A Study on the Indoor Environmental Quality-Driven Synergistic Design Method for Building Carbon and Health Performance

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***Abstract*—Amid the dual pressures on the construction industry to address climate change and safeguard occupant health, enhancing Indoor Environmental Quality (IEQ) often entails higher consumption of building materials and energy, thereby increasing the building's life-cycle carbon emissions and creating a significant trade-off. Existing research predominantly focuses on either energy conservation or health in isolation, lacking a systematic method for synergistically optimizing carbon and health performance during the early design stages. This study aims to fill this gap by proposing an IEQ-driven synergistic design method for building carbon and health performance. The method establishes an early-stage design evaluation framework that combines building performance analysis with multi-scheme comparative assessment to support coordinated decision-making on carbon and health performance. Through a case study of a typical office building, the proposed method was applied by considering key design variables, such as window-to-wall ratio, envelope thermal performance, and ventilation strategy, and by evaluating their impacts on life-cycle carbon performance and indoor environmental quality through a comprehensive assessment framework informed by existing healthy building standards. The results indicate that the method can help identify design schemes with improved health-related indoor environmental performance while maintaining carbon performance within an acceptable range. The case analysis suggests that appropriate combinations of envelope and ventilation parameters may support a better balance between carbon reduction and occupant health needs in early-stage design. This research provides architects and engineers with a practical tool for quantitative decision-making and for balancing building carbon emissions with occupant health needs in the early design stages. It promotes a paradigm shift from "energy-efficient buildings" to "sustainable healthy buildings" and offers significant theoretical and practical guidance for achieving the national goals of "dual carbon" and "Healthy China."**

***Keywords*—Indoor Environmental Quality,Building Carbo n Emissions,Healthy Building,Synergistic Design,Multi-Objecti ve Optimization**

I. Introduction

The building sector is a major contributor to global energy consumption and greenhouse gas emissions. In 2022, the global building sector accounted for more than 34% of energy demand and 37% of energy- and process-related CO_2 emissions [1]. In response to climate change, China has proposed the strategic goals of achieving carbon peaking by 2030 and carbon neutrality by 2060 [2][3]. In this context, the decarbonization of the building sector is of great significance, as building-related carbon emissions account for a substantial proportion of the national total [4]. Accordingly, reducing building life-cycle carbon emissions has become an important pathway toward achieving the “dual carbon” targets [5][6].

At the same time, with the improvement of living standards and growing public awareness of health, especially in the post-pandemic era, Indoor Environmental Quality (IEQ) has attracted increasing attention. Previous studies have shown that people spend most of their time indoors [7], and indoor environmental conditions have direct impacts on occupants’ comfort, health, and performance [8][9]. Recent studies further indicate that IEQ may influence health and productivity in office buildings [10][11]. Poor indoor environments may even lead to Sick Building Syndrome (SBS), thus posing risks to human health and well-being [12][13]. Therefore, providing a high-quality indoor environment has become an essential requirement of contemporary architectural design.

However, in current green building practice, reducing carbon emissions and improving IEQ often involve a trade-off. For example, increasing the fresh air supply can improve indoor air quality, but it may also increase HVAC energy consumption. Likewise, adopting high-performance envelope materials may reduce operational energy use while increasing embodied carbon [5][6]. As a result, the “carbon-health” conflict has become a challenging issue in building design. Existing studies tend to address these two objectives separately: one line of research focuses on energy conservation and carbon reduction, while another focuses on improving IEQ and occupant comfort or health [9][10]. A systematic design method that can coordinate both objectives is still lacking, particularly in the early design stage, when design decisions have the greatest influence on final performance.

Against this backdrop, the central question of this study is how to establish a systematic design method to achieve coordinated optimization of building carbon performance and health performance in the early design stage. To answer this question, this study proposes an IEQ-driven synergistic design method for building carbon and health performance. Specifically, the study aims to: 1) establish an integrated evaluation framework that considers both life-cycle carbon performance and health-related indoor environmental quality;

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2) propose a practical comprehensive assessment structure for comparing different design schemes; and 3) demonstrate the applicability of the method through a representative office-building case. By linking building physics, health-related IEQ concerns, and design decision-making, this study seeks to provide a practical basis for the development of sustainable healthy buildings.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on building carbon emission assessment, IEQ and health, and building performance optimization methods. Section 3 presents the proposed framework, the key indicators, and the case-study setup. Section 4 reports the comparative results of the design schemes. Section 5 discusses the implications and limitations of the study. Finally, Section 6 concludes the paper and outlines future research directions.

