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Management of Carbon Emissions Throughout the Building Life Cycle Based on the Analytic Hierarchy Process

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Abstract: The severe global warming driven by the large-scale emission of greenhouse gases has made the reduction of carbon emissions a critical priority for global economic and social development. Among various sectors, the construction industry stands out due to its significant consumption of natural resources throughout the building process, resulting in a considerable environmental burden. In China, carbon emissions from the construction industry account for approximately 40% of the total emissions. Therefore, mitigating carbon emissions in this sector is of the utmost importance. This study develops an evaluation model for low-carbon production management in construction enterprises, utilizing the Analytic Hierarchy Process (AHP). Through a case study, the research identifies practical challenges in implementing this model and offers actionable recommendations. Theoretically, the study provides a valuable reference for future research on energy conservation and emission reduction in the construction industry. In practice, it offers guidance to construction enterprises in achieving a low-carbon transition.

Keywords: construction enterprises; low-carbon production management; life cycle; evaluation system; analytic hierarchy process; carbon emissions

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1. Introduction

With the continuous development of industrialization and societal progress, the key factor driving global warming—"the greenhouse effect"—has come into focus, making the mitigation of its impact a global priority [1]. As the low-carbon economy gains momentum, low-carbon construction has emerged as a critical solution. According to the Buildings and Climate Change report released by the UNEP, energy consumption in the building sector accounts for 30% to 40% of the total global energy use [2,3]. The report highlights that the building industry contributes approximately one third of global greenhouse gas emissions, underscoring the importance of controlling emissions as a crucial step in achieving energy conservation and emission reduction. China, currently in its development phase, relies heavily on the construction industry as a pillar sector, such as for high-rises [4], bridges [5–8], tunnels [9,10], etc. The latest data reveal that the construction sector consumes 28% of the nation's energy, with its carbon emissions accounting for approximately 40% of the total emissions [11]. Therefore, implementing energy conservation and emission reduction measures in the construction industry has become an urgent necessity.

Many domestic and international experts have conducted in-depth studies on the design of the ISO14000 environmental management system, the specific application of low-carbon, green, and environmentally friendly production management in construction projects, and the use of waste plastics to produce environmentally friendly additives, which, in principle, do not require the consumption of natural resources [12,13]. Additionally, in some industrialized countries, the production of environmentally friendly and energy-saving building materials has already taken shape. Stimulated by funding policies, a large number of developers, manufacturers, and other stakeholders have shown great enthusiasm, and low-carbon building projects have quickly gained widespread attention [14]. In 2001 and 2003, the government formulated and issued the Low-Carbon Management Map and Technical Guidelines for Green Residential Areas and the Technical Evaluation Guidelines for Green Residential Areas. Furthermore, during the 2008 Beijing Olympics, the Low-Carbon Project Evaluation and Development System was released. In 2017, China's Ministry of Housing and Urban-Rural Development issued a "key advancement" plan for housing industrialization and green building development. The plan proposed that the proportion of new urban green spaces should reach 50%, and the use of eco-friendly construction materials should exceed 40% [15,16].

In terms of energy conservation and emission reduction, the Vanke Center features a clear, people-oriented design. It strictly adheres to the internationally recognized LEED-NC2.2 Green Certification System to ensure compliance across all aspects of the development project. Other projects support environmentally friendly transportation systems through long-term site planning. Advanced water-saving hardware has been adopted, reducing construction water consumption by 30% [17–19]. Utilizing a waste heat recovery system platform and ice storage air conditioning technology powered by solar energy, emissions from energy sources such as photovoltaic systems are significantly reduced [20]. The broader use of renewable materials and reduced use of traditional bricks have also substantially decreased carbon emissions in the transition from quantity to quality in construction [21,22]. In China, projects such as the winter heating initiative under the Bohai Rim Development Plan and the Sino-Singapore Tianjin Eco-City—a joint energy-saving and eco-friendly demonstration project by the Philippine and Singapore governments—combine commercial and residential functionalities. These projects integrate practical connections between buildings, transportation, and energy structures from the outset to achieve energy savings. Through multiple strategies, such as improving clean energy utilization and refining energy use standard procedures, the projects significantly enhance energy efficiency and promote the in-depth development of green, low-carbon, and eco-friendly initiatives. For instance, Tianjin Eco-City has reduced CO_2 emissions by 80%, with energy savings of 45% and water savings of 24%. Its energy structure, green transportation, and green building materials have achieved a 5% reduction in carbon intensity, reaching a level of 150 tons of CO_2 per 60 million GDP, consistent with average levels in the U.S. and U.K. In major cities such as Shanghai, Chongqing, and Beijing, there have been bold attempts to apply low-carbon building technologies to construction projects [23]. Although the marketization process remains slow, China's construction industry is steadily transitioning towards a low-carbon industrial development model [24,25].

Low-carbon production management is essential for the development of construction enterprises, as it not only enhances resource utilization efficiency but also minimizes resource waste to achieve energy conservation and emission reduction [26–28]. From a risk mitigation perspective, low-carbon management effectively guides enterprises in avoiding future risks and making informed decisions in carbon market trading, ultimately leading to greater economic benefits [29,30]. Similarly, in an era of rapid global low-carbon economic growth, adopting a low-carbon production management model enhances the overall competitiveness of related enterprises. It transforms the economic promotion model and positions enterprises to thrive in the era of low-carbon sustainable development [31,32].

