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Research on Carbon Reduction Path for Whole-Process Design of Prefabricated Envelope System Based on SEM

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Abstract: Prefabricated buildings, characterized by factory production, on-site assembly, and efficient and refined management, enhance construction efficiency, reduce building time, and promote material reuse and recycling. The energy consumption (and carbon emissions) during the building operational stage are significantly influenced by the performance of the building envelope component system. To minimize carbon emissions throughout the building's lifecycle, it is essential to focus on a comprehensive optimization design for carbon reduction in prefabricated envelope systems. This paper draws on grounded theory to construct a system of factors influencing carbon emissions throughout the lifecycle of prefabricated building envelopes. Using a questionnaire survey and leveraging Structural Equation Modeling (SEM), this study identifies key pathways and factors, influencing carbon emissions throughout the lifecycle of building envelope components. It provides insights into carbon emission mechanisms in these components and establishes a comprehensive design pathway for carbon control throughout the lifecycle of building envelope systems. Subsequently, the survey results were analyzed using Structural Equation Modeling (SEM) to identify key factors influencing carbon emissions throughout the lifecycle and their interrelationships. These findings were integrated into the various stages of the whole-process design, yielding actionable recommendations for carbon control in the design process. Additionally, the case study method was employed to illustrate how carbon control design and optimization techniques can be applied at each stage of a specific project, providing a practical demonstration of the research outcomes. The study offers optimized methods for carbon control across the entire process, utilizing optimization strategies to reduce carbon emissions at each stage of the building's lifecycle.

Keywords: prefabricated envelope system; building carbon emissions; whole-process design; structural equation modeling (SEM); carbon reduction path

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1. Introduction

1.1. Background

Prefabricated buildings consist of three hierarchical levels: individual components, the integrated component system, and the building itself. Building materials are processed into components in factories and then transported to construction sites, where they are assembled into a larger structural system. According to Chinese industry standards, the building's envelope component system protects the enclosed structural body, partitions,

equipment, and finishes. This system includes exterior walls, roofs, external doors and windows, bay windows, shading devices, railings, parapets, and exterior finishes.

Building carbon emissions refer to greenhouse gas emissions, expressed in CO_2 equivalents, generated directly or indirectly using fossil fuels during the building lifecycle. This includes emissions from raw material production, construction, transportation, operational energy use, and demolition. Globally, according to the World Green Building Council (WGBC), buildings are currently responsible for 39% of global energy-related carbon emissions: 28% from operational emissions, from the energy needed to heat, cool, and power them, and the remaining 11% from materials and construction [1]. The design of the building envelope as the interface between the building and its environment plays a critical role in optimizing energy performance. Beyond meeting requirements for waterproofing, airtightness, and structural strength to withstand external loads and resist shrinkage or freeze–thaw cycles, exterior walls must provide effective thermal insulation to minimize heat transfer. These attributes are essential for ensuring the building's durability and energy efficiency. According to the Tsinghua University Building Energy Research Center, China's building-related energy use aligns with the global average, with construction accounting for 16% and operations 22% [2]. Based on EN15978:2011 [3], the building lifecycle should be divided into three parts to better capture environmental carbon impact: materialization (the component production stage, transportation stage, and assembly stage), continuous operation (the operation and maintenance stage), and reuse (the renovation and reuse stage, demolition stage, and demolition and reuse stage) [4]. Recent studies have demonstrated that this extended and refined lifecycle stage category supported two rounds of recyclable construction in prefabricated light steel frame houses—C-House—designed by the research team, where the first cycle reduces carbon emissions by 43.53%, and the second cycle achieves a reduction of 70.57% [5].

1.2. Object of the Study

Prefabricated envelope systems are structural parts of building envelopes, such as exterior wall panels, roof panels, and window and door frames, that are pre-manufactured in a factory. These components are characterized by standardization, modularization, and ease of installation, significantly enhancing construction efficiency, reducing construction time, and improving the overall quality and sustainability of buildings.

The whole-process design discussed in this study covers the design of building envelopes, which includes the conceptual design, detailed design, and construction design. The conceptual design defines the completed form of the building envelope component system, while the detailed design focuses on the specifics of component integration, connections, and performance. The construction design is further divided into production, transportation, and assembly design, which together govern the component manufacturing, delivery, and on-site assembly. By implementing a whole-process design (as shown in Figure 1), construction stages and the final state of the building can be effectively managed, making it a highly effective strategy for minimizing carbon emissions throughout the building's lifecycle and reducing the construction industry's overall footprint.

1.3. Innovations and Highlights

This study focuses on the building envelope components most closely related to carbon emissions, conducting a comprehensive lifecycle analysis. The research scope is broad and holistic, ensuring a thorough understanding of the subject.

The survey data were analyzed using Structural Equation Modeling (SEM), which allows for the observation of how factors at each lifecycle stage influence other stages. This approach reveals the interconnections between various factors and provides insights into

how whole-process design strategies can be employed to reduce carbon emissions in stages such as production, transportation, and assembly.

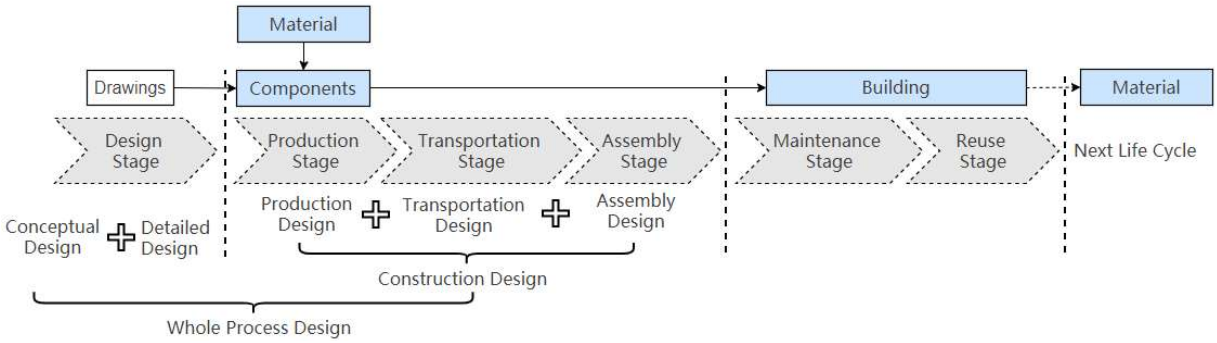


Figure 1. Relationship between lifecycle stages of a building and whole-process design.

In addition to data-driven research methods, this study incorporates case study analysis. Using a real-world prefabricated envelope design project in which the author was involved, the study demonstrates how carbon control design and optimization techniques can be applied at each stage of a specific project. This practical application makes the research findings more tangible and actionable.

1.4. Purpose of the Study

The purpose of this article is to provide designers with a structured and systematic approach, along with practical design recommendations, for reducing carbon emissions in prefabricated envelope systems.

This research takes prefabricated building envelope components as its primary focus, systematically investigating the factors influencing carbon emissions throughout their lifecycle. Through a literature review, expert interviews, and grounded theory, key influencing factors were identified. Survey data were collected via questionnaires and analyzed using Structural Equation Modeling (SEM) to outline whole-process carbon control design principles for prefabricated building envelope systems. These principles aim to guide designers in optimizing their designs for carbon reduction throughout the entire process.

2. Literature Review

2.1. Design of Prefabricated Envelope System

A wide range of research on prefabricated building components, envelope systems, detailed design, construction design, and design optimization has been conducted both domestically and internationally. These studies have significantly advanced the performance, design optimization, and construction efficiency of prefabricated buildings, especially in the context of carbon emission control and sustainable building practices.

In researching prefabricated component system design, scholars focus on modular coordination, component connections, and energy-saving designs. For instance, Xia et al. [6] emphasized the importance of modular coordination in architectural design, highlighting the need for comparison between domestic and international modular standards and the importance of technical standardization. In building envelope design, Song et al. [7] established a comprehensive framework for predicting energy consumption in light-framed temporary buildings. By analyzing the embodied and operating energy impacts of 1344 design schemes for exterior wall materials and configurations, this study provided insights into the influence of material selection and thickness on energy performance. Regarding detailed design, building on the construction limitations identified in Jung's doctoral research [8], Wang from our team, explored construction methods for external wall connections and energy-efficient

structures in prefabricated reinforced concrete systems. Some scholars have incorporated cost evaluations at this stage. For example, domestic researcher Yao Xinghao conducted a techno-economic evaluation for selecting wall insulation materials under local conditions, building on the Eco-indicator 99 method proposed by Audenaert et al. [9].

In construction design, BIM technology has been widely applied to optimize construction workflows and improve efficiency. For example, Al Hawarneh et al. [10] optimized wall-material transportation distances. Cheng and Chang [11] designed a heuristic algorithm considering both wall material selection and scheduling to optimize layout planning. Rui et al. [12] emphasized that industrialized construction should prioritize factory manufacturing and lean construction to enhance efficiency. In design optimization, researchers have begun to focus on comprehensive optimization throughout the building's lifecycle. Li and Yang et al. [13] from Tianjin University proposed a comprehensive green building design process tailored to the Chinese context. They developed a national/regional-specific database of building elements and materials, integrating BIM and lifecycle assessment (LCA). This database facilitates improvements at various building component levels, including envelope component systems, during different design stages, particularly in the early design phase, and supports environmental impact assessments. Huang [4] identified this approach as a future research trend for BIM-based environmental impact evaluations.

Therefore, the focus of architects should be shifted. They should not only consider both formal and performance design but also introduce a lifecycle perspective at the design stage, applying a whole-process design, which includes architectural scheme design, detailed design, and construction design. Scheme design addresses architectural form, while detailed design focuses on the division of components, ensuring compatibility with production, transportation, assembly, operation, maintenance, and reuse.

The main focuses were modular coordination, material selection, and the incorporation of lifecycle assessment (LCA) to enhance efficiency, minimize carbon emissions, and optimize construction processes. Despite these advancements in research, further progress in low-carbon and sustainable design requires enhanced interdisciplinary collaboration and innovative approaches. This aligns with ongoing research into carbon reduction pathways for the whole-process design of prefabricated envelope systems, ensuring a sustainable architectural design approach.

2.2. Application of BIM Technology

In 1975, Professor Eastman from the Georgia Institute of Technology [14] introduced the "Building Description System", a computer software system that organized architectural information and graphics into a logical data structure. In the 1980s, Finnish scholar Bjork [15] proposed the "Product Information Model". By 1992, Dutch scholars Nederveen and Tolman [16] formally defined the concept of "Building Information Models" as an object-oriented information management technology and system. Recently, BIM has become a digital modeling-based data-integrated workflow that supports the whole-process design of a building. By facilitating the creation, management, and exchange of building-related information, BIM supports design, construction, and operational management. Numerous solutions have been developed to address practical challenges in Architecture, Engineering, and Construction (AEC) by BIM.

