably calculating the window-to-wall ratio can ensure adequate indoor lighting levels while minimizing the need for artificial lighting systems. The thermal environment of a building encompasses aspects such as building envelope structures, natural ventilation, and passive heating technologies. These factors influence both building energy consumption and occupant comfort. According to data analysis, there is a high correlation between building energy consumption and thermal environment dissatisfaction, but a low correlation with effective natural daylighting levels.

Multi-objective optimization techniques based on non-dominant sorting genetic algorithms can effectively address the balance between building energy efficiency performance and indoor/outdoor light and thermal environment evaluation. Through population sorting and crowding degree calculations, numerous design schemes can be screened to derive one or more Pareto optimal solutions [7-8]. This provides scientific reference standards for overall building performance optimization and offers additional data support for optimized design. Energy prediction technology and optimization algorithms have good adaptability, providing long-term, continuous predictive data support for different designs during the optimization process. Currently, the Grasshopper plugin and Ladybug environmental analysis tools are widely used in parametric design, enabling complex geometric modeling through visual programming while simulating building energy performance [9-10].

In recent years, as building costs, energy consumption, and carbon emissions have continued to rise, the importance of building performance simulation, prediction, and optimization design in building energy conservation has become increasingly evident. Wang et al. [11] proposed a multi-objective genetic optimization algorithm model to assist designers in green building waste reduction optimization design. Case studies demonstrated the effectiveness of this method in identifying some Pareto optimal solutions for green building design. Liu, F et al. [12] set multiple objective functions based on two dimensions: building lifecycle carbon emissions and green building evaluation. They used the NSGA-II algorithm to optimize several indicators within the objectives, obtaining the Pareto solution set of optimal parameter combinations, thereby achieving optimized design for green building carbon reduction. Biyanto et al. [13] employed the binary algorithm, whale algorithm, and rain algorithm to optimize the selection of building glass types and roofs. The optimization results indicated that using 3.2mm-thick Planibel-G glass with a glass wool insulation layer achieves a maximum return on investment of 36.85%, a reduction in EUI of 54 kWh/m^2•year, carbon dioxide emissions reduction of 486.90 tons/year, and a cost reduction of 407,890,546 IDR. Hai et al. [14] employed an improved swarm optimization algorithm to optimize the most suitable building renovation scheme, aiming to reduce the use of non-renewable energy in buildings and achieve zero-energy buildings. The results indicated that the optimized scheme can save 761.6 MWh of electricity under a 70-month payback period and EPC pricing model. Lu et al. [15] proposed an improved particle swarm optimization algorithm to optimize renewable energy schemes for green buildings, comparing the results of energy system optimization designs based on different reliability levels. The results showed that the proposed method improved convergence speed by 15% and convergence effectiveness by 0.45%, effectively addressing reliability issues in energy system design. Liu, Z et al. [16] proposed a multi-objective energy-saving optimization algorithm to enhance the energy efficiency of green buildings. By scoring the environmental friendliness and environmental impact factors of candidate green building materials, they demonstrated the effectiveness of their algorithm in green energy-saving optimization. Yang et al. [17] investigated the feasibility of a multi-objective optimization model for building envelopes, using the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) to balance the design of building envelope structure cost (ENVCOST), minimize envelope structure energy performance (ENVLOAD), and maximize window opening rate (WOPR). The results showed that while achieving low ENVLOAD and high WOPR, a higher ENVCOST is required; however, the design cost based on the optimization algorithm is lower than that of the original manual design.

However, research on thermal environment and building daylighting optimization is relatively scarce. Harun et al. [18] proposed a single-objective genetic algorithm for decision support systems and inverse optimization in BIM-designed green buildings, successfully identifying the optimal material combination, which reduced the building's total thermal conductivity value by 16%, designing a green building compliant with national green building evaluation standards. Ruggiero et al. [19] employed a multi-objective optimization model based on genetic algorithms to optimize building materials and different configurations of light frames, verifying the balanced effect of genetic algorithms on building daylighting performance through Revit's illuminance rendering.

Building performance is influenced by multiple factors, yet existing building simulation and prediction technologies are insufficient to meet the demands for building performance assessment and analysis. Numerous factors must be considered in building performance design [20-21]. Balancing various optimization objectives to achieve optimal building energy-saving design remains a complex challenge. Therefore, multi-objective optimization of thermal environment and daylighting balance in green buildings still faces numerous issues and challenges.