II. Literature Review

To construct an IEQ-driven synergistic design method for building carbon and health performance, this study reviews the current research in three closely related areas: building carbon emission assessment methods, the relationship between IEQ and health, and building performance optimization methods. This review aims to clarify the research foundation, identify current gaps, and highlight the theoretical positioning of this study.

A. Building Carbon Emission Assessment Methods

The assessment of building life-cycle carbon emissions is fundamental to promoting carbon neutrality in the building sector. Life Cycle Assessment (LCA) is a widely recognized method for quantifying the environmental impacts of a product or system from "cradle to grave" [14]. In the field of buildings, LCA has been increasingly applied to evaluate carbon emissions throughout the stages of material production, transportation, construction, operation, maintenance, and demolition [15][16]. In general, building life-cycle carbon emissions are commonly divided into embodied carbon and operational carbon [17][18]. Embodied carbon refers to emissions associated with building materials and construction processes, whereas operational carbon mainly results from energy consumption during building use.

Early building energy-efficiency research mainly focused on reducing operational carbon, but this sometimes led to "carbon transfer," in which the additional embodied carbon of materials and technologies offset the carbon savings achieved during operation [19][20]. Therefore, increasing attention has been paid to integrated life-cycle carbon assessment in recent years [21][22]. In addition, parametric studies have shown that envelope-related design variables can significantly affect both embodied and operational carbon performance [23]. Although various tools and databases are now available to support building carbon assessment, challenges remain, including regional differences in emission factors, inconsistent system boundaries, and the difficulty of evaluating life-cycle carbon performance during the early design stage [24][25].

B. Indoor Environmental Quality (IEQ) and Health

Indoor Environmental Quality (IEQ) is a comprehensive concept that reflects the condition of a building's indoor environment and its effects on occupants' comfort, health, and productivity [9][13]. IEQ generally includes several major dimensions, such as thermal environment, luminous environment, air quality, and acoustic environment. A growing body of research has confirmed that these factors have important impacts on human well-being. For instance, poor indoor air quality may impair cognitive performance and decision-making [11], while lighting conditions may affect mood, sleep quality, and physiological rhythms [12]. Studies have also shown that IEQ can influence health and learning or working performance in different indoor settings [8][10].

In response to the increasing emphasis on health-oriented building design, research has gradually shifted from general comfort-based assessment toward health-related IEQ evaluation [9][10]. Poor indoor environments may contribute to Sick Building Syndrome (SBS) and other health-related complaints [12][13], which further highlights the importance of integrating health concerns into building design. However, IEQ involves multiple dimensions and indicators, making it difficult to assess overall health performance through a single metric. Therefore, developing a practical and comprehensive assessment method for IEQ-related health performance remains an important research challenge.

C. Building Performance Optimization Methods

With the development of digital design and simulation technologies, performance-based building design optimization has become an important approach for improving building performance. In general, such methods establish a parametric building model, define key design variables, evaluate the performance of alternative schemes, and then identify preferable design solutions through comparative or optimization procedures. This approach is particularly valuable in the early design stage, when designers must balance multiple performance objectives under uncertainty.

Because architectural design often involves conflicting goals, such as energy use, comfort, cost, and environmental impact, multi-objective optimization methods have been widely adopted in building research. These methods are able to explore trade-offs among design objectives and provide decision support for selecting balanced solutions. Existing studies have demonstrated the usefulness of computational frameworks for addressing the trade-off between energy and IEQ in sustainable building design . However, despite significant progress in carbon assessment, IEQ-health research, and performance-based optimization, current studies still rarely integrate life-cycle carbon emissions and multidimensional health-related IEQ performance within a unified design-assessment framework. Therefore, there remains a need for a practical method that can support coordinated decision-making on carbon and health performance in the early stage of building design.