To address the issue of carbon emissions in the construction sector, this paper constructs an evaluation model for low-carbon production management in construction enterprises based on the Analytic Hierarchy Process (AHP). The model is divided into four sections. The first section is the introduction, which mainly discusses the research background and significance of the paper. The second section covers the methodology, which introduces the life cycle approach, low-carbon buildings, the AHP, and the low-carbon evaluation index system. The third section presents a case study analysis, which includes an overview of the project, prefabricated structures, and low-carbon production management. The fourth section provides the conclusion, summarizing the findings and outlining future research plans. Specifically, the main innovative points of this study include summarizing and refining building management theories based on the low-carbon economy throughout the entire building lifecycle, and developing a targeted, systematic evaluation framework that encompasses the system's connotation, characteristics, and specific components; conducting a comprehensive analysis of factors related to low-carbon construction management within construction enterprises, integrating theory and practice to establish a standardized evaluation system for analyzing low-carbon production management in construction enterprises; and validating the proposed standardized evaluation system through analysis of real-world cases, confirming its effectiveness, and providing a series of recommendations to optimize the existing management system for low-carbon production management.

2. Methods

2.1. Life Cycle Analysis

Life cycle analysis (LCA), also known as life cycle evaluation, is a practical tool for assessing environmental impact factors associated with a product or process throughout its lifecycle. While there is no unified international definition of the life cycle to date, its framework structure remains fundamentally consistent [19,33]. LCA integrates the entire lifecycle of a product, from procurement, production, transportation, sales, usage, maintenance, and the processing of raw materials to the final disposal of environmental factors and their potential impacts [34]. Buildings, as products with their own lifecycles, differ significantly in lifecycle management compared to ordinary products. We divided the lifecycle of buildings into five primary stages: Production Stage of Building Materials, Construction Stage, Building Delivery and Usage Stage, Building Maintenance Stage, and Building Waste Disposal Stage [35,36].

2.2. Low-Carbon Building

Based on the precise definition of the low-carbon economy and life cycle assessment (LCA), broadly defined low-carbon wood-based buildings are designed to provide stable living and comfort while adhering to fundamental principles of form and functionality [37,38]. According to the initial plan, emphasis must be placed on leveraging opportunities to utilize new energy sources (e.g., solar, wind) to align with advancements in renewable energy development [39,40]. Continuous technological innovation is crucial to developing high-strength, high-performance materials as substitutes for high-carbon construction materials. Enhancing the strength and stiffness of these materials reduces the reliance on inorganic materials like cement and concrete [41].

Low-carbon technologies should be flexibly applied, incorporating new energy-saving methods into construction processes, and strengthening controls during the operation, maintenance, and demolition/recycling phases [42]. This ensures energy consumption and carbon emissions remain at a low level throughout the building's lifecycle. Low-carbon buildings exhibit the following three characteristics: (1) greenhouse gas emissions that affect the environment are determined to meet the standards, (2) they exhibit low carbon emissions throughout their entire lifecycle, and (3) they favor the reuse of internal resources and the use of new clean and low-carbon energy sources. The technological advancement of resource recycling can compensate for the demand for external energy from another perspective, and the use of clean energy can reduce the use of high carbon energy [43].

2.3. Analytic Hierarchy Process

The basic principle of the Analytic Hierarchy Process (AHP) is to evaluate the relative importance of factors at the same level based on their interrelationships and dependencies within a complex system, using expert judgment, intuition, and experience [44]. The consistency criterion is then applied to verify the accuracy, and the hierarchical structure is integrated to obtain an overall ranking of the decision factors' importance to the objective [45]. (1) First, to construct the hierarchical structure model, the complex problem is restructured and divided into layers to establish the AHP structural model. In this model, the complex problem is broken down into three distinct levels: the goal level, which typically includes only one element, representing the overall objective of the analysis; the criteria level, which is the intermediate stage required to achieve the goal, consisting of criteria dominated by the goal level; and the alternative level, comprising sub-criteria under the criteria level, representing the most direct form of system analysis. Each level is influenced by the factors in the level above it, creating a structured and hierarchical decision-making framework [46]. (2) Next, expert scoring is performed to establish the AHP judgment matrix and to determine the evaluation criteria for indicator weights and construct the evaluation matrix. This scale defines the relative importance of elements, as shown in Table 1, where experts assign scores based on the scale to quantify the comparative importance of each factor. Once the matrix is constructed, consistency checks are performed to ensure the logical accuracy of the judgments [47–51].

Table 1. Relative importance table a_{ij}.

Comparison Between Risk Factor i and Risk Factor j	**a_{ij}**	
Risk factor i is equally important as risk factor j	1	$a_i = a_j$
Risk factor i and risk factor j are slightly more important	3	$a_i = 3a_j$
Risk factor i is more important than risk factor j	5	$a_i = 5a_j$
Risk factor i and risk factor j are much more and more important	7	$a_i = 7a_j$
Risk factor i and risk factor j are much more important	9	$a_i = 9a_j$
The importance of risk factor i and risk factor j lies between the above judgments	2, 4, 6, 8	/
The important results of risk factor i and risk factor j are reciprocal to each other	$a_{ij} = 1/a_{ji}$	/

(3) The feature vectors and indicator weights are calculated for consistency testing.

First, calculate the eigenvectors and weights of the main indicators, and then, use the geometric mean method to calculate the weights of the indicators.

a. Determine the product of each element in each row of matrix A:

$$m_i = \prod_{i=1}^{n} a_{ij}\ (i = 1, 2, 3, \cdots, n) \tag{1}$$

b. Calculate the indicator weights as follows:

$$\begin{aligned} w_i &= \overline{w_i} / \sum_{j=1}^{n} \overline{w_j} \\ \overline{w_i} &= \sqrt[n]{m_i} \end{aligned} \tag{2}$$

c. Multiply matrix A with the set of indicator weights to obtain the AW matrix.

d. Obtain the maximum eigenvalue as follows:

$$\lambda_{\max} = \sum_{i=1}^{n} (AW)i/nw_i \tag{3}$$

When constructing the judgment matrix, logical errors may occur. For example, A is more important than B, and B is more important than C, but C is considered more important than A. Therefore, consistency testing is required to check for any issues. The consistency test is analyzed using the CR value. If the CR value is less than 0.1, it indicates that the consistency test has passed; otherwise, it means the consistency test has failed. If the data fail the consistency test, it is necessary to check for logical issues and re-enter the judgment matrix for analysis.

$$CR = \frac{\lambda_{\max}}{RI} \tag{4}$$

where the CI value is obtained when calculating the eigenvector, and the RI value can be cited in the reference, for example, when the order is 3, the RI is 0.52; when the order is 4, the RI is 0.89; when the order is 5, the RI is 1.12; and when the order is 6, the RI is 1.26.