In BIM design applications, scholars have advanced the use of BIM tools for visualization and design optimization. For instance, Ullah et al. [5] leveraged BIM design integrated with energy simulation to propose a design process aimed at achieving lifecycle carbon reduction benefits for circular campus buildings. This approach demonstrates how BIM can facilitate sustainable design by enabling comprehensive analysis and optimization of energy efficiency and carbon emissions across the entire building lifecycle. Vincent J.L. et al. [17]

employed BIM parametric modeling combined with genetic algorithms to optimize the topology of high-rise reinforced concrete structures. Additionally, BIM design applications can also be utilized for optimization analysis in deconstruction design; Huang [18] utilized BIM in the deconstruction design phase, integrating it with multi-objective optimization to minimize mechanical energy consumption. This highlights BIM's advantages in design optimization, supporting efficient and low-emission deconstruction. In building information management, BIM has addressed inefficiencies in manual data input and reliability. Deng et al. [19] proposed a six-step method for calculating embodied carbon emissions based on Industry Foundation Classes (IFCs). Al-Mashta et al. [20] proposed an integrated cost estimation model based on Uniformat and Master Format systems, automating data statistics and generation.

In building project management, BIM has facilitated optimization across design, production, and assembly stages. Tian [21] proposed a management approach for prefabricated buildings based on BIM, analyzing its impact on different project stages including design, construction, production, and installation links in the industrial chain. Liu et al. [22] applied BIM technology to dynamic cost management, introducing a schedule–cost model for performance evaluation and control. Through collision detection and error correction, Liu identified 503 design issues, reduced 15 change orders, and achieved significant economic benefits, highlighting BIM's efficiency in project management. Furthermore, Arbabi et al. [23] expanded traditional BIM project management methods by integrating the Iran Green Building Rating System (IGBRS), introducing automated compliance checks and early evaluation of green building scores. These advancements underscore BIM's role in improving efficiency, sustainability, and collaboration across the prefabricated construction lifecycle.

2.3. Management of Building Carbon Emission

On the research front, the national project titled Research on Green Residential Areas Emission Reduction and Low-Carbon Evaluation Standards has proposed a comprehensive theoretical framework covering "system, industries, processes, society, and elements" to guide low-carbon residential developments. In terms of building carbon-related policies, "Building Carbon Emission Calculation Standard" GB/T-51366 [24], issued by China's Ministry of Housing and Urban-Rural Development in 2019, employs a bottom-up process-based approach to establish carbon emission calculation rules for new, expanded, and renovated buildings. In January 2022, the Chinese Cities Greenhouse Gas Working Group (CCG), in collaboration with the Ministry of Ecology and Environment's Carbon Neutrality Research Center and other institutions, established the China Product Lifecycle Greenhouse Gas Emission Factor Database.

Regarding carbon emission accounting, methods tailored to different design stages have been proposed. For example, Luo et al. [25] developed predictive models in the conceptual design stage based on extensive case studies, correlating carbon emissions with building height and floor area. In terms of carbon reduction design, studies by Cang [26] demonstrated the effectiveness of integrating LCA theory into schematic design to evaluate the environmental impacts of building products and equipment. Hong et al. [27] used inventory analysis to compare environmental impacts across different materials, providing insights for selecting eco-friendly alternatives. Similarly, Jeong et al. [28] emphasized the importance of inventory analysis in evaluating energy efficiency during the operational phase. Lu [29] investigated traditional cast-in-place buildings, assessing their maintenance costs, operational efficiency, and waste disposal strategies during demolition, ultimately promoting sustainable construction practices.

In summary, research on prefabricated envelope systems has advanced significantly but has mainly focused on specific characteristics, such as thermal performance, with limited attention to whole-process design approaches. These applications improve efficiency, which lacks integrated solutions for carbon reduction across the entire lifecycle. This study seeks to provide both theoretical and practical support for carbon emission reduction in prefabricated building envelopes to identify carbon reduction pathways throughout the design process.

3. Research Methodology

3.1. Research Framework

According to Figure 2, this paper strives to use grounded theory as the main method to collect the influencing factors of the questionnaire and formulate the initial questions. Based on the literature review at home and abroad, combined with the existing engineering practice experience and the full lifecycle performance characteristics of prefabricated buildings, the experts, designers, and practitioners of prefabricated buildings were interviewed and investigated to identify the influencing factors of carbon emissions in the full lifecycle of prefabricated peripheral protective components, and the key factors were extracted to form a questionnaire. The SEM structural equation model was used to analyze and interpret the survey data, and the carbon control path of the fabricated exterior envelope was explored, which provided guidance for the carbon control design of the fabricated exterior envelope.

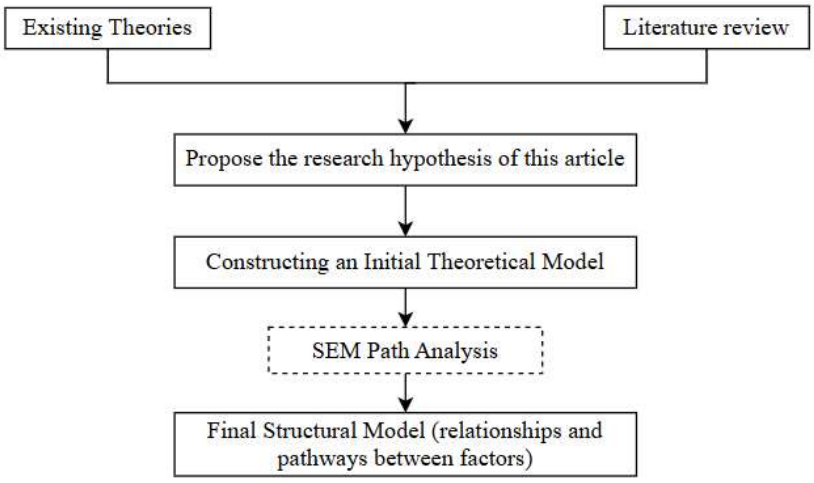


Figure 2. Research framework.

3.2. Grounded Theory

Grounded theory [30], a research methodology and theoretical framework in the social sciences, was first introduced by sociologists Barney Glaser and Anselm Strauss in the 1960s. This approach focuses on developing theories and constructing concepts by systematically analyzing and synthesizing data, allowing new theoretical models to emerge from empirical research. In this study, grounded theory serves as the primary method (as shown in Figure 3) for identifying influencing factors and designing the initial questionnaire. Drawing on a review of the domestic and international literature, the practical engineering experience of the research team, and the lifecycle performance characteristics of prefabricated buildings, interviews and surveys will be conducted with experts, designers, and professionals in the construction industry. These efforts aim to identify lifecycle carbon emission factors for prefabricated envelope systems, extract the key factors, and develop a comprehensive questionnaire.

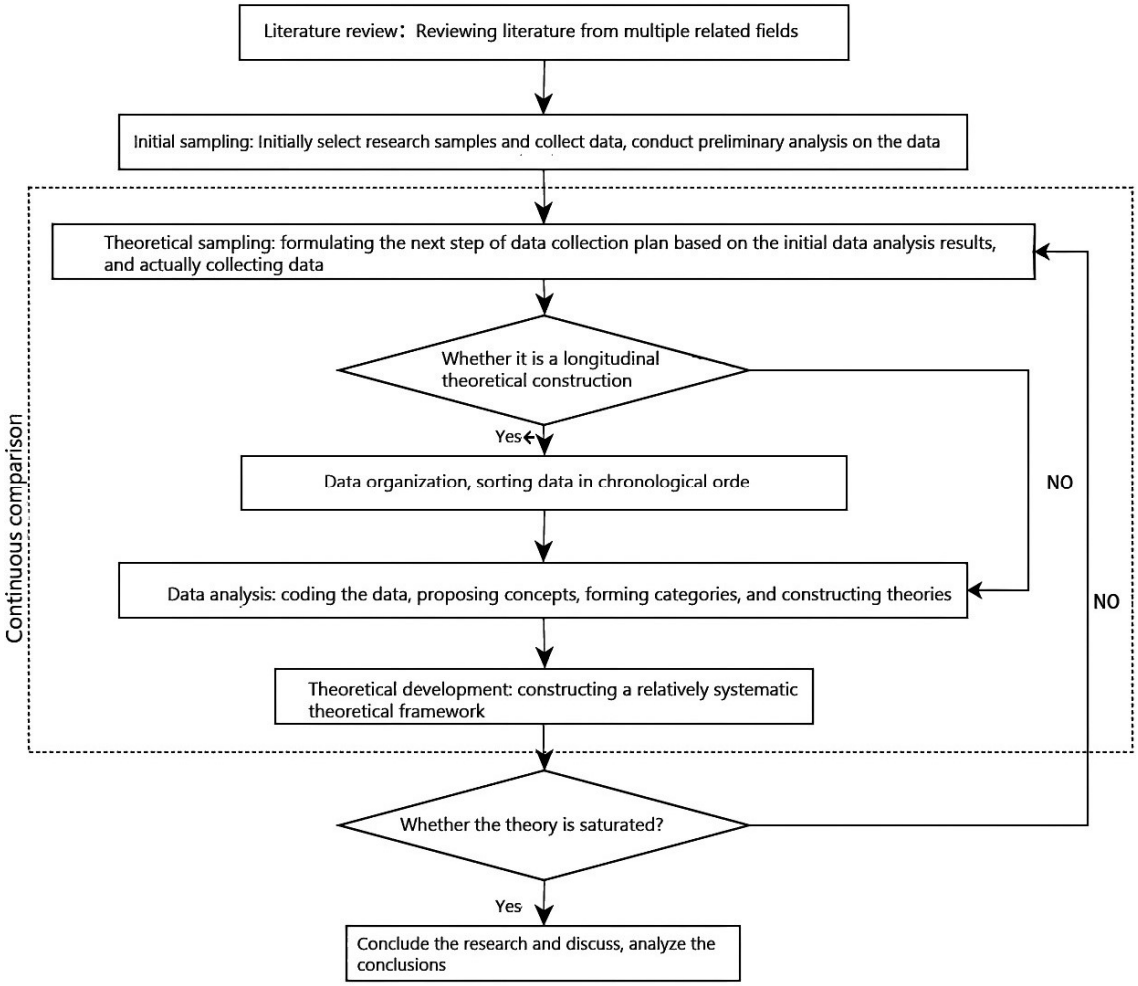


Figure 3. Grounded theory research process.