III. Methodology

To support the coordinated consideration of building life-cycle carbon performance and occupant health performance in early-stage design, this study proposes a practical assessment framework. The framework combines simplified parametric scheme generation, building performance analysis, and comparative evaluation of multiple design alternatives, forming a structured process for exploring trade-offs between carbon and health-related performance. This chapter will elaborate on the composition of this framework, the definition and quantification methods of key performance indicators, and the case study setup used to validate the method.

A. *Synergistic Design Framework*

The synergistic design framework proposed in this study is illustrated in Figure 1. Its core idea is to rapidly and extens ively explore the performance of different design options in t he two dimensions of "carbon" and "health" during the early design stages, and to identify the optimal trade-off solutions. The framework consists of three closely integrated modules: Parametric Modeling, Performance Simulation and Assessme nt, and Multi-Objective Optimization.

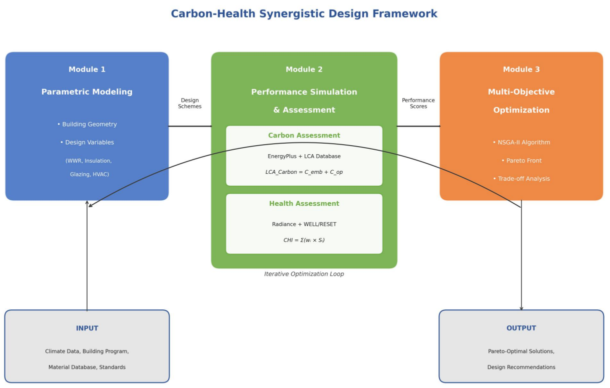

Fig. 1. Carbon-Health Synergistic Design Framework. The framework integrates three core modules: (1) Parametric Modeling for generating design schemes with variable parameters; (2) Performance Simulation & Assessment for evaluating carbon emissions and health performance; and (3) Multi-Objective Optimization using NSGA-II algorithm to identify Pareto-optimal solutions.

Module 1: Parametric Modeling. This is the input end of the entire framework. We use Rhinoceros and Grasshopper as the parametric modeling platform to establish a digital geometric model of the target building. Unlike traditional fixed-dimension BIM models, the key design elements of this model, such as building orientation, window-to-wall ratio (WWR), thickness of insulation for exterior walls and roofs, glazing type, and shading device depth, are all defined as variable "genes" (design variables). By adjusting the values of these variables within reasonable ranges, multiple representative building design schemes can be generated for comparative analysis.

Module 2: Performance Simulation and Assessment. This is the computational core of the framework, responsible for "decoding" the performance of each design scheme generated by the parametric module. This module uses commonly adopted building performance analysis methods to evaluate the environmental implications of different design schemes. For Carbon Emission Assessment, the EnergyPlus engine is used to conduct an annual hourly energy consumption simulation of the building to obtain its operational energy consumption for heating, cooling, lighting, etc. Embodied carbon is estimated based on the quantities of major building materials and corresponding emission factors reported in relevant literature and standards. Finally, the operational carbon (converted based on the local energy structure) is added to the embodied carbon to obtain the life-cycle carbon emissions for that scheme. For health-related performance assessment, the study evaluates key IEQ-related aspects, including daylight, thermal environment, and ventilation-related indoor air quality, using a combination of performance analysis and standards-based judgment. obtaining key IEQ indicators such as spatial Daylight Autonomy (sDA), percentage of thermal comfort hours, and indoor CO_2 concentration. These raw simulation results are then integrated and quantified according to the Comprehensive Health Index (CHI) model defined in Section 3.2, ultimately calculating a single, comparable health performance score for each scheme.

Module 3: Multi-Objective Optimization. This is the decision-making engine of the framework. Instead of focusing on a single design target, this study compares multiple design alternatives under a dual-perspective evaluation framework covering carbon and health-related performance. Through comparative analysis of representative schemes, the study identifies design tendencies and balanced solutions that may better support coordinated decision-making in early-stage building design. This module takes the design variables defined in the parametric model as "decision variables," and the "life-cycle carbon emissions" and "comprehensive health performance index" calculated by the performance simulation module as two conflicting "optimization objectives" (minimizing the former, maximizing the latter). The algorithm simulates the natural selection process of "survival of the fittest," iteratively calculating and automatically searching for and recording "Pareto-optimal" design schemes that perform well on both objectives. This ultimately forms the Pareto front, providing support for design decisions.