(4) The combination weights are calculated.

After determining the weight of the first level indicator, the next step is to calculate the weight of the next level indicator. If the relative weight of the first layer is the metric layer of the target layer, its weight is represented as follows:

$$\overline{W_i} = \left(\overline{W_1}, \overline{W_2}, \cdots, \overline{W_k}\right)^T \tag{5}$$

After determining the weights of the first layer indicators, the relative importance weights of the second layer indicators relative to the first layer indicators can be expressed as follows:

$$\overline{w_i} = (w_{1i}, w_{2i}, \cdots, w_{ni}) \tag{6}$$

By this equation, we can obtain the comprehensive weight values for each combination of factors:

$$\begin{aligned} w_1 &= \sum_{j=1}^{k} w_j w_{1j} \\ w_2 &= \sum_{j=1}^{k} w_j w_{2j} \\ w_n &= \sum_{j=1}^{k} w_j w_{nj} \end{aligned} \tag{7}$$

(5) The comprehensive weight calculation results are analyzed.

After comprehensive weight calculation, factors with different levels of importance will be selected in each scheme layer, and their correlations will be marked. Then, different weights will be used to reorder the results based on the varying degrees of impact of each factor, in order to obtain the most sensitive factors, as shown in Figure 1.

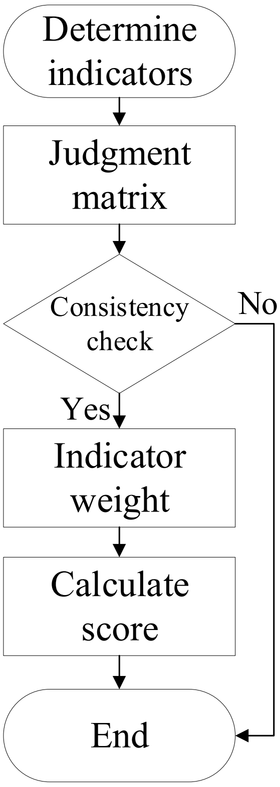


Figure 1. Framework for Analytic Hierarchy Process.

2.4. Low-Carbon Evaluation Index System

The low-carbon management evaluation system is established based on input–output theory [52]. To achieve large-scale low-carbon production management in construction enterprises, the primary focus is on the early assessment of six key areas: land conservation, water resource conservation, energy-saving utilization, environmental organization management, energy consumption during construction, and methane emissions [53]. These six components are defined as primary indicators. Due to the vast scope of low-carbon-related factors in daily life, which are less directly observable, they are defined as secondary indicators. Field research on several similar residential projects in Hefei, Anhui Province, summarized the specific measures and outcomes influencing the implementation of secondary indicators, further categorizing them into tertiary indicators. The evaluation system consists of 6 primary indicators, 21 secondary indicators, and 61 tertiary indicators [54].

$$\begin{aligned} T &= \sum_{i=1}^{n} T_i w_i \\ T_i &= \sum_{i,j=1}^{n} T_{ij} w_{ij} \\ T_{ij} &= \sum_{i,j=1}^{n} P_{ijk} w_{ijk} \end{aligned} \tag{8}$$

where, T represents the total score of low-carbon production management for the construction enterprise; T_i represents the score for the first-level indicator of low-carbon production management; T represents the score for the second-level indicator of low-carbon production management; P_{ijk} represents the actual score for the third-level indicator; w_i represents the weight of the first-level indicator; w_{ij} represents the weight of the second-level indicator; w_{ijk} represents the weight of the third-level indicator; and n represents the number of indicators.

The management of primary indicators includes construction organization management, cost management, construction process management, and evaluation management. These four areas require the establishment of a scientific and reasonable regulatory framework to provide organizational and institutional guarantees for low-carbon production management. The specific methods are as follows [55,56]: (1) Construction Organization Management: Engage professional technical personnel with corresponding research and development capabilities and construction experience to actively organize and manage projects. These professionals are responsible for the technical quantity, quality, and safety of the project. Clearly define the rights and responsibilities of each department within the project team, appoint a low-carbon construction leader, and ensure overall coordination and personnel arrangement. Assign responsibilities to each management role, provide training on the implementation of environmentally friendly and green building practices, and enhance organizational management to clarify the specific roles of all project participants in low-carbon construction management. (2) Construction Planning Management: Develop low-carbon construction management guidelines, including construction planning, quality control objectives, cost management goals, and safety targets. Scientifically allocate blueprint project layouts, material budget preparation, construction timelines, and processes. Formulate energy-saving and consumption-reducing management plans and implement them strictly in accordance with the established project plans. (3) Construction Process Management: Adjust and improve detailed design drawings before construction based on the actual conditions of the construction site. General and specialized construction plans should meet the requirements of the actual construction process. Hire a design quality management team to monitor the quality of low-carbon construction. During construction, protect completed works based on the established protection system. (4) Evaluation Management: Evaluate the low-carbon technologies used during construction and assess their emission reduction effects. This work includes regularly evaluating the environmental impact of construction projects on the natural environment during the construction process as shown in Figure 2.