3.3. Structural Equation Modeling

The model was compared with alternative models, including a null model, a saturated model, and a competing model based on theoretical plausibility. The chosen model showed better fit indices, greater parsimony, and stronger theoretical justification. Validation criteria included theoretical plausibility, statistical fit, parsimony, and cross-validation. Additionally, a sensitivity analysis confirmed model parameter stability across different data subsets. This rigorous validation process ensured that the SEM path model was statistically robust and theoretically sound.

Structural Equation Modeling (SEM), introduced in the mid-1970s by Swedish statistician and psychometrician Karl G. Jöreskog, is a statistical method used to analyze relationships between variables and measure latent constructs [31]. SEM provides a framework for model fitness assessment and parameter estimation, enabling the development and testing of complex causal models (as shown in Figure 4). The measurement model and the structural model are included. The model describes the relationships between latent variables and their corresponding observed variables, expressed as follows:$X = L\xi + \varepsilon$. Where X represents the values of observed variables, L is a factor loading matrix that defines the relationships between observed variables and latent variables, ξ denotes latent variables, and ε represents measurement errors.

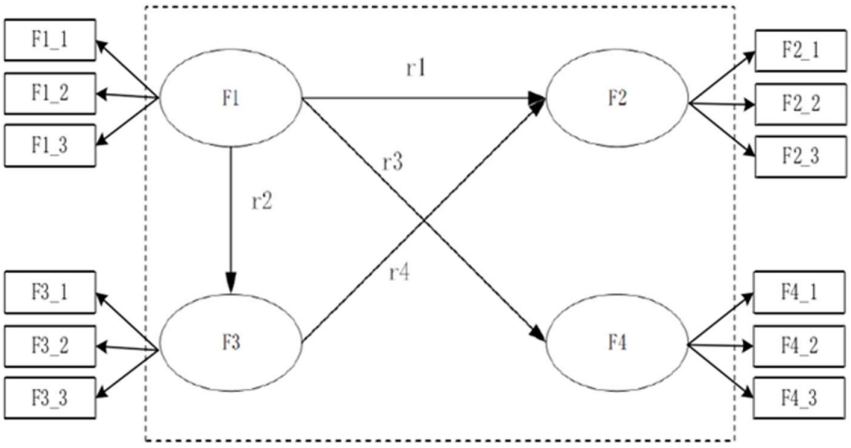


Figure 4. Variable relationships of SEM.

The structural model can be understood as a set of equations describing the relationships among latent variables. It is typically established using path analysis or regression analysis and can be expressed as follows: $\xi = B\xi + \zeta$. Where ξ represents latent variables, B is a regression coefficient matrix that describes the relationships between latent variables, and ζ represents the error.

According to Figure 4, F1, F2, F3, and F4 represent latent variables, serving as influencing factors. r1, r2, r3, and r4 denote the intrinsic relationships between latent variables, reflecting their interactions. F1_1, F1_2, and F1_3 are observed variables for F1, representing specific indicators and measurements corresponding to the latent variable. Similarly, the observed variables divided from F2, F3, and F4 follow the same pattern.

To validate the SEM path model, a comprehensive validation process was conducted, including model specification, estimation, evaluation, and comparison with competing models. The initial model was constructed based on the grounded theory approach, which identified seven key factors influencing the lifecycle carbon emissions of prefabricated envelope systems: management factors, design factors, production factors, transportation factors, assembly factors, operation and maintenance factors, and reuse factors. Maximum likelihood estimation (MLE) was used to estimate the model, and its goodness-of-fit was evaluated based on χ^2/df, CFI, TLI, RMSEA, and SRMR.

3.4. Influencing Factors Identification

3.4.1. Research Review Approach

To refine the research direction and avoid omitting critical indicators, this study conducted a comprehensive literature review from the Web of Science, EI, the Chinese Master's and Doctoral Dissertations Database, Nanjing University's Core Journals, and Peking University's Core Journals. Using keywords like "prefabrication AND carbon emissions", "envelope (OR external walls) AND carbon emissions", "lifecycle AND carbon emissions", and "prefabrication AND management", a total of 500 relevant papers were retrieved.

This review reveals that existing research covers diverse perspectives, including building types, project management roles, indoor and outdoor environments, and construction organization. Based on the current development model of prefabricated buildings in China, this study identifies lifecycle stages as primary indicators and extracts key influencing factors for each stage as secondary indicators.

3.4.2. Interviews Approach

Before the interview, the author provides the explanations. The participants included 10 experts in the field of prefabricated construction and 25 front-line and secondary-line workers, such as production line operators, crane operators for wall assembly, grouting

workers, welders, truck drivers, property managers, maintenance personnel, and curtain wall cleaning professionals. Guided by grounded theory, the research focused on the carbon emissions of prefabricated envelope systems throughout their lifecycle. An interview outline comprising 27 questions was developed, addressing aspects such as component design, production, transportation, assembly, operation and maintenance, retrofitting, reuse, and carbon emissions. This approach aims to pinpoint leverage points for low-carbon technologies and provide a foundation for subsequent low-carbon design and carbon emission management strategies. This process ensured the preparation of data for the next phase of grounded theory coding and analysis.

3.5. Influencing Factors Coding and Model Test

The coding process adopted the procedural version of grounded theory by Strauss and Corbin as well as the constructive version by Charmaz [32]. The data processing followed a three-stage coding procedure, including open coding, axial coding, and selective coding, to gradually approach the essence of the research and validate the saturation of the coding system (as shown in Figure 5).

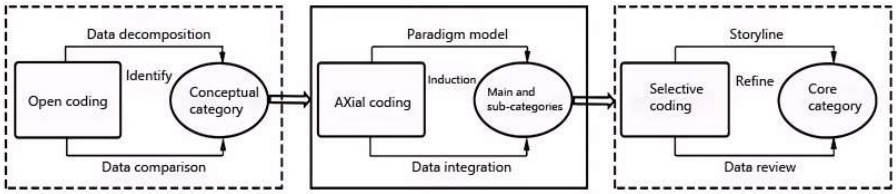


Figure 5. Coding process of influencing factors based on grounded theory.

Firstly, we conducted first-level open coding on the majority of the data, meticulously organizing and performing a comparative analysis line by line and sentence by sentence to identify initial "conceptual categories." Subsequently, we engaged in second-level axial coding to distill the "main categories" from the clues and their encompassing "conceptual" classifications. Finally, we proceeded with third-level selective coding to verify and rectify omissions, ultimately constructing an overarching system that includes "main categories", "subcategories", dimensions, and attributes.

3.5.1. Open Coding

Open coding refers to the unrestricted labeling and categorization of collected raw data to uncover connections and summarize clear concepts and themes. From the 35 interview results, 30 were randomly selected for open coding. The open coding data were organized to eliminate contradictory viewpoints and ambiguous statements, resulting in over 870 original statements. To extract valuable influencing factors, this paper selected original statements mentioned more than five times as the basis for inductive analysis, which was then used for category formation.

During the open coding, interviewees reported that the manufacturing of components typically involves or requires multiple processes, such as raw material preparation, processing, forming, and assembly, each consuming energy. Complex production processes further increase energy consumption. Some materials, such as metal alloys and concrete, are inherently energy intensive. Additionally, there is a lack of awareness and application of energy-saving technologies in some component production processes. Government and industry organizations can introduce relevant policies and standards, which we coded as "complex component production processes with significant energy consumption". Using a similar approach, we identified a total of 30 open codes.

3.5.2. Axial Coding

Axial coding builds upon open coding, delving deeper into data mining and analysis. During axial coding, similar conceptual categories are clustered and classified to determine the most critical themes and factors. Below is an example using the main category C production factors to illustrate its four primary initial categories and their respective connotations (as shown in Table 1):

Table 1. Initial categories and category connotations of C production factors.

Initial Categories	Category Connotation
C1 Use of high carbon emission materials as raw materials for production	Design should prioritize recyclable green envelope materials to reduce carbon emissions throughout the building's lifecycle; optimize design to minimize material usage
C2 Complex component production processes with high energy consumption	Specify component production precision meticulously, optimize process design, improve product surface flatness; strengthen quality inspection to ensure component quality, conduct research on prefabricated products and technologies to enhance production processes; employ scientific methods for production management

3.5.3. Selective Coding

Selective coding is the final stage of the coding process, delineating the relationships between main categories and describing their main categories, subcategories, attributes, and dimensions. It tests established relational hypotheses, refines conceptual categories requiring further development, clarifies core conceptual categories, and establishes systematic connections between core and other categories.

To ensure the reliability and validity of the research, we strictly followed the grounded theory coding procedures outlined by Strauss and Corbin [33]. We randomly selected 30 interview transcripts for grounded coding analysis. Due to the volume of interview data, only a portion is presented here to illustrate the three coding processes:

Through grounded coding analysis of 30 interview questionnaires, we identified 7 main categories and 28 initial categories (as shown in Table 2).

Table 2. Main categories of factors influencing carbon emissions.

Main Categories	Initial Categories
A Management factors	A1 Units focus only on solving problems within their own stages, not on aiming for the lowest carbon emissions throughout the lifecycle
	A2 Inadequate coordination among design, production, transportation, assembly, and operation and maintenance units across stages
	A3 Lack of a unified BIM management platform, leading to poor information transfer across stages
	A4 Absence of appropriate carbon emission statistical tools; unable to provide real-time carbon emission statistics and feedback
B Design factors	B1 Adoption of a "reverse" component detailing design approach, leading to unreasonable component design
	B2 Lack of standardized design; insufficient attention to controlling the diversity of component specifications and sizes

Table 2. *Cont.*

Main Categories	Initial Categories
B Design factors	B3 Inconsistent design software; separate modeling by units; unable to achieve "one model to the end"
	B4 Unreasonable component combination and connection methods, inconvenient for production and assembly
	B5 Failure to adopt active or passive energy-saving technologies to reduce later energy consumption
	B6 Non-utilization of renewable energy sources (solar, geothermal, wind, etc.) as energy sources
C Production factors	C1 Selection of high carbon emission materials as raw materials for component production
	C2 Complex component production processes with high energy consumption
	C3 Significant material waste during the processing from materials to components
	C4 Diverse component specifications and sizes; low production efficiency
D Transportation factors	D1 Long transportation distances from component factories to project sites
	D2 Crude transportation plans, lacking detailed logistics and control plans
	D3 Low transportation efficiency for components with complex shapes and oversized dimensions
	D4 Failure to select suitable transportation vehicles for prefabricated components
E Assembly factors	E1 Complex building plane design and numerous atriums and recesses, complicating construction
	E2 Unreasonable design of prefabricated nodes for exterior wall components; low installation efficiency
	E3 Wall panels not pre-embedded with pipes and openings, requiring on-site temporary work
	E4 Lack of detailed site layout, necessitating multiple transfers of components
F Operation and maintenance factors	F1 Poor insulation performance of the envelope; high equipment energy consumption
	F2 Poor indoor ventilation, requiring mechanical ventilation
	F3 Inadequate waterproofing and seepage prevention at component joints; frequent repairs needed
	F4 Weak anti-pollution and anti-aging capabilities of envelope components, requiring frequent cleaning or refurbishment
G Reuse factors	G1 Buildings or components are demolished or renovated before reaching their design lifespan
	G2 Difficulty and inefficiency in recycling raw materials used in components
	G3 Unreasonable connection design, complicating partial facade updates and renovations
	G4 Lack of universality in envelope design, necessitating envelope modifications for internal function changes

3.5.4. Theoretical Saturation Test

The theoretical saturation test is a common method in grounded theory research, used to assess whether the research has reached theoretical saturation. After analyzing the 30 interview results, the remaining 5 were used for the theoretical saturation test, revealing that the issues raised in these 5 surveys were essentially covered in the earlier analysis, thus concluding this round of data collection and moving into the stage of theoretical development and integration.