B. *Definition and Calculation of Key Indicators*

To quantitatively assess and optimize "carbon" and "health," this study defines two core objective functions:

Objective Function 1: Life-Cycle Carbon Emissions (LCA_Carbon)

This indicator aims to comprehensively measure the carbon footprint of a building scheme throughout its entire life cycle, from construction to demolition. Its calculation formula is as follows:

$$LCA\_Carbon = C_{mbodied} + C_{perational} \quad (1)$$

where C_embodied represents the building's embodied carbon, obtained by multiplying the material quantities of each building component by their corresponding carbon emission factors (from an LCA database) and then summing them up. C_operational represents the building's operational carbon, calculated by multiplying the building's total annual energy consumption by the carbon emission factor of the local power grid or energy supply.

Objective Function 2: Comprehensive Health-Oriented Assessment Score

This indicator aims to integrate complex Indoor Environmental Quality (IEQ) parameters into a single, easy-to-understand comprehensive health performance score. This study adopts a practical composite assessment approach informed by healthy building standards and previous IEQ studies. The model first decomposes health performance into four main dimensions: thermal comfort, luminous environment, air quality, and acoustic environment. Then, the performance score for each dimension is calculated based on simulation results, and finally, the composite index is obtained through a weighted sum. Its calculation formula is as follows:

$$CHI = w_t \cdot S_{thermal} + w_l \cdot S_{light} + w_a \cdot S_{air} \quad (2)$$

where S_thermal, S_light, S_air, and S_sound represent the normalized scores (0-100) for the four dimensions of thermal, luminous, air, and acoustic environments, respectively. The score for each dimension is derived from one or more specific simulation indicators (e.g., percentage of thermal comfort hours, average daylight illuminance) through a functional mapping based on a comparison with the performance requirements in the WELL standard.The weight coefficients were assigned based on a review of relevant literature and the relative importance of major IEQ dimensions in office buildings.

C. *Case Study Setup*

To validate the effectiveness and practicality of the proposed synergistic design method, this study selected a typical medium-sized office building located in China's hot-summer and cold-winter climate zone as a case study. The building has five floors above ground, a total construction area of approximately 5,000 square meters, and conventional functional layouts for offices, meetings, etc.

TABLE I. DESIGN VARIABLES AND THEIR VALUE RANGES

Design Variable	Symbol	Unit	Range
South-facing Window-to-Wall Ratio	WWR_s	-	0.30 – 0.70
North-facing Window-to-Wall Ratio	WWR_n	-	0.20 – 0.50
Exterior Wall Insulation Thickness	d_ins	mm	50 – 150
Glazing U-value	U_g	$W/(m^2 \cdot K)$	1.0 – 2.5
Glazing Solar Heat Gain Coefficient	SHGC	-	0.20 – 0.60
Fresh Air Change Rate	ACH	h^{-1}	0.5 – 1.5
Horizontal Shading Depth	L_sh	m	0.0 – 1.0
Roof Insulation Thickness	d_roof	mm	80 – 200

This study selected a total of 8 key design variables that have a significant impact on the building's carbon emissions and health performance, and set reasonable value ranges for them, as shown in Table I. These variables together form a vast design solution space.

In terms of multi-objective optimization settings, we used the NSGA-II algorithm,A set of representative design schemes was established by combining different values of the key design variables, so as to compare their carbon and health-related performance under typical design conditions. The scheme settings are intended to cover the main design tendencies of early-stage office-building design and to support a structured comparison of carbon and health-related performance.

IV. RESULTS

This chapter will present in detail the results obtained from the multi-objective optimization of the case study building using the synergistic design framework. The analysis will focus on the convergence of the optimization process, the "carbon-health" trade-off relationship revealed by the Pareto-optimal solution set, the characteristics of representative design schemes, and the degree of influence of key design variables on the optimization objectives.

A. *Comparative Performance of Design Schemes*

The comparative analysis of the representative design schemes shows a clear trade-off tendency between carbon-related performance and health-related indoor environmental quality. Schemes emphasizing lower carbon emissions generally adopt more conservative envelope and ventilation settings, while schemes with better health-related performance tend to use larger window areas and enhanced ventilation. A balanced scheme can be identified by moderately improving indoor environmental conditions without causing a disproportionate increase in carbon impact.