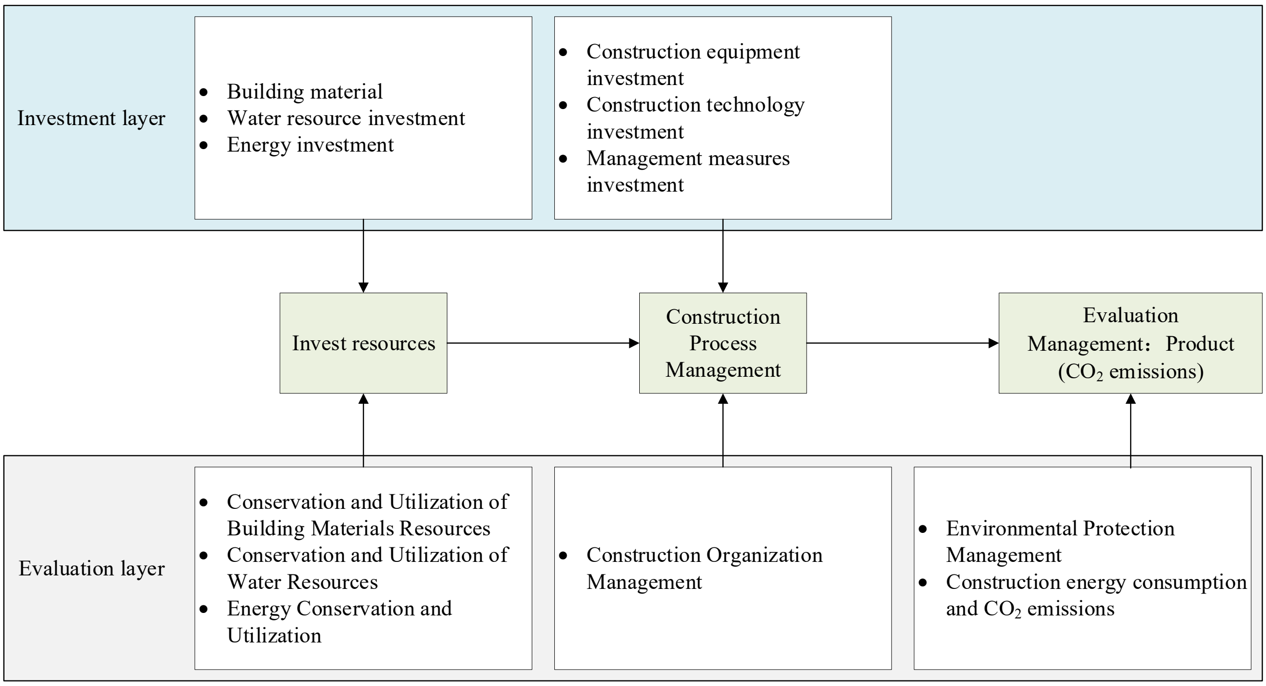


Figure 2. Construction enterprise low-carbon production management evaluation system.

3. Case Study: Engineering Project

3.1. Project Overview

The He Ping Jia Yuan project is located in Hefei City, Anhui Province, with a residential area of 28,000 square meters and a total area of approximately 120,000 square meters. The project comprises five residential buildings, a public facility, and a large underground parking lot. The parking lot is divided into above-ground and underground spaces, with only 29 parking spaces above ground and over 440 underground. The initial investment for the project was estimated at 170 million RMB, and it was completed and delivered on 21 June 2019.

Building 4 of He Ping Jia Yuan is a prefabricated high-rise with an overall reinforced concrete shear wall structure. It boasts a prefabrication rate of 60%, reflecting a high level of industrialization. The internal structure is simple and smooth, free from obstructive elements like structural columns that might limit space utilization, demonstrating a human-centered design. Prefabricated components were manufactured by Anhui Wan Sida Construction Technology Co., Ltd., Hefei, Anhui, China, transported using large flatbed trailers, and assembled via lifting and installation. As of now, the main structure of Building 4 is fully enclosed. This prefabricated building showcases the application of low-carbon construction technologies and concepts by the construction company.

At the beginning of construction, the project contractor adhered to the Hefei Environmental Protection Bureau's requirements, emphasizing environmental education and awareness for all projects. The environmental impact during construction was monitored in real-time. Dust and pollutants generated by earthworks were effectively mitigated with appropriate dust prevention and suppression measures. The project employed efficient and energy-saving transportation methods, significantly contributing to dust reduction. During construction, measures were taken to minimize dust, wastewater, and noise pollution affecting surrounding residential areas. To prevent soil erosion, green spaces were planted promptly in enclosed areas. Given the special location of the project near schools and nursing homes, specific adjustments were made for large transportation machinery, such as controlling transportation schedules and limiting construction durations. Nighttime construction was strictly prohibited to avoid disturbing residents and students. Special attention was paid to noise control, with advice sought from research institutions and the use of specialized equipment and machinery to reduce noise levels during construction. These measures allowed surrounding residents to maintain their regular work and living routines. The measures implemented in this project align with the principles of low-carbon production management set during the initial planning phase. Strategies such as energy-efficient transportation, real-time environmental monitoring, dust and noise suppression, and green space management were integrated into the construction process, effectively demonstrating the project's commitment to low-carbon and environmentally friendly building practices.

3.2. Application of Prefabricated Structures

Building 4 of the He Ping Jia Yuan project is a high-rise structure constructed with an integrated reinforced concrete shear wall system. To meet Hefei City's high-quality building standards, the contractor aimed to establish itself as a benchmark for green and low-carbon construction in Anhui Province. This was achieved through meticulous construction planning, the incorporation of advanced technologies, the involvement of skilled professionals, and the integration of low-carbon construction management throughout the process. The building consists of 24 floors, including low-rise commercial spaces, four underground levels, and a floor height of 3.1 m. The above-ground portion includes 20 floors with a floor height of 2.9 m, covering a total site area of approximately 22,400 square meters.

The superstructure features a concrete frame for the first through fifth floors, while the sixth and subsequent floors use prefabricated reinforced concrete structures. Key prefabricated elements used in the project include precast staircases, balconies, and air conditioning platforms. The structural system is based on shear walls, with the project utilizing prefabricated components at a 60% coverage rate. Given current construction practices, this project represents a highly industrialized building.