4. Questionnaire Setup and Initial Data Analysis

4.1. Questionnaire Design and Distribution

4.1.1. Questionnaire Design

The questionnaire was structured into three sections. In the first section, the objectives and purpose of the research were presented, alongside assurances regarding the confidentiality of respondents' information. The second section collected demographic and

professional background data, including gender, age, educational level, employment affiliation, and work experience, to provide context for the responses. The third section aimed to evaluate the impact of various factors on the lifecycle carbon emissions of prefabricated envelope systems. This section was categorized into seven domains: (A) management factors, (B) design factors, (C) production factors, (D) transportation factors, (E) assembly factors, (F) operation and maintenance factors, and (G) reuse factors. Each domain included specific questions addressing key issues, followed by a five-point Likert scale (very small, small, moderate, large, and very large) designed to assess the extent of their influence on lifecycle carbon emissions.

The survey sample predominantly comprised young to middle-aged participants, with those aged 31–45 representing the largest group, at 50.8% of the total. Regarding workplace distribution, the majority were from design units (24.6%) and assembly units (23.1%). In terms of education, most respondents held a bachelor's degree, accounting for 70.4% of the sample. For work experience, the majority had over three years in the field, with those exceeding ten years making up the largest proportion, at 50.5%, indicating that the respondents possessed considerable professional experience in the prefabricated construction industry.

4.1.2. Questionnaire Distribution

The questionnaire was distributed in two ways. First, targeted distribution was conducted via WeChat to partner enterprises and industry contacts, with 250 questionnaires distributed and 199 responses collected. Second, a professional survey agency was engaged for customized distribution, ensuring proportional targeting across design, production, transportation, assembly, and other units at a ratio of 1:1:1:1:1, with no more than five questionnaires distributed per unit. This method distributed 250 questionnaires and received 208 responses. In total, 500 questionnaires were distributed, yielding 407 responses, resulting in a response rate of 81.4%. Collected responses underwent a screening process to exclude invalid questionnaires, such as those with abnormal response times or repetitive answers across multiple questions. After excluding 13 invalid responses, 394 valid questionnaires were retained. The questionnaire comprised 26 items, with a valid questionnaire-to-item ratio exceeding 10, indicating structural stability.

4.2. Initial Data Analysis

4.2.1. Questionnaire Design Data Reliability Analysis

Reliability refers to the consistency and stability of a questionnaire under identical measurement conditions. Key concepts in reliability analysis include latent variables, observed variables, subscales (Cronbach's alpha), and the overall scale. Latent variables represent constructs that cannot be directly measured, while observed variables are those that can be directly assessed. Subscales are commonly used to evaluate internal consistency and assess the correlation between multiple items in a questionnaire, while the overall scale reflects the influence of the latent variables. The reliability analysis (as shown in Table 3) revealed that the overall reliability coefficient of the questionnaire was 0.962, with all subscale reliability coefficients exceeding 0.85. These results indicate strong internal consistency among the items and demonstrate that the questionnaire exhibits a high level of reliability.

Table 3. Reliability analysis results.

Latent Variables	Observed Variables	Subscalar Cronbach's Alpha	Total Meter Quantity
A Management factors	A1–A4	0.865	0.962
B Design factors	B1–B6	0.895	
C Production factors	C1–C4	0.896	
D Transportation factors	D1–D4	0.864	
E Assembly factors	E1–E4	0.889	
F Operation and maintenance factors	F1–F4	0.886	
G Reuse factors	G1–G4	0.856	

4.2.2. Data Validity Analysis

Validity refers to the extent to which a questionnaire accurately measures the intended concepts. Common methods for validity analysis include the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity. The KMO measure evaluates the suitability of sample data for factor analysis by assessing the degree of correlation among variables. Its value ranges from 0 to 1, with values closer to 1 indicating higher suitability for factor analysis due to strong inter-variable correlations. Bartlett's test of sphericity examines whether the correlations among observed variables are sufficiently large to justify factor analysis. A statistically significant result (p-value < 0.05) indicates that the observed variables are interrelated enough for factor analysis. In this study, the validity analysis (as shown in Table 4) revealed a KMO value of 0.962 for the questionnaire data, with Bartlett's test of sphericity yielding a statistically significant result. These findings confirm that the questionnaire exhibits strong validity, and the sample data provide a reliable basis for further analysis.

Table 4. Validity analysis results.

Test		Value
KMO Sample Appropriateness		0.962
Bartlett's test of sphericity	Approximate chi-square	8580.824
	DOF	435
	Significance	0.000

5. Results Analysis

5.1. Descriptive Statistical Analysis

Descriptive statistical analysis summarizes and describes the basic characteristics, distribution patterns, and variability of collected sample data. This section presents an analysis of 394 valid samples used in the study. Based on the grounded theory approach, a lifecycle influence factor model for prefabricated envelope systems was established. The model incorporates seven latent variables from variable A to variable G, under which 26 observed variables are categorized. The descriptive analysis provides insights into the central tendencies, distribution characteristics, and variability of these sample data (as shown in Table 5).

Table 5. Descriptive statistical analysis.

Observed Variable	Number	Average	Standard Deviation	Skewness		Kurtosis	
	Statistics	Statistics	Statistics	Statistics	Standard Error	Statistics	Standard Error
A1	394	3.44	1.239	−0.528	0.123	−0.705	0.245
A2	394	3.31	1.194	−0.277	0.123	−0.809	0.245
A3	394	3.09	1.346	−0.181	0.123	−1.163	0.245
A4	394	3.51	1.285	−0.524	0.123	−0.786	0.245
B1	394	3.40	1.230	−0.353	0.123	−0.869	0.245
B2	394	3.21	1.351	−0.270	0.123	−1.176	0.245
B3	394	3.46	1.244	−0.505	0.123	−0.673	0.245
B4	394	3.29	1.204	−0.345	0.123	−0.730	0.245
B5	394	3.37	1.204	−0.448	0.123	−0.673	0.245
B6	394	3.32	1.237	−0.240	0.123	−0.922	0.245
C1	394	3.63	1.260	−0.626	0.123	−0.631	0.245
C2	394	3.21	1.339	−0.283	0.123	−1.141	0.245
C3	394	3.29	1.212	−0.320	0.123	−0.738	0.245
C4	394	3.41	1.152	−0.425	0.123	−0.531	0.245
D1	394	3.35	1.146	−0.385	0.123	−0.575	0.245
D2	394	3.12	1.200	−0.174	0.123	−0.794	0.245
D3	394	3.26	1.156	−0.324	0.123	−0.623	0.245
D4	394	3.07	1.240	−0.039	0.123	−0.875	0.245
E1	394	3.18	1.271	−0.250	0.123	−0.973	0.245
E2	394	3.15	1.245	−0.218	0.123	−0.922	0.245
E3	394	3.25	1.255	−0.256	0.123	−0.862	0.245
E4	394	3.21	1.217	−0.287	0.123	−0.704	0.245
F1	394	3.41	1.272	−0.403	0.123	−0.879	0.245
F2	394	3.25	1.267	−0.335	0.123	−0.894	0.245
F3	394	3.05	1.273	−0.123	0.123	−1.077	0.245
F4	394	3.12	1.170	−0.210	0.123	−0.780	0.245
G1	394	3.32	1.330	−0.349	0.123	−1.083	0.245
G2	394	3.40	1.282	−0.400	0.123	−0.843	0.245
G3	394	3.30	1.272	−0.311	0.123	−0.953	0.245
G4	394	3.38	1.135	−0.414	0.123	−0.506	0.245

The sample data exhibit the following characteristics: the standard deviation, which measures the dispersion of the data, ranges between 1.0 and 1.5, indicating moderate variability. The narrow range of the standard deviation suggests that the dispersion of the data is relatively balanced. Skewness, a metric that assesses the symmetry of data distribution, has an absolute value of less than 0.7, indicating that the data distribution is approximately symmetric. This symmetry implies that the data are evenly distributed around the mean, with no significant skew. Kurtosis, which indicates the peakedness of the data distribution, has an absolute value lower than 1.2, suggesting that the distribution is relatively flat without extreme peaks or flattening. Given that the data distribution follows the characteristics of normality, the SEM model is deemed suitable for verification in this context.

5.2. Application of SEM

5.2.1. Modeling Assumptions

Project management decisions and planning involve coordination across the whole lifecycle stage. The scientific nature of the management decision-making process significantly impacts each stage's operations. In the design phase, decisions regarding the type,

connection methods, and final state of building components directly influence the carbon emissions during subsequent stages, including production, transportation, assembly, operation, and reuse. Therefore, the design phase not only determines the operational framework for later stages but also plays a critical role in carbon emission control. Communication between designers and project managers influences the management process, thereby indirectly affecting carbon emissions at each stage. The production phase determines material selection, which in turn influences the recycling and reuse potential of components in later stages. Thus, management decisions throughout the whole-process project are interconnected and have a profound impact on carbon emissions across all stages. Based on the literature review, expert interviews, and practical involvement, the following hypotheses regarding the intrinsic relationships between the latent variables are proposed:

H1. *Management factors have a significant impact on design factors.*

H2. *Management factors have a significant impact on production factors.*

H3. *Management factors have a significant impact on transportation factors.*

H4. *Management factors have a significant impact on assembly factors.*

H5. *Management factors have a significant impact on operation and maintenance factors.*

H6. *Management factors have a significant impact on reuse factors.*

H7. *Design factors have a significant impact on management factors.*

H8. *Design factors have a significant impact on production factors.*

H9. *Design factors have a significant impact on transportation factors.*

H10. *Design factors have a significant impact on assembly factors.*

H11. *Design factors have a significant impact on operation and maintenance factors.*

H12. *Design factors have a significant impact on reuse factors.*

H13. *Production factors have a significant impact on reuse factors.*

5.2.2. Model FITNESS and Modification

The fitness of the SEM is used to evaluate the degree to which the established model fits the actual data. Fitness indicators provide an overall assessment of the model's quality, helping researchers determine whether the model effectively explains and predicts the observed data. Common indicators included the ratio of chi-square to degrees of freedom (CMIN/DF), Incremental Fit Index (IFI), root mean square error of Approximation (RMSEA), standardized fit index (GFI), Comparative Fit Index (CFI), and non-standardized fitness indicators.