B. *Trade-off Analysis of Carbon and Health Performance*

The comparative results of the design schemes reveal a clear trade-off relationship between life-cycle carbon performance and comprehensive health-related performance. as shown in Figure 2. Each point in the figure represents a specific building design scheme that achieves an optimal trade-off between the two dimensions of "carbon" and "health." This Pareto front clearly reveals the negative correlation trade-off relationship between the building's life-cycle carbon emissions and its comprehensive health performance.

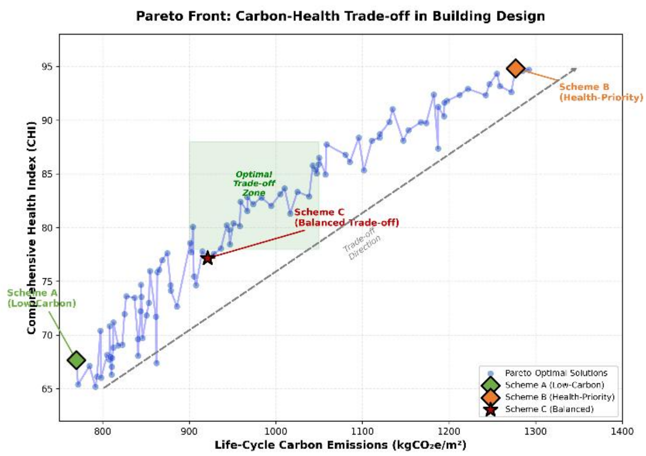

Fig. 2. Pareto Front: Carbon-Health Trade-off in Building Design. The scatter plot shows 100 Pareto-optimal solutions, with Life-Cycle Carbon Emissions on the x-axis and Comprehensive Health Index on the y-axis. Three representative schemes are highlighted: Scheme A (Low-Carbon, green diamond), Scheme B (Health-Priority, orange diamond), and Scheme C (Balanced Trade-off, red star). The shaded green area indicates the optimal trade-off zone.

From the comparison of the design schemes, it can be observed that as health-related performance improves, the associated carbon impact may also increase. This tendency suggests that an appropriate balance should be sought rather than pursuing a single objective in isolation. For example, to raise the CHI from 70 to 80, the cost in terms of the minimum carbon emissions increased by only about 10%; however, to further raise it from 80 to 90, the increase in carbon emissions jumped to nearly 30%. This suggests that after reaching a certain level of health, achieving even a small performance improvement may require a disproportionately large carbon emission cost. This curve provides decision-makers with an intuitive quantitative tool to select an appropriate design range based on the specific goals of the project (e.g., a carbon emission cap or a desired health rating).

C. Comparison of Representative Design Schemes

To gain a deeper understanding of the design wisdom embodied in the Pareto front, we selected three representative schemes from the solution set for a detailed comparison: Scheme A (Low-Carbon Priority), Scheme B (Health Priority), and Scheme C (Balanced Trade-off). Scheme C is located in the "inflection point" area of the Pareto front, representing the choice with the highest "cost-performance" ratio. Table II shows the performance scores of these three schemes on the two optimization objectives and the four health sub-dimensions.

TABLE II. PERFORMANCE COMPARISON OF REPRESENTATIVE DESIGN SCHEMES

Performance Indicator	Scheme A (Low-Carbon)	Scheme C (Balanced)	Scheme B (Health-Priority)
Life-Cycle Carbon Emissions ($kgCO_2e/m^2$)	850	980	1250
Comprehensive Health Index (CHI)	68.5	85.2	92.5
Thermal Comfort Score (S_thermal)	70	88	95
Luminous Environment Score (S_light)	65	85	93
Air Quality Score (S_air)	72	86	94
Acoustic Environment Score (S_sound)	67	82	88

Compared with the low-carbon-oriented scheme, the balanced scheme shows a noticeable improvement in comprehensive health-related performance while keeping the increase in carbon impact within a moderate range. On the other hand, while Scheme B (Health Priority) achieved the highest level in all health indicators, its carbon emissions were nearly 28% higher than Scheme C's, showing lower marginal benefits. To investigate the design reasons behind these performance differences, Table III further compares the key design variable values of the three schemes.