One notable innovation is the use of PK precast concrete composite slabs [57–59]. These slabs are easy to construct and offer excellent performance across various metrics. The defining characteristics of PK slabs can be summarized as "assembly and welding, fast", which highlights their efficiency and ease of installation, as illustrated in Figure 3. PK precast composite slabs combine simplicity in construction with high performance, making them a preferred choice for this project [60–63]. The insulation and decorative surfaces of brick walls are integrated into prefabricated concrete panels, streamlining the construction process while ensuring high-quality results. This application of prefabrication underscores the project's commitment to advancing low-carbon, sustainable construction methods [64,65].

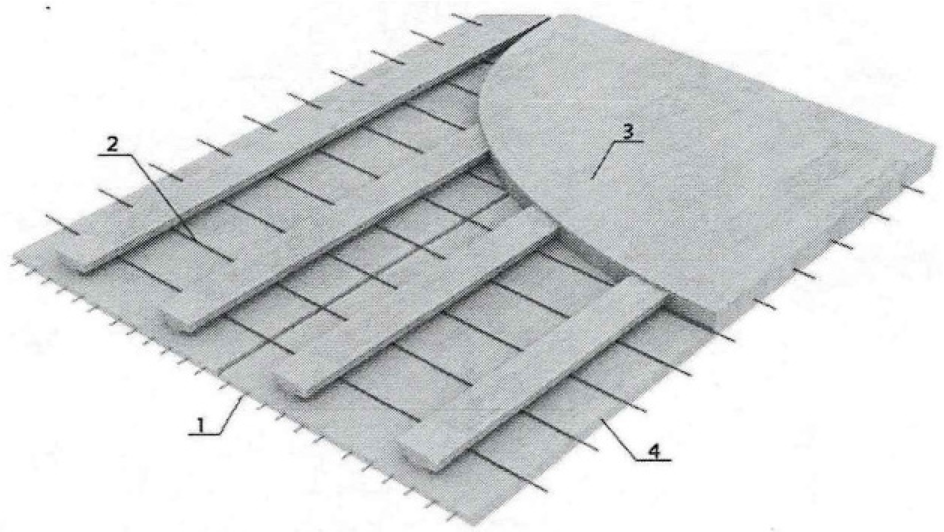


Figure 3. Prefabricated ribbed floor concrete composite floor slab. Note: 1—longitudinal prestressed steel bars; 2—transverse perforated steel bars; 3—post-cast layer; 4—precast base slab of pk composite panel.

The PK composite panel uses an inverted "T"-shaped prestressed reinforced concrete precast rib as the base slab. The rib is designed with elliptical holes that connect with horizontally pressure-free displacement walls. Composite concrete is then poured to form the final structure, creating stress redirection ramps that improve the placement and anchorage of the slab. This results in high load-bearing capacity, stiffness, and crack resistance. The precast concrete structure also incorporates sandwich insulation wall cladding, which is a "sandwich"-type insulated concrete wall. This wall system integrates an inner panel, an insulation layer, and an outer panel, formed simultaneously. It addresses common issues with traditional external insulation systems, such as detachment. The features of the wall panels are as follows. 1. Connectors: Both metallic and non-metallic connectors are used between the concrete layers to prevent stress on the outer shell. 2. Thermal and Energy Efficiency: The wall panels offer excellent insulation and energy-saving performance. 3. Durability: The lifespan of the insulation and exterior layers matches the structural lifespan, ensuring long-term reliability. 4. Fire Resistance: The panels are made of fire-resistant materials with high-performance efficiency, making them effective and sustainable external wall products, as shown in Figure 4.

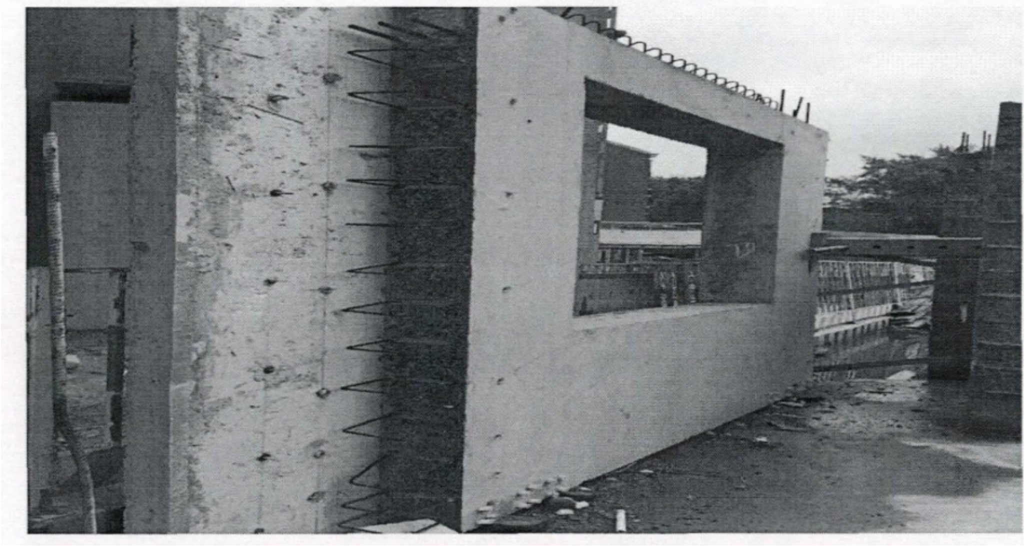
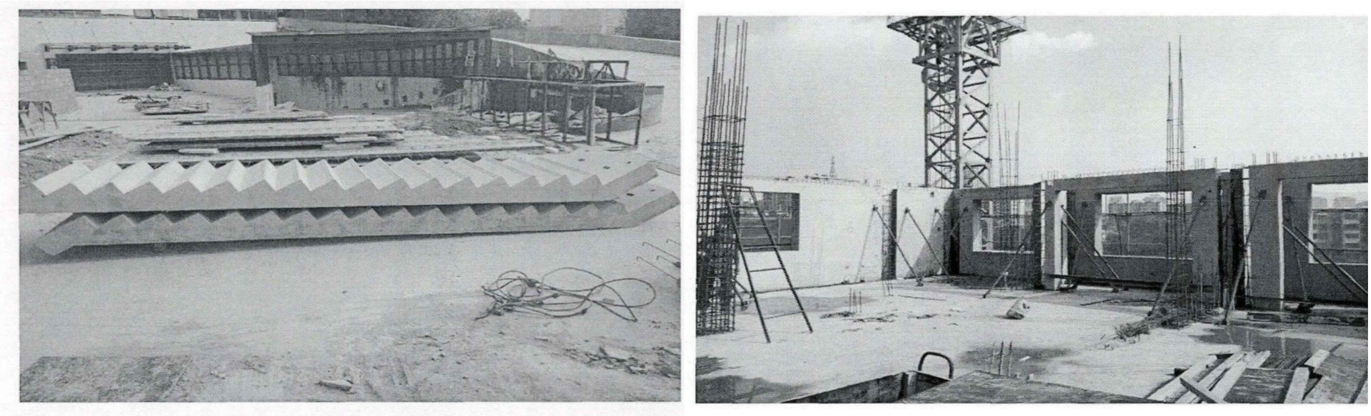