2.2. Innovative aspects of this study

This study investigates an optimization design method for the thermal environment and daylighting balance efficiency of green buildings, based on a research methodology and philosophy that abandons the previous reliance on architects' subjective experience. Creatively transforming the complex relationships between design variables in the architectural design process—such as nonlinearity and discontinuity—into a mathematically expressible form for computational analysis, this study establishes a comprehensive workflow and methodology by integrating a non-dominated sorting genetic algorithm with the Grasshopper parametric platform. This mathematically formalized design and optimization logic fundamentally addresses the shortcomings of traditional methods, offering new approaches to tackling issues such as the nonlinearity and discontinuity of design variables. The algorithm's optimization objective function can be expressed as:

$$F(x)=\begin{cases} f_1(x)=\min(E_{heating}+E_{cooling}+E_{lighting}) \\ f_2(x)=\max(UDI_{useful}) \\ f_3(x)=\min(PMV_{deviation}) \end{cases} \quad (1)$$

The theoretical innovation capability of this paper, which verifies theory through practice, is achieved through a systematic empirical validation process. By combining field research and questionnaire surveys conducted in practice, the optimized architectural design approach yields favorable energy consumption outcomes. This optimization method integrates the design stages from conceptual design, schematic design, to construction drawing design. By mapping the quantitative relationships between design elements and performance indicators across these stages, it provides designers with specific parametric adjustment information. This research, which bridges theory and application, addresses existing gaps in theoretical research and offers concrete operational pathways for practical engineering applications.

3. Research Methods for Analyzing the Thermal Environment and Daylighting Balance Efficiency of Green Buildings

3.1. Simulation and Optimization

Optimizing building energy consumption and other performance indicators is a multi-objective balancing problem. This paper uses professional software EnergyPlus and Radiance to integrate and solve building performance issues. EnergyPlus uses a thermal balance algorithm to calculate building energy consumption dynamically throughout the year, while Radiance uses a reverse ray tracing algorithm to calculate and analyze indoor natural light illumination. Therefore, the objective function established in this paper is to minimize total building energy consumption and maximize natural illumination. The optimization objective function is:

$$D(x)=\min(E_{total},\max(D_{natural})) \quad (2)$$

In the formula, E_{total} represents the total energy consumption of the building, and $D_{natural}$ represents the degree of natural lighting.

In multi-objective optimization, the non-dominated sorting genetic algorithm is used as the optimization algorithm. This algorithm uses an elite retention and crowding degree calculation retention mechanism to prevent it from falling into local extrema. By writing an automatic script, the optimization software and the algorithm are linked together. The main design parameters and design ranges of the optimization design are shown in Table 1.

Table 1. Design parameter optimization range.

Design parameters	Min value	Max value	Step length
Window-to-wall ratio (%)	20	60.0	5.0
Floor height (m)	3.0	4.5	0.3
Shading Angle (°)	0.0	60.0	5.0
Visible light transmittance of glass	0.4	0.8	0.1

Heat transfer coefficient of exterior wall (W/m^2·K)	0.3	0.8	0.1

When optimizing the solution, the population size was set to 200, the number of evolutionary generations to 100, and the crossover probability and mutation probability to 0.9 and 0.1, respectively, enabling the algorithm to converge more quickly to the Pareto optimal solution set. In this study, we conducted a detailed analysis of the nonlinear influence relationships among building performance indicators. For example, increasing the window-to-wall ratio is beneficial for improving indoor natural lighting levels, but it also increases the building's own heat loss and adds to the building's air conditioning cooling load. Through the analysis of these nonlinear influence relationships, a set of non-dominated solutions was obtained. The Pareto optimal frontier corresponding to these solutions provides the direction for selecting building design schemes. In practice, it has been proven that in actual project applications, building design schemes with suitable thermal environments or daylighting can be selected from the non-dominated solutions based on specific requirements.

3.2. Field Research and Data Collection

The validation of building performance assessment indicators still requires on-site inspections. We studied continuous monitoring data from three typical office buildings in North China and maintained it for six months (control area 1—Shenzhen Overseas Chinese Town Creative Cultural Park, control area 2—Changsha Xingsha Century Park, control area 3—Xi'an Software New City Innovation Building). These three buildings differ significantly in design philosophy, construction year, and the level of technological equipment adoption. Indoor thermal environment, building lighting, and energy consumption data were obtained through fixed-point and corridor measurements. Indoor temperature, humidity, and air velocity data were continuously collected and tracked in real-time using building data acquisition units distributed in a grid pattern. Indoor lighting conditions were tracked using illuminance and brightness data, including monitoring of illuminance levels on various work surfaces, glare index tracking, and assessment of indoor and outdoor lighting quality. Building energy consumption data was categorized into heating, air conditioning, lighting, and equipment-related energy consumption. Additionally, a questionnaire survey was conducted among building occupants, with 200 questionnaires distributed and approximately 180 returned, enabling the collection of subjective evaluations of building performance from indoor users. The correlation analysis of building performance indicators is shown in Table 2. There is a significant linear correlation between indoor air conditioning energy consumption and the percentage of dissatisfaction with air conditioning comfort (r = 0.78). However, there is no significant correlation between indoor air conditioning energy consumption and the effective natural daylight illuminance indoors and outdoors (r = 0.32). This provides a reference for allocating weights among multiple objectives during multi-objective optimization.