TABLE III. COMPARISON OF KEY DESIGN VARIABLES FOR REPRESENTATIVE DESIGN SCHEMES

Design Variable	Scheme A (Low-Carbon)	Scheme C (Balanced)	Scheme B (Health-Priority)
South-facing WWR	0.35	0.55	0.70
Ext. Wall Insulation Thickness (mm)	120	100	80
Glazing U-value ($W/m^2 \cdot K$)	1.8	1.2	1.1
Glazing SHGC	0.40	0.25	0.22
Fresh Air Change Rate (ACH)	0.5	0.8	1.2

An analysis of Table III reveals that the low-carbon Scheme A tends to use a smaller window-to-wall ratio and thicker insulation to reduce heat loss, but at the expense of natural lighting. The health-priority Scheme B, on the other hand, uses large windows and a high fresh air rate to maximize the luminous environment and air quality, but this leads to higher energy consumption and embodied carbon. In contrast, the balanced Scheme C embodies the wisdom of "synergistic" design: by using high-performance glazing (with a very low U-value and SHGC), it moderately increases the window-to-wall ratio to improve lighting while effectively controlling the additional thermal load, thus achieving the best balance between carbon and health.

D. Sensitivity Analysis of Design Variables

To identify the design factors that have the greatest impact on the "carbon-health" synergistic performance, This study examined the influence of major design variables by comparing the performance tendencies of representative schemes. As shown in Figure 3, each polyline in the plot represents an optimal design scheme.

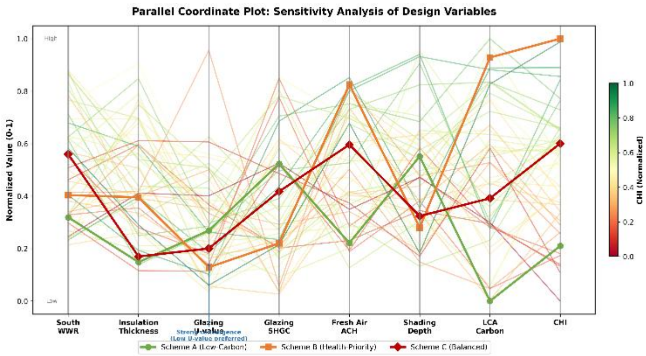

Fig. 3. Parallel Coordinate Plot: Sensitivity Analysis of Design Variables. Each polyline represents a Pareto-optimal solution, with colors indicating CHI values (green = high, red = low). The three representative schemes are highlighted. The plot reveals that glazing U-value shows strong convergence toward lower values across all optimal solutions, indicating its critical importance for achieving synergistic carbon-health performance.

By observing the convergence or divergence patterns of the polylines on the different variable axes in Figure 3, their sensitivity can be determined. The comparison suggests that glazing thermal performance, solar heat gain control, and ventilation rate are among the most influential variables affecting the balance between carbon and health-related performance. Almost all optimal solutions tend to choose glazing with a low U-value, indicating that high-performance glazing is the foundation for achieving a "win-win" situation. The fresh air change rate, on the other hand, shows a clear positive correlation with CHI and a negative correlation with LCA_Carbon, making it the core lever for balancing air quality and energy consumption. In contrast, the thickness of the exterior wall insulation, within a certain range (e.g., after exceeding 80mm), has a lower sensitivity to the overall performance, which provides greater flexibility and potential for cost optimization in the design.

V. DISCUSSION

This study, by constructing a synergistic design framework that integrates parametric modeling, multi-domain performance simulation, and multi-objective optimization, has successfully quantified and revealed the complex trade-off relationship between building life-cycle carbon emissions and comprehensive health performance.

This chapter will provide an in-depth interpretation of the research results, analyze the underlying mechanisms, compare them with existing studies, and discuss their practical application value in architectural design, as well as the study's limitations and future prospects.