According to the values provided in Table 6, the CMIN/DF ratio is 1.820, which is below the acceptable threshold of 3. Additionally, the standardized fitness indicators (such as CFI, GFI, RMSEA, and SRMR) are close to or meet the predefined thresholds. Specifically, the RMSEA value is 0.046, which is below the 0.08 threshold. All fitness indicators meet the acceptable criteria, indicating that the structural model demonstrates a good fit to the

sample data and satisfies the requirements for SEM analysis; thus, no further modifications are necessary.

Table 6. Fitness indicators requirements and values for SEM model path analysis.

Fitting Index	Tolerance Interval	Observed Value
The ratio of chi-square to degrees of freedom (CMIN/DF)	1 < chi-square/df < 3 shows that the model has a reduced fit degree, and chi-square > 5 shows that the model needs to be rested; the smaller the index, the higher the fitting degree.	1.820
Number of incremental fit values (IFI)	>0.8 Receivability, >0.90 Relatively ideal, Close to 1, Best fit	0.964
Root mean square error approximates the exponent (RMSEA)	<0.05 Relatively ideal, <0.08 Receivability	0.046
Standardize the fit index (NFI)	>0.8 Receivability, >0.90 Relatively ideal, Close to 1, Best fit	0.922
Compare the fit index (CFI)	>0.90 Relatively ideal, >0.8 Receivability, Close to 1, Best fit	0.963
Non-standardized fit index TLI (NNFI)	>0.90 Relatively ideal, >0.8 Receivability	0.958

5.2.3. SEM Path Analysis

Maximum likelihood estimation (MLE) is a statistical method used to estimate unknown parameter values from observed data. The path coefficients of SEM represent the strength of the relationships between variables. When the sample data follow a normal distribution, MLE is suitable for estimating the path coefficients in SEM. Based on the descriptive data analysis, it was found that the sample data follow a normal distribution, making MLE appropriate for estimating the path coefficients.

The author writes the SEM code and generate a path analysis diagram, and the direct path test results for each latent variable are obtained, with the corresponding standardized path coefficients presented in Figure 6.

In the context of whole lifecycle management, the direct effects on the dominant dimensions of lifecycle management, ranked by the path coefficient from highest to lowest, are as follows: unified BIM management platform (1.543), establishment of low-carbon lifecycle goals (1.401), level of collaboration (1.301), and carbon emission statistics tools (1.000). For design factors, the direct effects, ranked by the path coefficient, are as follows: standardization of components (1.657), connection and combination of components (1.391), application of active or passive energy-saving technologies (1.375), use of renewable energy technologies (1.350), adoption of "reverse" design processes (1.270), and use of a unified design platform for "one-model-to-the-end" implementation (1.000). In production factors, the direct effects, ranked by the path coefficient, are as follows: production processes of components (1.335), material utilization rates (1.120), component specifications and dimensions (1.060), and carbon emissions of materials (1.000). For transportation factors, the direct effects, ranked by the path coefficient, are as follows: refined transportation (1.095), selection of transportation vehicles (1.051), transportation distance (1.034), and complexity of component shapes (1.000). In assembly factors, the direct effects, ranked by the path coefficient, are as follows: architectural floor plan design (1.187), consideration of wall panel openings (1.116), refined site preparation (1.075), and node design (1.000). For operation and maintenance factors, the direct effects, ranked by the path coefficient, are

as follows: water resistance and permeability of components (1.262), thermal insulation performance of components (1.178), ventilation levels of the envelope (1.149), and durability and resistance to aging and pollution of components (1.000). In reuse factors, the direct effects, ranked by the path coefficient, are as follows: building service life (1.403), ease of component recycling (1.187), versatility of the envelope (1.009), and whether the connection structure is conducive to renovation (1.000).

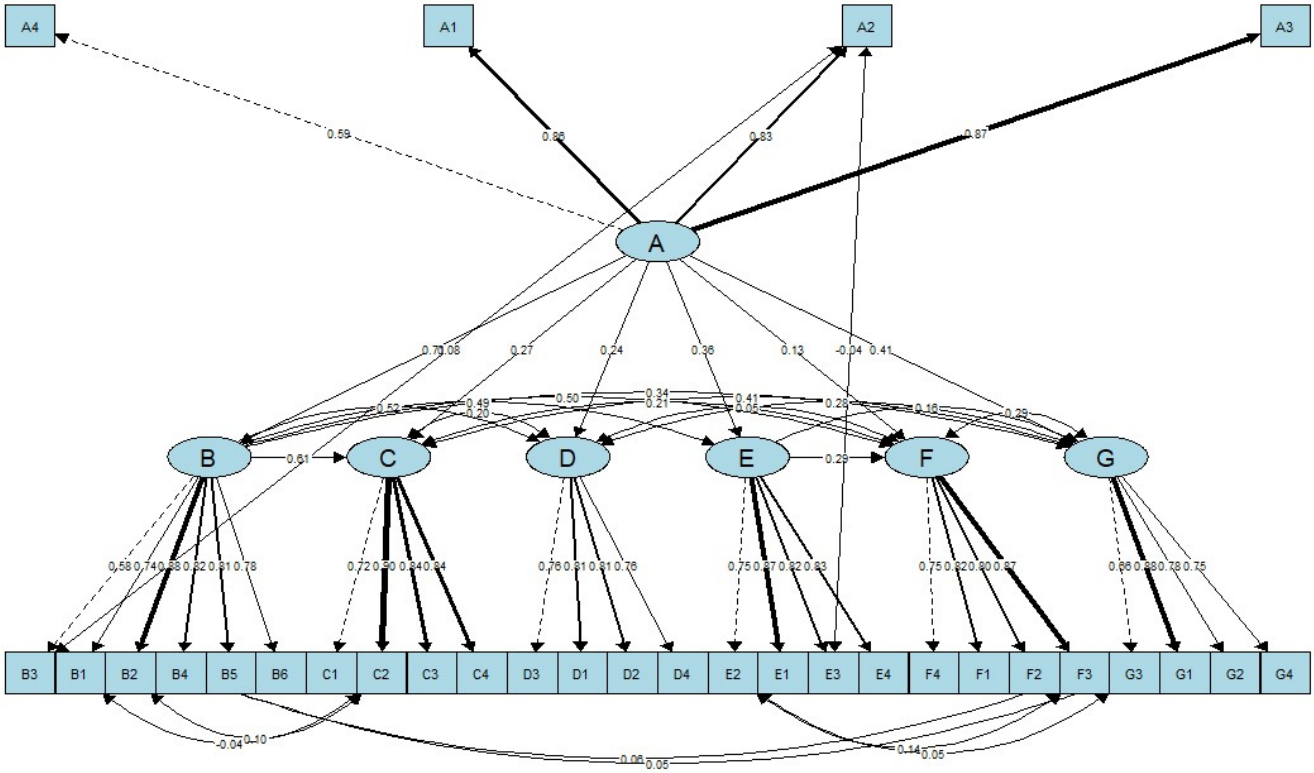


Figure 6. The SEM path analysis diagram.

The analysis results of the path relationships between observed variables in Table 7 were obtained through path coefficient calculations using SEM by R language, with the corresponding standardized path coefficients presented in Figure 6.

Table 7. Analysis results of the path relationships between observed variables.

Latent Variable	Observed Variable	Non-Normalized Coefficient	*p*-Value	Normalized Coefficient	Conclusion
A	A1	1.401	***	0.858	Pass
	A2	1.301	***	0.827	Pass
	A3	1.543	***	0.870	Pass
	A4	1.000	***	0.591	Pass
B	B1	1.270	***	0.733	Pass
	B2	1.657	***	0.873	Pass
	B3	1.000	***	0.571	Pass
	B4	1.391	***	0.821	Pass
	B5	1.375	***	0.810	Pass
	B6	1.350	***	0.775	Pass

Table 7. *Cont.*

Latent Variable	Observed Variable	Non-Normalized Coefficient	*p*-Value	Normalized Coefficient	Conclusion
C	C1	1.000	***	0.722	Pass
	C2	1.335	***	0.906	Pass
	C3	1.120	***	0.840	Pass
	C4	1.060	***	0.836	Pass
D	D1	1.034	***	0.802	Pass
	D2	1.095	***	0.812	Pass
	D3	1.000	***	0.770	Pass
	D4	1.051	***	0.754	Pass
E	E1	1.187	***	0.869	Pass
	E2	1.000	***	0.749	Pass
	E3	1.116	***	0.828	Pass
	E4	1.075	***	0.822	Pass
F	F1	1.178	***	0.818	Pass
	F2	1.149	***	0.800	Pass
	F3	1.262	***	0.874	Pass
	F4	1.000	***	0.754	Pass
G	G1	1.403	***	0.886	Pass
	G2	1.187	***	0.776	Pass
	G3	1.000	***	0.658	Pass
	G4	1.009	***	0.745	Pass

Infuse: *** Shows *p*-value less than 0.001.

Based on the analysis of the sample data, the research hypotheses in Table 8 are evaluated. The SEM results support the following hypotheses:

Hypothesis H1. *Management factors have a positive effect on design factors.*

Hypothesis H2. *Management factors have a positive effect on production factors.*

Hypothesis H3. *Management factors have a positive effect on transportation factors.*

Hypothesis H4. *Management factors have a positive effect on assembly factors.*

Hypothesis H5. *Management factors have a positive effect on operation and maintenance factors.*

Hypothesis H6. *Management factors have a positive effect on reuse factors.*

Hypothesis H7. *Design factors have a positive effect on management factors.*

Hypothesis H8. *Design factors have a positive effect on production factors.*

Hypothesis H9. *Design factors have a positive effect on transportation factors.*

Hypothesis H10. *Design factors have a positive effect on assembly factors.*

Hypothesis H11. *Design factors have a positive effect on operation and maintenance factors*

Hypothesis H12. *Design factors have a positive effect on reuse factors.*

Hypothesis H13. *Production factors have a positive effect on reuse factors.*

Table 8. The path analysis results for the variables in the structural model.