Table 2. Correlation analysis of Building Performance indicators.

Performance index	Energy-saving potential (%)	Influence on photothermal performance	r
Optimization of natural lighting	15~25	Significant improvement	0.32
Utilization of natural ventilation	20~30	Basically unchanged	0.45
Thermal environment control	25~35	Significant improvement	0.78
Comprehensive optimization strategy	35~45	Collaborative improvement	0.85

The performance results of buildings of different sizes are shown in Table 3. As can be seen from Table 3, there are significant differences in the performance results of buildings of different sizes. Small-scale buildings (with an area of 5,000 m^2 or less) have the best annual energy consumption per unit building area, at 145.2 kWh/m^2, with a daylighting area ratio of 82.5%. Large-scale buildings (with an area of 15,000 m^2 or more) have an annual energy consumption per unit building area of 167.4 kWh/m^2, with a daylighting area ratio of 65.8%. Through comparison, it can be seen that natural daylighting and natural ventilation can indeed achieve significant energy-saving effects without compromising indoor light and thermal comfort, thereby validating the hypothesis of performance synergy optimization.

Table 3. Performance comparison of buildings of different volumes.

Building volume type	Annual energy	Proportion of areas	Thermal comfort

	consumption per unit area (kWh/m²)	meeting lighting standards (%)	satisfaction (%)
Small volume	145.2	82.5	89.2
Medium volume	158.7	71.3	76.8
Large volume	167.4	65.8	68.5
Optimized average	152.1	78.9	83.7

The first-hand data obtained through on-site research not only provides evidence for the correctness of the theoretical model, but also proves that there is considerable room for optimization between the optimization of reasonable building performance and practice. The optimization model constructed as a result has high predictive accuracy and operability. The relevant raw data obtained from the research can be used as a reference for the next round of algorithm refinement and parameter adjustment, and also accumulates a wealth of practical cases for green building design.

3.3. Parametric Design

Parametric design software serves as a tool for optimizing thermal environment and daylighting performance in green building design. Its core functionality lies in establishing a dynamic relationship between design parameters and performance metrics, thereby fundamentally transforming the traditional static design process into a computer-based dynamic design process. This paper employs Grasshopper, a visualization programming software based on Rhino, for complex component modeling and algorithm programming, alongside Bug—a software specifically designed for simulating building environments—to constitute the parametric design framework. In the specific implementation, we use Grasshopper software for parametric design of architectural geometry, setting parameters such as window-to-wall ratio, building orientation, building height, and sunshade tilt angle as variable parameters. We then use the Sun Path Analysis, Wind Environment Analysis, and Thermal Environment Analysis functions of the Grasshopper tool to dynamically analyze the performance parameters of the building design under different parameter conditions. The primary advantage of parametric design is the ability to rapidly analyze multiple parameters, thereby providing a sufficient number of design samples for parameter optimization. The fundamental steps of parametric design involve establishing design expressions between design parameters and performance parameters, and automating the generation of architectural geometric models and the output of analysis results through custom scripts in Grasshopper. When design parameters change, the geometric model is automatically regenerated, and the Ladybug tool calls EnergyPlus and Radiance to perform energy consumption and daylighting performance calculations. The calculation results are visualized and output in Grasshopper. Finally, the calculation process is refined, i.e., first, a coarse-grained mesh is used to roughly eliminate better performance, and then a fine-grained search is conducted in the remaining space to identify even better performance.

Figure 1 shows the parameter sensitivity analysis, where WWR, ORI, FH, SA, GT, and WM represent seven design parameters: window-to-wall ratio, building orientation, floor height, shading angle, glass type, and wall material. The diagram indicates that different design parameters have varying degrees of impact on building performance. The window-to-wall ratio has the most direct impact on natural lighting performance. When the window-to-wall ratio increases from 30% to around 50%, the average indoor illuminance increases by approximately 40%, and the building's energy consumption also increases by 15–20%. Changes in building orientation significantly affect the indoor thermal environment. A south-facing building orientation can receive more solar radiation-induced heat in winter, resulting in increased indoor thermal loads. Shading design significantly influences the balance between daylighting performance and energy-saving requirements. Appropriate shading angles can meet basic daylighting performance requirements while effectively reducing summer cooling energy consumption.