Figure 4. Precast concrete sandwich panel.

Prefabricated concrete staircases have an aesthetically pleasing appearance and eliminate the need for on-site formwork, saving construction time. During installation, the support process is simple and efficient, and the staircases can also be used as construction access routes. This design effectively resolves the challenges of vertical transportation during construction and ensures the safety of evacuation pathways during the construction phase, as shown in Figure 5.



(**a**) Precast concrete stairs

(**b**) Precast concrete balcony

Figure 5. Precast building.

3.3. Calculation of Carbon Emissions from Building Materials During Construction

The carbon emissions and consumption of related building materials during the construction phase of the Peace Home project are shown in Table 2:

Table 2. The accounting of main building materials consumption and carbon dioxide emissions.

Water/m^3	C-W	BQ	C-CO_2/kg	A-CO_2/kg	T-CO_2/kg	DR/%
	133,386.75	138,544.69	0.194	25,877.03	26,877.67	−3.7%
	T-W	BQ	C-CO_2/kg	A-CO_2/kg	T-CO_2/kg	DR/%
	6473.28	6951.43	0.194	1255.82	1348.58	−6.9%

	C-E	BQ	C-CO_2/kg	A-CO_2/kg	T-CO_2/kg	DR/%
Electricity/KWh	853,675.2	919,908.62	0.7802	666,037.39	717,712.71	−7.2%
	T-E	BQ	C-CO_2/kg	A-CO_2/kg	T-CO_2/kg	DR/%
	94,852.8	97,988.43	0.7802	74,004.15	76,450.57	−3.2%
	C-C	BQ	C-CO_2/kg	A-CO_2/kg	T-CO_2/kg	DR/%
Rebar/t	8181.05	8365.09	982	8,033,795.03	8,214,514.34	−2.2%
Concrete/m^3	106,709.4	108,665.38	250	26,677,350.00	27,166,345.00	−1.8%
Cement/t	42,769.42	47,324.08	700	29,938,594.00	331,268,556.00	−9.6%

Note: budget quantity (BQ); CO_2 emissions generated by unit resource consumption (C-CO_2); actual total CO_2 emissions (A-CO_2); total budget for CO_2 emissions (T-CO_2); difference ratio between actual carbon emissions and budget (DR); actual construction water consumption (C-W); actual temporary domestic water consumption (T-W); actual construction electricity consumption (C-E); actual temporary living electricity consumption (T-E); actual construction consumption (C-C).

3.4. Application of Low-Carbon Production Management in Construction Period

Through in-depth investigation, the construction and management content of the Peace Home project was analyzed, and five engineers with over 10 years of housing construction experience were hired to conduct a comprehensive evaluation and assessment based on the proposed evaluation points. The average score of five judges was collected as the final score for evaluation, and the score was rounded to the nearest whole. The specific score details are shown in Table 2.

Table 2. The scoring sheet of construction enterprise low-carbon production management index.

D_{ijk}	**P_{ijk}**
Equip professional technical personnel—D_{111}	65
Low-carbon construction organization structure—D_{112}	68
Responsibilities of low-carbon construction positions—D_{113}	64
Development of low-carbon construction management plan—D_{121}	76
Layout of project construction plan—D_{122}	78
Develop energy-saving and consumption reduction management plans—D_{123}	64
Refine and improve the design drawings before construction—D_{131}	65
Develop overall and specialized construction plans—D_{132}	76
Establish a construction quality management team—D_{133}	70
Protection of completed processes—D_{134}	72
Evaluate the effectiveness of low-carbon technologies and processes adopted during the construction process—D_{141}	60
Assess the natural environmental impact caused by construction—D_{142}	49
Use wall materials with good insulation and thermal insulation performance, as well as lightweight aggregates—D_{211}	78
Use building materials with good corrosion resistance and waterproof performance—D_{212}	72
Replace traditional high energy consuming materials with green and environmentally friendly materials—D_{213}	70
Choose local building materials—D_{221}	60
Adopting energy-efficient and effective transportation methods—D_{222}	58
Developing technology for separating recyclable construction waste—D_{231}	71
Adopting an industrialized construction model—D_{232}	78
Significantly reduce the application of brick materials—D_{233}	80
Temporary facilities use detachable structures—D_{241}	78
The auxiliary tools are rented out—D_{242}	67
Reasonably divide the construction flow section—D_{243}	74
Establish a strict water management system—D_{311}	76
Adopting water-saving construction techniques—D_{312}	75
The construction water pipe network should be arranged according to the water consumption, and the installation and maintenance of pipelines should be supervised—D_{313}	63
The domestic water supply at the construction site adopts intelligent water-saving devices—D_{314}	74
Measure domestic water and engineering water separately—D_{315}	75
On-site production of reservoirs and circulating water tanks, and installation of treatment devices—D_{321}	59
On-site equipment and vehicle washing should be equipped with a circulating water device—D_{322}	61