Construction Number	Path Relationship	Non-Standardized Estimates	*p*-Value	Standardized Estimates	Conclusion
H1	Management → Design	0.291	***	0.311	Pass
H2	Management → Production	0.322	***	0.269	Pass
H3	Management → Transportation	0.273	***	0.232	Pass
H4	Management → Assembly	0.455	***	0.371	Pass
H5	Management → Operation and Maintenance	0.282	***	0.243	Pass
H6	Management → Reuse	0.424	***	0.385	Pass
H7	Design → Management	0.545	***	0.509	Pass
H8	Design → Production	0.788	***	0.615	Pass
H9	Design → Transportation	0.648	***	0.517	Pass
H10	Design → Assembly	0.623	***	0.475	Pass
H11	Design → Operation and Maintenance	0.794	***	0.639	Pass
H12	Design → Reuse	0.271	***	0.230	Pass
H13	Production → Reuse	0.289	***	0.315	Pass
H14	Management → Design → Production	0.229	***	0.191	Pass
H15	Management → Design → Assembly	0.181	***	0.148	Pass
H16	Management → Design → Operation and Maintenance	0.231	***	0.199	Pass

Infuse: *** Shows *p*-value less than 0.001.

Through model fitting and optimization, several key driving paths are identified, such as the following:

"Management" → "Design" → "Production";
"Management" → "Design" → "Assembly";
"Management" → "Design" → "Operation and Maintenance".

The findings suggest that design and management factors significantly influence transportation, assembly, operation and maintenance, and reuse factors across the entire lifecycle, making them crucial factors in determining the carbon emissions of the entire lifecycle. To reduce carbon emissions in the lifecycle of the building envelope component system, optimizing design and management (including carbon emission management) through paths such as "Management" → "Design" → "Production" "Management" → "Design" → "Assembly" and "Management" → "Design" → "Operation and Maintenance" should be considered for minimizing carbon emissions in other stages.

6. Discussion

6.1. Analysis of Survey Results

In the SEM model, the covariance matrix between observed variables is calculated to determine their degree and direction of association. Based on previous literature research, the influence paths of measurement variables between different latent variables were

hypothesized, revealing certain relationships between them. The specific indicators are shown in the Table 9 below:

Table 9. Covariance matrix between observed variables.

Non-Standard Covariance	Standard Covariance
0.046	0.068
0.042	0.116
0.049	0.132
0.059	0.142
0.032	0.076
0.048	0.085
0.033	0.050
0.070	0.135
0.065	0.127
0.037	0.048

In the process of building lifecycle management, the correlation between A2 and B3 indicates that the synergy between stages is related to the design platforms applicable at each stage. To achieve efficient collaborative work, it is essential to adopt a unified working platform as much as possible, thereby enhancing information transfer efficiency and cross-stage collaboration levels.

From the production phase perspective, the correlations of B1–C2, B2–C2, and B2–C4 show that the method of component splitting and the adoption of standardized design during the design phase significantly impact the efficiency and carbon emissions of the production phase. Reasonable component splitting methods and a high standardization rate can optimize production processes, reduce material waste, and improve production efficiency, thereby effectively lowering carbon emissions during the production phase.

Considering the operation and maintenance phase, the correlation of B5–F1 reveals that the failure to adopt active or passive energy-saving technologies during the design phase will increase reliance on high-energy-consuming equipment during the operation and maintenance phase, significantly raising carbon emissions. Therefore, the design phase should prioritize the application of energy-saving technologies, optimizing the performance of the building envelope to reduce energy consumption in subsequent operation and maintenance phases.

From the perspective of reuse, the correlation of F4–G1 indicates that poor resistance to pollution or aging in the building envelope can shorten the building's lifespan, leading to premature demolition or renovation before reaching the designed lifespan. This highlights the need for durability design and material selection in the building envelope, with a preference for materials with excellent durability to extend the building's lifecycle.

Additionally, the strong correlations of B4–G3 and E2–G3 show that the connection methods of exterior walls significantly affect the reuse level of components. To improve the recycling efficiency of components, flexible connection methods such as reversible connections should be adopted in node design, allowing components to be reused or modified after disassembly, thereby achieving resource recycling of components.

6.2. Design Recommendations

From the above research, it is evident that the design of the building envelope plays a crucial role in influencing carbon emissions during its lifecycle, including production, transportation, operation and maintenance, and reuse. Optimizing the design to meet the low-carbon requirements of these phases during the initial design stage is essential in minimizing overall carbon emissions.

By correlating the key factors influencing carbon emissions throughout the lifecycle, as identified through questionnaire analysis, with the various stages of the whole-process design, we can derive carbon control design recommendations for the entire process. These recommendations encompass design management, facade design, and component design. Taking material selection in the component design stage as an example, this phase is linked to management factor A4, production factor C1, assembly factor D1, and reuse factor G2 from the questionnaire. Therefore, during material selection, these aspects must be considered to optimize the design at the design stage, thereby reducing carbon emissions in subsequent processes such as production, assembly, and reuse. By summarizing other factors in a similar manner, we can establish key points for carbon control throughout the lifecycle of the building envelope (as shown in Figure 7). This diagram enables designers to understand how to approach each stage of design to achieve low-carbon goals across the building's entire lifecycle.

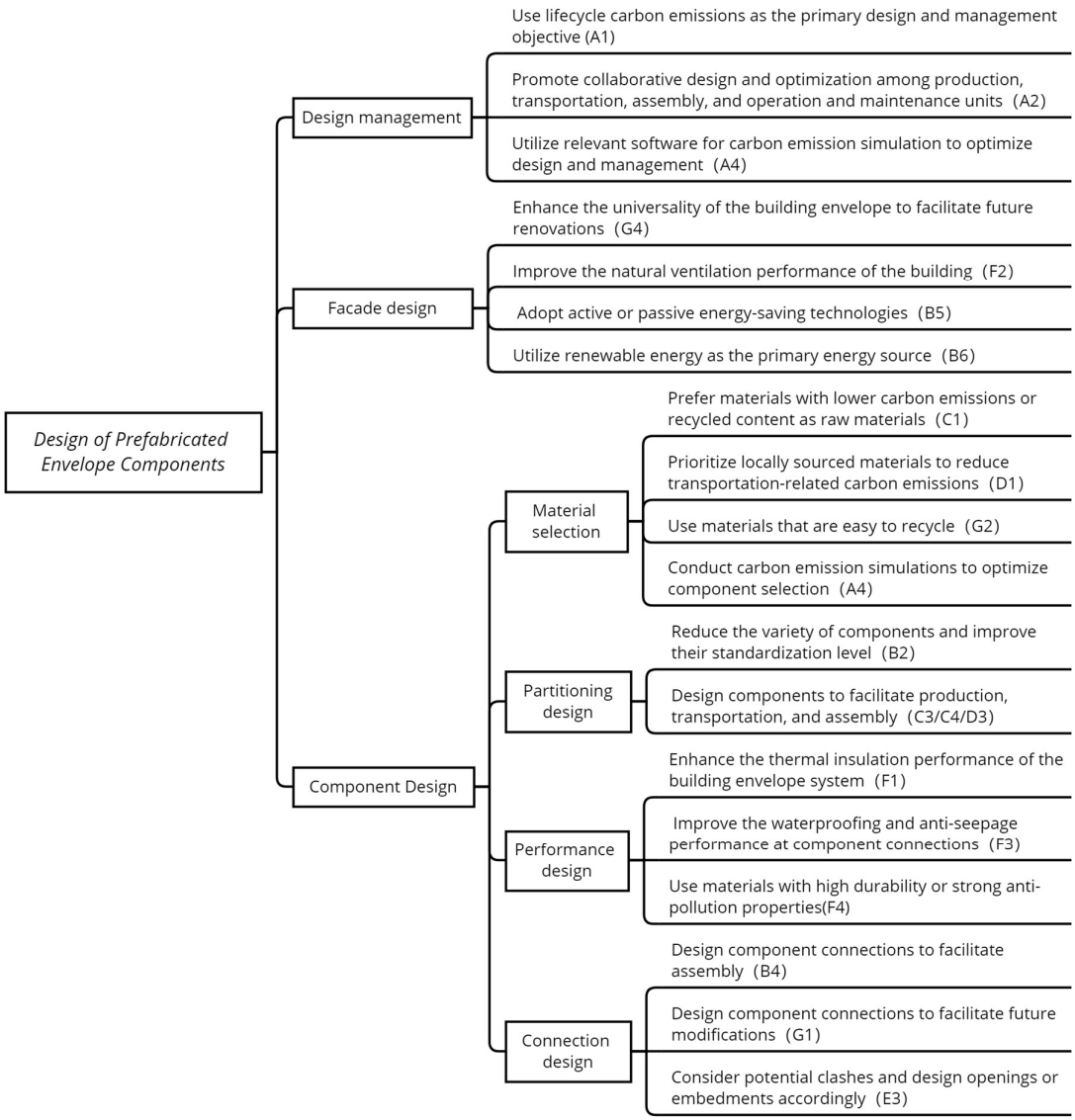


Figure 7. Key design recommendations at each stage.

6.3. Limitations

The lifecycle of building envelopes is influenced by a wide range of components. Despite conducting a thorough investigation, this study was unable to account for all conceivable influences, indicating the need for additional research in follow-up studies.

Furthermore, reducing carbon emissions in one stage may result in greater emissions of carbon in subsequent stages since components are operational entities that exceed the production, transportation, and assembly phases. More accurate analysis is needed to determine whether the overall effect is a decrease in carbon emissions or an increase. As a result, this study can only offer qualitative operational advice to designers. More accurate techniques, including software-based simulation and comparison, can be needed to accomplish exact goals.

7. Case Study—Restroom Renovation Project of the Outpatient Building of Jiangsu Maternal and Child Health Hospital

7.1. Case Introduction

Guided by the aforementioned research on carbon reduction pathways, the author applied the "component-based" architectural design approach to a practical project. During the design phase, the project comprehensively considered the low-carbon requirements throughout the building's lifecycle. By utilizing relevant platforms for carbon emission simulations, the project selected material types and thickness combinations with the lowest carbon emissions. Additionally, BIM technology was employed to achieve efficient management of the external envelope system (as shown in Figure 8) across various stages, including production, transportation, assembly, and operation and maintenance, resulting in a high-quality restroom renovation project.



Figure 8. The design of the outpatient building of Jiangsu Maternal and Child Health Hospital.