A. *Interpretation of Results and Analysis of Mechanisms*

The case analysis in this study further illustrates the commonly observed trade-off between carbon-related performance and health-related indoor environmental quality in architectural design. This trade-off relationship is rooted in the fundamental principles of building physics. For example, to enhance the indoor luminous environment and visual comfort (an aspect of health performance), designs typically favor a larger window-to-wall ratio. However, compared to opaque walls, transparent glass envelopes generally have poorer thermal performance, which leads to more heat loss in winter and more solar heat gain in summer, thereby increasing the operational energy consumption of the HVAC system, i.e., increasing operational carbon. Similarly, increasing the fresh air exchange rate to ensure excellent indoor air quality also directly increases the energy required to treat the fresh air. The results of this study quantitatively and clearly demonstrate this inverse relationship, and also point out its non-linear nature, i.e., at the extreme end of pursuing health performance, the marginal carbon cost rises sharply.

More importantly, In addition to highlighting the trade-off, the comparative analysis also suggests that a more balanced design solution may be achievable through the coordinated adjustment of multiple design variables. The reason why Scheme C is able to achieve an excellent balance between carbon emissions and health performance lies in the synergistic effect of the design variables. It does not simply make a choice between "large windows" and "small windows," but rather breaks the two-dimensional deadlock by introducing a third-dimensional variable—glazing performance. The use of high-performance glazing with a very low U-value (good insulation) and a moderate SHGC (solar heat gain coefficient) makes it possible to effectively suppress the additional thermal load while increasing the window-to-wall ratio to obtain sufficient natural light. This strategy reflects the practical value of coordinated design thinking in early-stage building design. It proves that through systematic, multi-variable comprehensive optimization, we can find innovative, all-encompassing solutions between seemingly contradictory objectives, rather than being forced to make simple, either-or compromises.

B. *Comparison with Existing Studies*

This study deepens and expands upon existing research in three key aspects. First, in terms of comprehensiveness of assessment, most existing building performance optimization studies focus on operational energy consumption , or only consider the trade-off between embodied and operational carbon. In contrast, this study extends the assessment boundary to the entire life cycle of the building, achieving a more complete accounting of total carbon emissions. At the same time, in terms of health performance assessment, this study goes beyond the limitation of focusing on a single thermal comfort indicator (such as PMV) and innovatively constructs a Comprehensive Health Index (CHI) that covers the four dimensions of thermal, luminous, air, and acoustic environments. This index is directly linked to cutting-edge healthy building standards like WELL, making its assessment results more comprehensive and practically instructive.

Second, in terms of research perspective, traditional green building research often treats IEQ as a "constraint condition" to meet minimum standards, on the basis of which energy consumption or carbon emissions are minimized. In contrast, this study elevates IEQ to an "optimization objective" of equal importance to carbon emissions, representing a new paradigm of "IEQ-driven" design. This shift in perspective means that the optimization process is no longer simply about "meeting the bottom line," but is actively "seeking the optimum," exploring the upper limits of health performance, which is more in line with the current societal pursuit of a high-quality living environment.

Finally, in terms of methodological integration, this study constructs a highly integrated and automated workflow from parametric modeling to multi-objective optimization. Compared to studies that manually compare multiple schemes or only optimize a few design variables, this framework can efficiently explore a huge design space containing tens of thousands or even millions of possibilities, thus making it more likely to discover non-intuitive, innovative optimal design strategies.

C. *Practical Significance and Application Prospects*

The synergistic design method proposed in this study has significant practical application value. For architects and engineers, this method can serve as a practical reference tool in the early design stages. At the beginning of a project, the design team can use this framework to input the project's specific constraints (such as climate zone, building function, cost budget, etc.) and compare a series of representative design schemes. Decision-makers can then, based on the project's different positioning (e.g., creating a "zero-carbon benchmark" or a "health model"), intuitively select the most suitable design scheme on the visualized Pareto front, and clearly understand the "cost" of that decision in the other dimension. This helps make the early-stage design trade-off process more structured and evidence-informed.

Looking to the future, this synergistic design framework has broad prospects for expansion. On the one hand, it can be further integrated with cost databases to include "initial investment" or "life-cycle cost" as a third optimization objective, thereby achieving the synergistic optimization of the three core dimensions of "carbon-health-cost." On the other hand, the framework can be deeply integrated with Building Information Modeling (BIM) technology to form an integrated management platform covering the entire life cycle from design, construction, to operation. The optimal design parameters determined by this method in the design phase can be seamlessly transferred to the BIM model to guide detailed design. In the operation phase, the actual operational data of the building can also be used to calibrate the initial model, achieving continuous optimization of the building's performance.