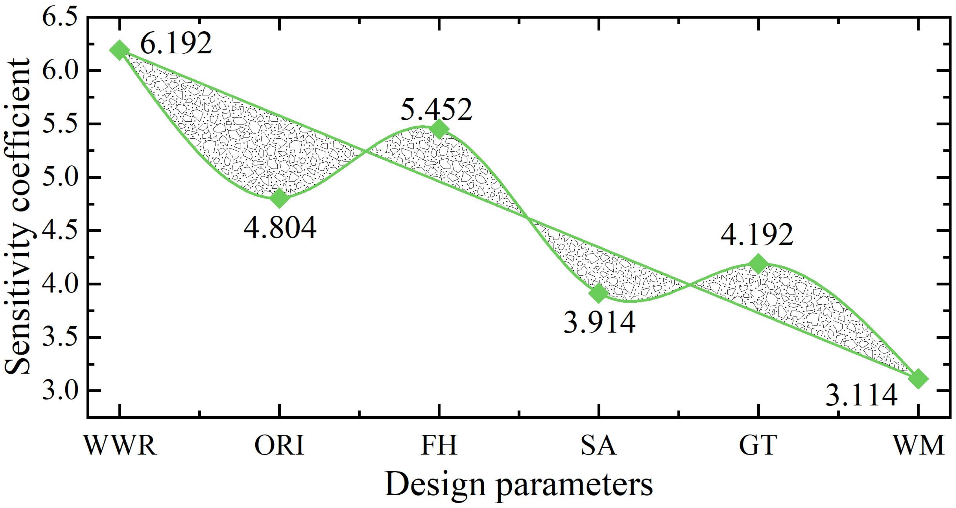

Figure 1. Result of parameter sensitivity analysis.

The effectiveness of parameter optimization design can be verified through repeated iterative parameter solutions, achieved by multiple optimizations of parameter values. Using the parametric design method proposed in this paper, among 200 iterative solution results, it was found that a set of 45 non-dominated solutions could be obtained, forming a Pareto optimal design solution set. These optimal solutions exhibit varying degrees of trade-off between building energy consumption and daylighting quality, providing multiple alternative design options for subsequent decision-making. The introduction of parametric design significantly reduces the time required for the design process. What previously took weeks of scheme comparison and evaluation can now be completed in just a few days, improving design efficiency and facilitating the promotion and application of green building design methods. The standardized parametric design method, design process, and design template library established in this study provide a mature technical foundation for the rapid implementation of similar projects in the future, contributing to the promotion and popularization of green building design methods.

4. Analysis of Thermal Environment and Daylighting Balance Efficiency in Green Buildings

4.1. Design Scheme Performance Analysis

In order to verify the effectiveness of the design feasibility, this paper identifies four green building schemes (A1~A4) that combine thermal environment and lighting conditions of green buildings under different thermal design and natural light conditions, and the performance comparison analysis of different schemes is shown in Table 4. The data in the table show that the thermal performance of the building envelope and the natural lighting design form a complex interaction, and the two work together to affect the overall comfort performance of the building. The natural lighting effect formed by different window-to-wall ratios has obvious improvement of the indoor light environment, and also leads to the increase of building energy consumption. When the window-to-wall ratio is increased from 30% to 60%, the average indoor lighting coefficient increases by 71.4%, and the annual indoor building energy consumption increases by 30.0%. The combination of different window-to-wall ratios, glass material selection, and sunshade device layout has formed a design scheme with significant performance differences, and the corresponding design parameters affect the thermal performance of the building and the ability of the indoor light environment to show certain regularity characteristics.

Table 4. Performance comparison of different design schemes.

Scheme	WWR (%)	Day-lighting coefficient (%)	Annual energy consumption (kWh/m²)	Comprehensive score
A1	30	2.8	142.5	78.6
A2	40	3.5	156.8	82.3
A3	50	4.2	168.4	76.9
A4	60	4.8	185.2	71.5

Figure 2 shows the results of the multivariate regression analysis. As can be seen from the figure, there is a nonlinear relationship between building energy consumption growth and improvements in daylighting performance. After the window-to-wall ratio exceeds the critical threshold of 40%, the marginal improvement in daylighting effectiveness begins to diminish, while energy consumption shows an accelerating upward trend. This phenomenon provides quantitative evidence for determining the optimal window-to-wall ratio for buildings. We recommend that the window-to-wall ratio for office buildings be controlled within the reasonable range of 35–45%, combined with appropriate shading measures to achieve a balanced coordination of light and thermal environments.