7.2. Design Scheme

The restroom renovation project of the outpatient building of Jiangsu Maternal and Child Health Hospital is located in Gulou District, Nanjing, Jiangsu Province, China. The project covers an area of approximately 105 m^2, with a building area of about 420 m^2. The building has four floors and includes public restroom facilities.

Given that the surrounding buildings include the outpatient and inpatient buildings of a maternal and child health hospital, prefabricated construction techniques were adopted for all component systems to minimize noise during construction. The building features a square layout and facade, with the distance from the existing building designed to accommodate the installation of the external envelope. The structural system consists of a frame steel structure, while the interior system employs lightweight partition walls and prefabricated interior finishes with aluminum cladding. The external envelope system uses prefabricated composite wall panels, combining standardized vertical wall panels with high windows to ensure each space has access to natural light. The building's color scheme harmonizes with the adjacent structures.

7.3. External Envelope Detailed Design

For the envelope component design, the structural panel size is 9 m × 9 m, with the external envelope components designed to match the structural system's dimensions. The horizontal structural grid is 1.0 m × 1.0 m, and the facade uses standardized 1.0 m × 4.0 m (floor height) wall panels, with L-shaped panels at corners. Windows are uniformly designed as high windows, with a sill height of 1800 mm and a window height of 900 mm.

During the material selection and combination design phase, BIM technology was used to simulate carbon emissions at various stages to identify the external envelope design with the lowest carbon emissions. Given the prefabricated construction method and the constrained construction environment, sandwich insulation or self-insulating walls were prioritized to avoid damage to the insulation layer during assembly. Based on relevant standards for compressive and tensile strength, freeze–thaw resistance, and insulation coefficients, self-insulating walls were narrowed down to foamed ceramics and foam concrete, while sandwich insulation prefabricated walls used a composite wall scheme, and materials were selected that meet regulatory requirements for the inner leaf, core, and outer leaf.

The construction requirements and thicknesses for walls, roofs, and windows were based on relevant building codes and material application guidelines, with the minimum allowable values used as the baseline for simulations. Single-layer walls did not exceed 240 mm, and composite walls did not exceed 360 mm, with increments of 1 cm for ease of material production and processing. This resulted in 2940 external envelope design options, which were numbered and simulated for lifecycle carbon emissions using BIM to identify the option with the lowest carbon emissions.

The lifecycle carbon emissions were calculated based on the GB/T-51366 standard, covering production, transportation, assembly, and operation and maintenance stages. To enhance simulation reliability, auxiliary materials and labor hours for production, transportation, and assembly were referenced from the "Jiangsu Prefabricated Concrete Engineering Quota" (Trial) Su Jian Price [2017] No. 83. Since current quotas are based on precast concrete wall panels, analogies were made for new wall panel types. The carbon emission simulation process involved the following: a. using Rhino 7.5 to extract geometric model information related to the external envelope; b. importing weather data (temperature, humidity, wind speed, and solar radiation); c. input construction and operational data (personnel, time, and equipment); d. conducting energy consumption simulations; e. integrating all material, equipment, energy, and personnel data, applying carbon emission factors to calculate lifecycle emissions in Table 10.

Table 10. External wall, window, and roof construction options.

No.	The Thickness	Heat Preservation Thickness	Roofing Insulation Thickness	Exterior Window	Build Carbon Emissions	Operating Carbon Emissions (at 50 Years)	Full Lifecycle Carbon Emissions
1	RC-0	FC-130	PUR-60	W1	22,523.30	223,976.10	246,499.39
2	RC-0	FC-130	PUR-60	W2	22,781.65	223,976.10	246,757.75
3	RC-0	FC-130	PUR-60	W3	22,781.65	223,976.10	246,757.75
4	RC-0	FC-130	PUR-70	W1	22,688.25	223,156.91	245,845.16
5	RC-0	FC-130	PUR-70	W2	22,946.61	223,156.91	246,103.52

In the embodied carbon stage (production, transportation, and assembly), material selection had the most significant impact, followed by insulation and window choices. For

example, using RC precast concrete panels resulted in 2.4 times higher carbon emissions compared to FC foamed ceramic panels. As material thickness increased, embodied carbon emissions also rose significantly. For instance, Option 1 (RC-0-FC-130-PUR-60-W1) had embodied carbon emissions of 22,523.30, while Option 252 (RC-0-FC-240-PUR-120-W3) had 33,513.32, a 1.5-fold difference. The lowest embodied carbon option was 434 (RC-0-FC-130-EPS-90-W1) at 22,349.80.

Operational carbon emissions decreased as wall thickness increased, showing an inverse correlation with embodied carbon. Operational carbon accounted for 73–91% of lifecycle emissions, while embodied carbon contributed 9–27%, The variation in operational carbon emissions was comparable in magnitude to total embodied carbon emissions, emphasizing the need to consider both factors in design. For connection design, quick assembly was prioritized. External envelope components were attached to the structure using hanging brackets. Seams were sealed with foam strips, polyurethane foam, and exterior sealant to enhance airtightness and water resistance.

Simulation results (as shown in Figures 9 and 10) revealed significant variations: the maximum difference in embodied carbon emissions among different exterior envelope options was nearly two-fold. Under ideal operational and maintenance conditions, low-carbon exterior envelope options could reduce carbon emissions by nearly 25%. From a lifecycle perspective, the option with the lowest carbon emissions could save almost 17% compared to the highest-emitting option. While actual construction and operational conditions may deviate from simulations, these results still demonstrate that design strategies for carbon emission optimization can achieve considerable carbon reduction effects. As the simulation results showed, Option 250 had the lowest lifecycle carbon emissions, featuring 240 mm foamed ceramic walls, 120 mm rigid polyurethane roof insulation, and 6 mm + 12 A + 6 mm Low-E windows, which were selected for the final design.

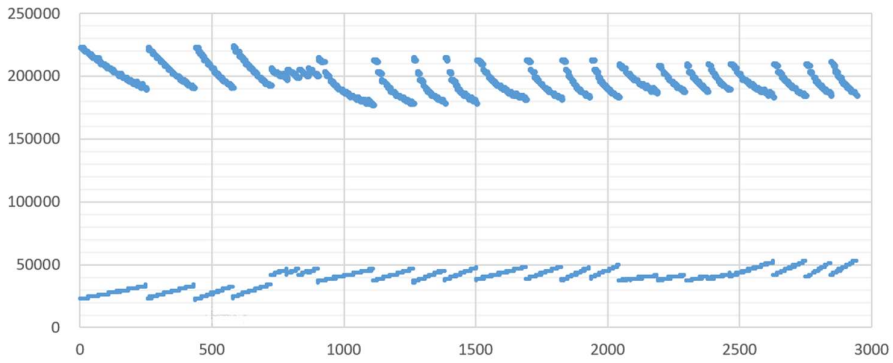


Figure 9. Simulation of carbon emissions comparison during materialization, construction, and operation stages (for 50 Years).

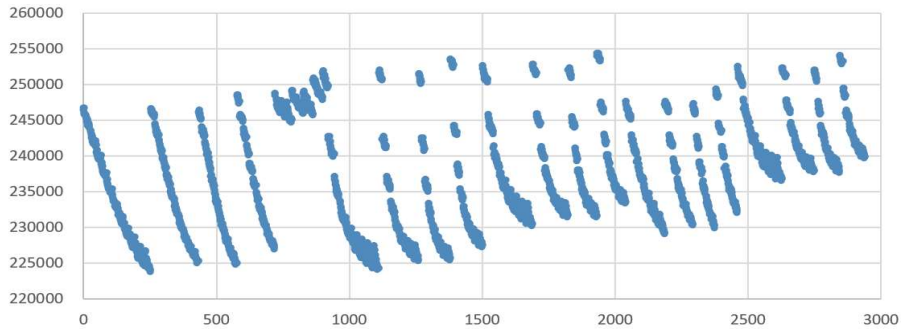


Figure 10. Comparison of carbon emissions during materialization, construction, and operation stages.

7.4. Carbon Reduction Design in Construction

During component production, each step was analyzed to optimize the process, reduce waste, and improve efficiency. Industrial waste such as ceramic tailings, fly ash, and slag were recycled to produce a high-porosity, low-density ceramic material, reducing carbon emissions from cement production and brick firing. A customized production process was developed for large-format foamed ceramic panels. The process included cutting, grooving, reinforcing, laminating, curing, bracket installation, putty application, painting, and packing. The production of all components was completed within 15 days.

The packaging was designed for efficient transport, incorporating wooden frames to facilitate forklift handling. BIM simulations ensured smooth assembly. However, some rework was necessary due to paint damage during installation. This highlights the importance of anticipating assembly challenges to prevent additional carbon emissions.

7.5. BIM-Based Project Management

BIM was used to model structural, envelope, interior, and MEP systems, optimizing design details and simulating clashes to ensure comprehensive and data-driven planning. The BIM model guided production, transportation, and assembly, with all project data integrated into the platform for efficient management. The project utilized the Nanjing Prefabricated Building Information Service and Supervision Platform, which tracks prefabricated components and assembly rates across Jiangsu Province. Each external envelope component was assigned a unique QR code, enabling all stakeholders to track production, transportation, assembly, and inspection in real time via a map-based interface.

In summary, the project successfully implemented carbon reduction strategies across all stages, leveraging BIM for simulation and management to ensure efficient production, transportation, and assembly.

8. Conclusions

8.1. Summary of the Study

This study systematically investigates the carbon emissions of prefabricated building envelope components throughout their lifecycle, employing grounded theory, a literature review, questionnaire surveys, and interviews to identify key influencing factors. Seven main categories and 26 initial categories were identified, which were further analyzed using Structural Equation Modeling (SEM) to explore the relationships and interactions among these factors. The findings reveal that design and management factors significantly impact carbon emissions across various stages, including production, transportation, assembly, operation, maintenance, and reuse. Key pathways were identified, such as management influencing design, which in turn, affects production, assembly, and operation and maintenance. This highlights the critical role of design and management in achieving low-carbon goals for building envelope systems.

8.2. Quantitative Results

1. Design and management impact: Among design factors, the level of component standardization, the method of connection and disassembly, and the adoption of energy-efficient designs are crucial in influencing lifecycle carbon emissions. In terms of management factors, a unified work platform, cross-stage collaboration efficiency, and the use of carbon emission statistical tools are key influencers. Design and management factors were found to be the most influential in reducing carbon emissions across all lifecycle stages. For instance, optimized design strategies can reduce operational carbon emissions by up to 25%, while lifecycle carbon emissions can be reduced by nearly 17% through optimal material and component selection.