D. *Limitations and Future Prospects*

Although this study has achieved certain innovative results, there are still some limitations that need to be addressed in future research. First, model uncertainty is one of the main challenges faced by this study. The calculation results of building performance simulation software, the accuracy of carbon emission factors in LCA databases, and the randomness of occupant behavior all introduce uncertainty into the final optimization results. Future research needs to incorporate uncertainty analysis and sensitivity analysis to assess the robustness of the results.

In addition, the present study adopts a simplified assessment framework for early-stage design decision support. Therefore, the results should be interpreted as comparative guidance among design alternatives rather than as precise predictions of final operational performance.

Second, the construction of the Comprehensive Health Index (CHI), although based on existing standards and expert knowledge, still involves a certain degree of subjectivity in the determination of weight coefficients. Different populations (such as the elderly and children) may have different sensitivities and preferences for environmental factors. Therefore, future research could conduct more extensive empirical studies on different user groups to establish a more universally applicable and personalized CHI model.

Finally, the case study of this research has certain limitations. The study was only validated for one type of building (office building) in a specific climate zone. The applicability of the method to other climate zones (such as severe cold regions) and other building types (such as residential buildings, schools), as well as the differences in optimization results under different economic and technical conditions, all require further research and validation.

Future research will be dedicated to addressing the above limitations, for example, by calibrating the building energy consumption and IEQ models with on-site measurement data to improve simulation accuracy; developing a dynamic weight CHI model that considers the preferences of multiple user groups; and conducting large-scale comparative studies across different climate zones and building types to build a more comprehensive knowledge base for the synergistic design of building carbon and health.

VI. Conclusion

This study, addressing the increasingly prominent challenge of balancing "carbon reduction" and "health and comfort" in architectural design, has proposed and validated an innovative "IEQ-driven synergistic design method for building carbon and health performance." Through systematic research, this paper draws the following main conclusions:

First, this study has proposed a structured assessment framework for coordinated consideration of carbon performance and health-related indoor environmental quality in early-stage design. This framework can effectively explore a complex design space with numerous design variables in the early stages of architectural design, and synergistically optimize for both life-cycle carbon emissions and a comprehensive health performance index. The case study demonstrates that the method has good feasibility and reliability, and can provide a scientific, quantitative basis for design decisions.

Second, through comparative scheme analysis, this study illustrates the trade-off relationship between carbon-related performance and health-related indoor environmental quality. The study found that in the pursuit of extreme health performance, the marginal carbon cost increases significantly. However, the study also proved that by optimizing the synergistic combination of design parameters, it is entirely possible to find a "cost-effective" optimal solution that balances both. For example, in the case study, by using high-performance envelope components, a significant improvement in health performance can be achieved with an acceptable increase in carbon emissions, and in certain conditions, even a "win-win" situation can be realized.

Third, this study has identified the key design variables that affect the "carbon-health" synergistic performance. In the case study, the thermal performance of glazing, solar heat gain control, and ventilation rate appear to be important variables influencing the balance between carbon and health-related performance. This finding provides clear guidance for designers to quickly grasp the main contradictions and make effective design interventions in practice.

In summary, this study has made contributions on three levels: theoretical, methodological, and practical. Theoretically, it enriches the connotation of sustainable architectural design by quantitatively integrating the "people-oriented" concept of health with the "earth-oriented" concept of low carbon. Methodologically, it provides a practical and adaptable assessment framework for supporting early-stage building design decisions. Practically, it offers the architectural design industry a powerful scientific decision-making tool that helps to break down the information silos in the traditional design process and promotes the realization of high-quality, low-carbon healthy buildings, which is of positive significance for helping to achieve the two major national strategies of "Healthy China" and "dual carbon."

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AVAILABILITY OF DATA

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AUTHOR CONTRIBUTIONS

Yudong Ye: Conceptualization, Methodology, Investigati on, Formal analysis, Writing – original draft, Visualization.

Huawan Zheng: Supervision, Validation, Resources, Writing – review & editing, Project administration.

COMPETING INTERESTS

The authors declare no competing interests.