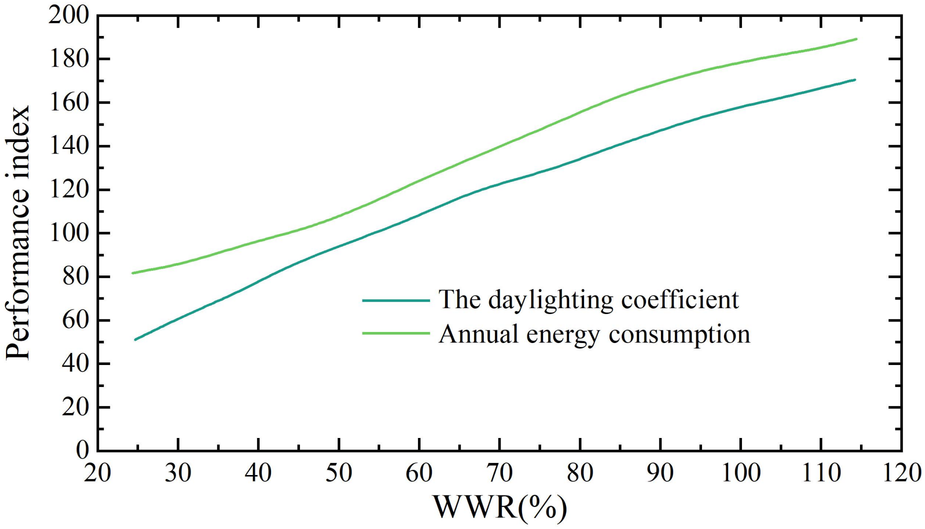

Figure 2. Results of multivariate regression analysis.

4.2. Application effects of optimized design methods

Taking a newly constructed office building in the Beijing-Tianjin-Hebei region as the analysis subject, based on extensive on-site research and data collection, the comparison results of building performance before and after the implementation of the optimization calculation method are shown in Table 5. Through the analysis of various factors, the following main achievements were obtained in building design after adopting the optimization calculation method:

(1) A reduction in annual electricity consumption per unit area of 19.5%, from 180.5 kW•h/(m²) to 145.2 kW•h/(m²).

(2) An increase in the indoor natural daylighting coefficient from 2.5% to 4.0%, representing a 60% increase.

(3) An 85% satisfaction rate among building occupants regarding indoor thermal comfort, representing a 15% increase.

Upon further comparative analysis of building performance before and after optimization, we found that under reasonable window-to-wall ratios, the window-to-wall ratio plays a significant role in controlling natural light and building energy consumption. This suggests the need for optimized design of building facade shading systems in actual design practice.

Table 5. Optimize the comparison of building performance before and after.

Index	Before	After	Change	Remarks
Annual energy consumption per unit area (kWh/m²)	180.5	145.2	-19.5%	Significantly reduced
Natural lighting coefficient (%)	2.5	4.0	+60.0%	Obvious improvement
Thermal comfort satisfaction (%)	70	85	+21.4%	User feedback improvement

Based on accumulated practical application experience, future design processes should actively analyze window-to-wall ratios and shading control settings, while establishing an annual performance testing and feedback system to ensure the effective operational performance of buildings. This optimized design scheme provides a new direction for green building design, and research on strategies for climate zone adaptability optimization will be the focus of subsequent work.

5. Conclusion

This paper proposes the use of an optimization calculation method to develop an optimized design approach for the thermal environment and daylighting balance in green buildings. It integrates the NSGA-II optimization algorithm, EnergyPlus, and Radiance software to achieve coordinated optimization control of building energy consumption and daylighting performance. Optimization results from a typical case study show that the annual energy consumption per unit area of the building decreased from 180.5 kWh/m² to 145.2 kWh/m², the natural daylighting coefficient increased from 2.5% to 4.0%, and the thermal comfort satisfaction rate improved from 70% to 85%. Finally, the paper proposes the optimal technical measures to maintain the window-to-wall ratio between 35% and 45%, combined with a shading system to achieve light-heat balance, providing reference suggestions for the detailed optimization strategies and design guidelines for implementing this method in buildings. The method proposed in this paper will have theoretical guidance value and practical reference value for the development of green building design.

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