2. Material and component optimization: Simulation results demonstrated that material selection and thickness significantly impact carbon emissions. Under the premise of meeting design specifications, thicker envelope materials result in higher embodied carbon emissions during the production phase but lower operational carbon emissions. From the lifecycle carbon emission simulations conducted in this study, operational carbon emissions accounted for 73–91% of the total lifecycle emissions, while embodied carbon contributed 9–27%. This underscores the importance of considering both operational and embodied carbon in design decisions.
3. Connection and assembly design: quick assembly and airtight connection designs, such as the use of hanging brackets and sealants, were shown to enhance the overall performance of the building envelope, reducing both operational and embodied carbon emissions.

8.3. Strengths and Significance of the Study

Comprehensive industry survey: The study involved a survey of professionals in the construction industry, providing a holistic view of carbon emissions across the entire lifecycle of prefabricated building envelope systems. This broadens the scope of optimization considerations for designers.

Integration of qualitative and quantitative methods: the combination of grounded theory, SEM analysis, BIM simulations, and case studies offers a robust methodological framework for identifying and addressing key factors influencing carbon emissions.

Practical design recommendations: This study translates its findings into actionable design guidelines for carbon control throughout the lifecycle of building envelopes, covering three main stages: conceptual design, detailed design, and construction design. These recommendations, supported by case studies, provide designers with practical tools to achieve low-carbon goals.

8.4. Implications, Limitations, and Future Work

This study's recommendations are based on ideal conditions and may need to be adjusted for specific project contexts. Future research should explore the application of these strategies in diverse real-world scenarios.

While the study provides qualitative recommendations, further quantitative analysis using BIM and other simulation tools is needed to validate the carbon reduction potential of different design strategies.

Future work could extend the study's framework to other building systems and components, exploring the potential for carbon reduction across the entire building lifecycle.

8.5. Design Considerations

To summarize the key findings and recommendations, a concise roadmap for the low-carbon design of prefabricated building envelope systems is provided below (as shown in Table 11):

By following this roadmap, designers can effectively control carbon emissions throughout the lifecycle of prefabricated building envelope systems, contributing to the broader goals of carbon peaking and carbon neutrality in the construction industry.

Table 11. Low-carbon design considerations of prefabricated building envelope systems.

Design Stage	Design Considerations
Design management	- Set lifecycle carbon reduction as a primary design goal. - Collaborate with production, transportation, assembly, and maintenance teams. - Use simulation tools to optimize design for carbon reduction.
Facade design	- Enhance the versatility of the building envelope for future modifications. - Improve natural ventilation and adopt passive or active energy-saving technologies. - Integrate renewable energy sources.
Component design	- Material Selection: choose low-carbon, recyclable, and locally sourced materials. - Component Configuration: use simulation tools to optimize material thickness and configuration. - Connection Design: ensure quick assembly and airtight connections.
Performance optimization	- Improve thermal insulation and waterproofing performance. - Use durable and easy-to-maintain materials.

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References

1. Bringing Embodied Carbon Upfront: Coordinated Action for the Building and Construction Sector to Tackle Embodied Carbon. Available online: https://worldgbc.org/article/bringing-embodied-carbon-upfront/ (accessed on 3 November 2024).
2. Luo, T.; Xue, X.; Wang, Y.; Xue, W.; Tan, Y. A Systematic Overview of Prefabricated Construction Policies in China. *J. Clean. Prod.* **2021**, *280*, 124371. [CrossRef]
3. *EN 15978:2011*; Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. European Committee for Standardization: Brussels, Switzerland, 2011. Available online: https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011 (accessed on 19 April 2024).
4. Huang, B.; Zhang, H.; Ullah, H.; Lv, Y. BIM-Based Embodied Carbon Evaluation during Building Early-Design Stage: A Systematic Literature Review. *Environ. Impact Assess. Rev.* **2025**, *112*, 107768. [CrossRef]
5. Ullah, H.; Zhang, H.; Huang, B.; Gong, Y. BIM-Based Digital Construction Strategies to Evaluate Carbon Emissions in Green Prefabricated Buildings. *Buildings* **2024**, *14*, 1689. [CrossRef]
6. Xia, H.; Li, M. Modular Coordinated and Intelligent Construction of New Architectural Industrialization. *Build. Sci.* **2019**, *35*, 147–154.
7. Song, Y.; Zhang, H.; Mithraratne, N. Research on Influences of Wall Design on Embodied and Operating Energy Consumption: A Case Study of Temporary Building in China. *Energy Build.* **2023**, *278*, 112628. [CrossRef]
8. Jung, Y.Y.-S. A Design of Structural Precast Reinforced Concrete Facade for a High Rise Urban Housing Type. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 1962.
9. Audenaert, A.; De Cleyn, S.H.; Buyle, M. LCA of Low-Energy Flats Using the Eco-Indicator 99 Method: Impact of Insulation Materials. *Energy Build.* **2012**, *47*, 68–73. [CrossRef]
10. Al Hawarneh, A. Dynamic Facilities Planning Model for Large Scale Construction Projects. *Autom. Constr.* **2019**, *98*, 72–89. [CrossRef]

11. Cheng, M.-Y.; Chang, N.-W. Dynamic Construction Material Layout Planning Optimization Model by Integrating 4D BIM. *Eng. Comput.* **2019**, *35*, 703–720. [CrossRef]
12. He, R. BIM-Enabled Computerized Design and Digital Fabrication of Industrialized Buildings: A Case Study. *J. Clean. Prod.* **2021**, *278*, 123505. [CrossRef]
13. Li, Q.; Yang, W.; Kohler, N.; Yang, L.; Li, J.; Sun, Z.; Yu, H.; Liu, L.; Ren, J. A BIM–LCA Approach for the Whole Design Process of Green Buildings in the Chinese Context. *Sustainability* **2023**, *15*, 3629. [CrossRef]
14. Eastman, C. General Purpose Building Description system. *Comput. Aided Des.* **1976**, *8*, 17–26. [CrossRef]
15. BjSrk, B.-C. Basic Structure of a Proposed Building Product Model. *Comput.-Aided Des.* **1989**, *21*, 71–78.
16. Van Nederveen, G.A.; Tolman, F.P. Modelling Multiple Views on Buildings. *Autom. Constr.* **1992**, *1*, 215–224. [CrossRef]
17. Gan, V.J.L.; Wong, C.L.; Tse, K.T.; Cheng, J.C.P.; Lo, I.M.C.; Chan, C.M. Parametric Modelling and Evolutionary Optimization for Cost-Optimal and Low-Carbon Design of High-Rise Reinforced Concrete Buildings. *Adv. Eng. Inform.* **2019**, *42*, 100962. [CrossRef]
18. Huang, B.; Zhang, H.; Yang, W.; Ye, H.; Jiang, B. Mechanical Carbon Emission Assessment during Prefabricated Building Deconstruction Based on BIM and Multi-Objective Optimization. *Sci. Rep.* **2024**, *14*, 27103. [CrossRef]
19. Deng, X.; Lu, K. Multi-Level Assessment for Embodied Carbon of Buildings Using Multi-Source Industry Foundation Classes. *J. Build. Eng.* **2023**, *72*, 106705. [CrossRef]
20. Al-Mashta, S.; Alkass, S. Integrated Cost Budgeting and Estimating Model for Building Projects. In Proceedings of the 54th Annual Meeting of the American Association of Cost Engineers International, Atlanta, GA, USA, 27–30 June 2010; pp. 22–36.
21. Tian, D.; Li, X.; Ma, T. Research on Design and Analysis of Prefabricated Concrete Building Component System Based on BIM. *Build. Struct.* **2016**, *46*, 58–62.
22. Liu, N.; Yu, L.; Tong, G. Application of BIM Technology in Dynamic Management and Control of Construction Project Costs. *Appl. Math. Nonlinear Sci.* **2024**, *9*. [CrossRef]
23. Arbabi, A.; Taherkhani, R.; Ansari, R. A Novel Approach for Integrating BIM and Green Building Rating system in the Construction Projects Design Phase. *Eng. Constr. Archit. Manag.* **2024**. [CrossRef]
24. *GB/T 51366-2019*; Ministry of Housing and Urban-Rural Development of the People's Republic of China Standard for Building Carbon Emission Calculation. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2019. Available online: https://www.chinesestandard.net/PDF/English.aspx/GBT51366-2019 (accessed on 11 May 2024).
25. Luo, Z.; Cang, Y.; Zhang, N.; Yang, L.; Liu, J. A Quantitative Process-Based Inventory Study on Material Embodied Carbon Emissions of Residential, Office, and Commercial Buildings in China. *J. Therm. Sci.* **2019**, *28*, 1236–1251. [CrossRef]
26. Cang, Y.; Luo, Z.; Yang, L.; Han, B. A New Method for Calculating the Embodied Carbon Emissions from Buildings in Schematic Design: Taking "Building Element" as Basic Unit. *Build. Environ.* **2020**, *185*, 107306. [CrossRef]
27. Hong, J.; Shen, G.Q.; Feng, Y.; Lau, W.S.; Mao, C. Greenhouse Gas Emissions during the Construction Phase of a Building: A Case Study in China. *J. Clean. Prod.* **2015**, *103*, 249–259. [CrossRef]
28. Jeong, Y.; Choi, G.; Kang, J.; Lee, S. Development of Life Cycle Assessment Program (K-LCA) for Estimating Environmental Load of Buildings. *Archit. Inst. Korea Mag.* **2008**, *24*, 259–266.
29. Lu, K.; Jiang, X.; Tam, V.W.Y.; Li, M.; Wang, H.; Xia, B.; Chen, Q. Development of a Carbon Emissions Analysis Framework Using Building Information Modeling and Life Cycle Assessment for the Construction of Hospital Projects. *Sustainability* **2019**, *11*, 6274. [CrossRef]
30. Nilsson, B.I. The Creation of Theory: A Recent Application of the Grounded Theory Method. *Qual. Rep.* **1996**, *2*, 1–15.
31. Jöreskog, K.G. Analysis of Covariance Structures. In *Handbook of Multivariate Experimental Psychology*; Nesselroade, J.R., Cattell, R.B., Eds.; Springer US: Boston, MA, USA, 1988; pp. 207–230, ISBN 978-1-4612-8232-7.
32. Turner, N.; Chmiel, N.; Walls, M. Railing for Safety: Job Demands, Job Control, and Safety Citizenship Role Definition. *J. Occup. Health Psychol.* **2005**, *10*, 504–512. [CrossRef]
33. Strauss, A.; Corbin, J. Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, 2nd edn, reviewed by Nic Beech. *Manag. Learn.* **2000**, *31*, 521.

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