Table 2. *Cont.*

D_{ijk}	P_{ijk}
Establish a management system for construction machinery and equipment—D_{411}	82
Configure construction machinery and equipment with power matching the load—D_{412}	68
Reasonably divide processes to improve equipment utilization and full load rate—D_{413}	70
Adopting energy-saving construction equipment and tools-D_{414}	70
The lighting layout is based on the principle of meeting the minimum illuminance required for room functionality—D_{421}	62
Adopting energy-saving lighting system—D_{422}	72
Develop reasonable construction and living electricity consumption quotas, and measure and assess construction and living electricity separately—D_{423}	58
Temporary board houses use energy-saving materials with good thermal insulation performance–D_{431}	60
Utilize the existing natural conditions of the site—D_{432}	56
Utilization of solar energy—D_{441}	57
Utilization of wind energy—D_{442}	40
Utilization of geothermal energy—D_{443}	0
Material transport vehicles should be cleaned before leaving the site—D_{511}	61
Control measures for materials that are prone to dust formation—D_{512}	76
The main road at the exit should be hardened—D_{513}	82
Reasonably dispose of construction wastewater—D_{521}	50
Reasonably dispose of domestic sewage on construction sites—D_{522}	55
Conduct water quality testing on treated wastewater and sewage—D_{523}	0
Reasonably stack and cover the backfill soil excavated during construction—D_{524}	59
Cover the exposed soil with gravel and planted vegetation in a timely manner—D_{525}	58
Select low-noise construction equipment and set up noise reduction enclosures—D_{531}	74
Reasonably arrange homework time—D_{532}	76
Classification and treatment of construction waste for convenient recycling and reuse—D_{541}	63
The disposal of waste must be legal and traceable—D_{542}	50
Construction water consumption—D_{611}	73
Non construction water consumption—D_{612}	75
Construction electricity consumption—D_{621}	58
Non construction electricity consumption—D_{622}	65
Steel consumption—D_{631}	65
Concrete consumption—D_{632}	67
Cement consumption—D_{633}	64

Based on the scores of each three-level indicator, referring to the weight of each evaluation indicator and three calculation formulas, the calculation is shown in Table 3.

Table 3. The scoring calculation table of construction enterprise low-carbon production management evaluation.

D_{ijk}	W_{ijk}	P_{ijk}	T_{ijk}	T_{ij}	C_{ij}	W_{ij}	T_i	B_i	W_i	T
D_{111}	0.54	65	35.10	65.18	C_{11}	0.06	66.36	B1	0.44	65.88
D_{112}	0.16	68	10.88							
D_{113}	0.30	64	19.20							
D_{121}	0.53	76	40.28	72.32	C_{12}	0.16				
D_{122}	0.14	78	10.92							
D_{123}	0.33	64	21.12							
D_{131}	0.12	65	7.80	71.22	C_{13}	0.54				
D_{132}	0.28	76	21.28							
D_{133}	0.53	70	37.10							
D_{134}	0.07	72	5.04							
D_{141}	0.25	60	15.00	51.75	C_{14}	0.24				
D_{142}	0.75	49	36.75							

Table 3. *Cont.*

D_{ijk}	W_{ijk}	P_{ijk}	T_{ijk}	T_{ij}	C_{ij}	W_{ij}	T_i	B_i	W_i	T
D_{211}	0.12	78	9.36	71.5	C_{21}	0.24	72.62	B_2	0.09	65.88
D_{212}	0.27	72	19.44							
D_{213}	0.61	70	42.70							
D_{221}	0.67	60	40.20	59.34	C_{22}	0.10				
D_{222}	0.33	58	19.14							
D_{231}	0.10	71	7.10	78.58	C_{23}	0.14				
D_{232}	0.26	78	20.28							
D_{233}	0.64	80	51.20							
D_{241}	0.23	78	17.94	74.08	C_{24}	0.52				
D_{242}	0.12	67	8.04							
D_{243}	0.65	74	48.10							
D_{311}	0.47	76	35.72	74.37	C_{31}	0.67	69.52	B_3	0.06	
D_{312}	0.25	75	18.75							
D_{313}	0.08	63	5.04							
D_{314}	0.14	74	10.36							
D_{315}	0.06	75	4.50							
D_{321}	0.67	59	39.53	59.66	C_{32}	0.33				
D_{322}	0.33	61	20.13							
D_{411}	0.11	82	9.02	71.16	C_{41}	0.46	61.62	B_4	0.05	
D_{412}	0.08	68	5.44							
D_{413}	0.26	70	18.20							
D_{414}	0.55	70	38.50							
D_{421}	0.12	62	7.44	62.26	C_{42}	0.12				
D_{422}	0.27	72	19.44							
D_{423}	0.61	58	35.38							
D_{431}	0.33	60	19.80	57.32	C_{43}	0.18				
D_{432}	0.67	56	37.52							
D_{441}	0.65	57	37.05	46.25	C_{44}	0.24				
D_{442}	0.23	40	9.20							
D4$_{43}$	0.12	0	0.00							
D_{511}	0.12	61	7.32	75.82	C_{51}	0.30	59.33	B_5	0.14	
D_{512}	0.61	76	46.36							
D_{513}	0.27	82	22.14							
D_{521}	0.15	50	7.50	27.48	C_{52}	0.19				
D_{522}	0.15	55	8.25							
D_{523}	0.50	0	0.00							
D_{524}	0.13	59	7.67							
D_{525}	0.07	58	4.06							
D_{531}	0.67	74	49.58	74.66	C_{53}	0.06				
D_{532}	0.33	76	25.08							
D_{541}	0.75	63	47.25	59.75	C_{54}	0.45				
D_{542}	0.25	50	12.50							

Table 3. *Cont.*

D_{ijk}	W_{ijk}	P_{ijk}	T_{ijk}	T_{ij}	C_{ij}	W_{ij}	T_i	B_i	W_i	T
D_{611}	0.83	73	60.59	73.34	C_{61}	0.23	66.29	B_6	0.22	65.88
D_{612}	0.17	73	12.75							
D_{621}	0.83	58	48.14	59.19	C_{62}	0.22				
D_{622}	0.17	65	11.05							
D_{631}	0.12	65	7.80	64.93	C_{63}	0.67				
D_{632}	0.27	67	18.09							
D_{633}	0.61	64	39.04							

According to statistics, the scoring results for all tertiary indicators in this project are as follows: indicators in the range of $90 < Pi < 100$ are 0, indicators in the range of $75 < P_i \leq 90$ are 12, indicators in the range of $55 < P_{ijk} \leq 75$ are 42, and indicators in the range of $5 < P_{ijk} \leq 55$ are 7. These 7 indicators in the range of $5 < P_{ijk} \leq 55$ specifically include assessing the impact of construction on the natural environment, using wind energy and geothermal energy, properly treating construction wastewater, properly treating on-site domestic wastewater, verifying wastewater and treated wastewater quality, and ensuring waste disposal measures are legal and traceable. To address the above 7 indicators, the following recommendations are proposed to improve the application of low-carbon construction management by construction companies:

1. During construction, contractors should identify all sources of pollution at the site and comprehensively monitor the emissions, timing, and intensity of pollutants. In addition, low-carbon evaluations should assess pollution control measures during construction and use these evaluations to drive improvements, thereby promoting the continuous enhancement of low-carbon production control systems.

2. Construction units should design layouts for living and office areas on construction sites based on the site conditions, with a primary focus on adapting to the natural environment to reduce the use of energy-intensive equipment for lighting, ventilation, and heating. If geological conditions at the construction site are suitable for geothermal energy development, the feasibility of this should be studied in collaboration with relevant developers and investors.

3. Drainage ditches should be installed along both sides of site roads to facilitate the discharge of construction wastewater and domestic sewage. A water interception ditch should be set up on the slopes at the entrance of the construction site to collect rainwater, which should then be directed to washing pools for cleaning vehicles. Collected rainwater should be reused for vehicle washing. Permeable pipes and road surface moisturizing materials should be used to allow rainwater to infiltrate into the ground, ensuring groundwater recycling. Inspection wells should be installed for toilets, with timely anti-seepage protection. Before entering municipal pipelines, wastewater must meet treatment standards.

4. Construction units should engage relevant testing agencies to sample and test construction wastewater and domestic sewage. The testing reports must confirm that the wastewater meets national standards.

4. Conclusions

Globally, emission reduction has become an inevitable trend, and implementing green emission reduction measures worldwide will be the new mission of the 21st century. As a populous country, China’s construction industry, as a cornerstone of national infrastructure, inevitably becomes the “main contributor” to carbon emissions. Therefore, if China aims to make significant progress in reducing carbon emissions, the process must begin with the construction industry to achieve the goal of low-carbon transformation. According to existing studies, research on low-carbon buildings in China remains insufficient, and the implementation of low-carbon production management by construction companies has not been effectively carried out. Thus, this study focuses on the research and application status of low-carbon construction and low-carbon production management at both domestic and international levels. By collecting and compiling extensive data, consulting experts, and conducting discussions, a low-carbon production management evaluation system for construction enterprises was established. Based on a case study—the Hefei He Ping Jia Yuan residential project—the following conclusions were drawn:

1. For construction enterprises, implementing low-carbon production management in real projects must be discussed across all stages of the building lifecycle. Low-carbon production and management should minimize the negative environmental impacts throughout the entire construction process—from planning and construction to usage and demolition. Compared to traditional construction management models, which primarily focus on investment schedules and cost budgets, resources should be allocated more effectively in each stage to reduce environmental harm. Adopting low-carbon production management not only aligns with China's low-carbon economic development strategy but also reduces carbon dioxide emissions and environmental pollution. It also lays a solid foundation for creating a healthy, green, and sustainable living environment.

2. The low-carbon production management evaluation system for construction enterprises is a complex and systematic project requiring multidisciplinary technical and theoretical support. This system incorporates the specific characteristics of northern China, considering practical project perspectives to comprehensively cover various factors influencing low-carbon construction. Using the Analytical Hierarchy Process (AHP) method for weighting and combining relevant technical standards with actual construction conditions, scoring criteria were established.

3. By tracking the effectiveness of the low-carbon production management model during the construction management of the Hefei He Ping Jia Yuan project, it was demonstrated that the evaluation system has strong operability. It can scientifically and reasonably assess the production management model of construction enterprises while helping them address issues during the construction process, improve construction technologies, and enhance management capabilities. Gradually raising awareness of the low-carbon economy will also help other companies significantly improve their overall competitiveness.

4. Although the low-carbon production and operation management evaluation system for construction projects established in this paper consists of 6 first-level indicators, 21 second-level indicators, and 61 third-level indicators, the implementation progress and management effectiveness may vary significantly due to the complexity of the construction project system, as well as the differences in factors such as region, environment, and climate. Therefore, continuous improvement and expansion are required in terms of system structure, hierarchy, weight, scoring, and other aspects to make the structure, hierarchy, weights, and scoring system more scientific and reasonable, thus establishing a unified evaluation system.

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