Research on Low-Carbon Technology for the Whole Life Cycle of Prefabricated Buildings

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Abstract. This paper focuses on the application of low-carbon technologies throughout the entire lifecycle of prefabricated buildings. By analyzing the carbon emission characteristics in the design, production, construction, operation, and demolition stages, it comprehensively explores the low-carbon technology pathways at each stage. The study finds that compared with traditional cast-in-place buildings, prefabricated buildings reduce the carbon emission intensity per unit area over the entire lifecycle by 26.7%, and carbon emissions during the construction phase decrease by 38.8%; however, carbon emissions during the transportation phase increase by 138%. The operation phase accounts for the largest proportion of carbon emissions, reaching 69.8%, while the production phase of building materials accounts for 29.0%. The application of BIM technology reduces construction waste by 30% and carbon emissions by 15%, and photovoltaic building integration technology reduces annual carbon dioxide emissions by 11.9 tons. It is recommended to establish a three-dimensional linkage mechanism of 'policy-technology-market,' promote the integration of technologies such as modular design, green building materials, and intelligent operation and maintenance, achieve carbon reduction throughout the lifecycle of prefabricated buildings, and provide a practical path for the construction industry to reach carbon peaking and carbon neutrality.

Keywords: Low-carbon Technology, Carbon Emission, Life Cycle, Carbon Neutrality

1 Introduction

In recent years, with the advancement of global carbon neutrality goals, prefabricated construction has become an important direction for green building due to its high level of industrialization and low on-site pollution. In China, digital twin technology has been applied to the carbon emission management of the entire life cycle of prefabricated components, significantly improving construction efficiency[1]. Meanwhile, American scholars have simulated the carbon footprint of modular projects through BIM platforms and found that optimizing the design phase can reduce approximately 23% of

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embodied carbon emissions[2]. German research teams have further proposed that deeply integrating life cycle assessment (LCA) into BIM models can achieve comprehensive control from material procurement to demolition and recycling[3].

Against the backdrop of global climate change and China's "dual carbon" strategy, the construction industry, as a key sector of energy consumption and carbon emissions, has its green and low-carbon transformation as a national priority for sustainable development. Prefabricated construction, through its factory prefabrication and on-site assembly methods, combines construction efficiency with significant low-carbon potential, becoming the core form of new building industrialization. Various regions have successively introduced mandatory policies to promote its large-scale development. Wuhan, Urumqi, and Dongguan require that by 2025, the proportion of newly built prefabricated buildings should not be less than 50%, 30%, and 35% respectively[4]. Data from the Yangtze River Delta show that the carbon emission intensity per unit area of prefabricated buildings (4.4 $kgCO_2/(m^2 \cdot a)$) is far lower than that of traditional cast-in-place buildings (6.0 $kgCO_2/(m^2 \cdot a)$), demonstrating a significant emission reduction effect. However, carbon emissions during the transportation stage increase by 138% compared with traditional buildings, indicating that the emission reduction advantage is stage-specific. Current related studies mostly focus on a single stage or technology and lack systematic analysis. Based on the full lifecycle theory, this paper combines real project data and technical cases to conduct a comprehensive analysis of the low-carbon technical system of prefabricated buildings across all stages—from design, production, and construction to operation and demolition—aiming to provide theoretical support and practical reference for the low-carbon transformation of the construction industry.

2 Analysis of Carbon Emission Characteristics of Prefabricated Buildings Throughout Their Life Cycle

The carbon emissions throughout the lifecycle of prefabricated buildings span five key phases: building material production, component transportation, on-site construction, building operation, and demolition and recycling. As shown in Table1[5], data from a prefabricated steel structure residential project in East China illustrates this process.

Table 1. Proportion of Carbon Emissions at Each Stage of the Building Life Cycle and Notes.

stage	Carbon emission share	remarks
operational phase	69.8%	Highest proportion, key to emission reduction
Building materials production phase	29.0%	Second largest source
Material transportation, construction, and demolition	≤1%	Small proportion

In terms of carbon emission intensity per unit area, residential building cases in the Yangtze River Delta region show that, based on a building service life of 50 years, the carbon emission intensity per unit area for prefabricated buildings is 4.4 $kgCO_2/(m^2 \cdot a)$, while for traditional cast-in-place buildings it is 6.0 $kgCO_2/(m^2 \cdot a)$, indicating an overall emission reduction of 26.7% for prefabricated buildings [5]. Data from Xi'an in 2024 show that the proportion of newly started prefabricated building area to the total newly constructed building area has reached 38.47% [4]; however, the capacity utilization of component manufacturing enterprises is relatively low, reflecting the current industry situation where insufficient economies of scale constrain the potential for emission reduction.

Carbon Emission Characteristics at Each Stage. Based on measured data from the Yangtze River Delta (comparing three prefabricated projects against traditional benchmarks) as shown in Table 2. Although the transportation stage exhibits a significant increase of 138.0% compared to traditional construction, this is primarily due to the heavy weight of prefabricated components and the current geographical distribution of factories. However, this increase is outweighed by substantial reductions in other stages. Specifically, the operational phase accounts for nearly 70% of total life-cycle emissions (Table 1), and prefabricated buildings achieve a 38.8% reduction in the construction phase. The compounding effect of these high-impact stage reductions compensates for the transportation penalty, resulting in a net overall reduction of 26.7% in total life-cycle emissions. The operation stage is the key period for emission reduction.

Table 2. Based on measured data of residential buildings in the Yangtze River Delta region.

Stage	Key features	Prefabricated/traditional ratio	Core Data Description
Building materials production	Minor improvement	95.6%	Carbon emissions reduced by 4.4%[7]
Haulage stage	Weaknesses and shortcomings	238%	Carbon emissions increased by 138% [6]
Construction stage	Key Features	61.2%	Carbon emissions reduced by 38.8%[8]
operational phase	Determinative influence	Depends on the design	accounting for 68.9% of total lifecycle emissions
Demolition and Recycling	Environmental Benefits	negative emissions	Metal Recycling Reduces Carbon Emissions by 45%[9]
Full lifecycle	Comprehensive Benefits	73.3%	Total carbon emissions decreased by 26.7%

3 Construction of a Low-Carbon Technology System for the Entire Life Cycle of Prefabricated Buildings

- Low-Carbon Technology in the Design Phase

The challenge of a 138% increase in carbon emissions during the transportation phase of prefabricated buildings can be optimized through BIM modular design and parametric tools. Taking the Shanghai Rainbow Station as an example, BIM integrated 23 separate components into 5 modules, reducing the number of components by 78%, cutting transportation trips from 12 to 5, and lowering carbon emissions from 30.7 tons of CO_2 to 14.2 tons, a reduction of 54%. In a project in Wuhan, BIM parametric simulation adjusted the thickness of prefabricated wall panels from 200mm to 180mm, reducing the weight of each panel by 15%[5], with embodied carbon and transportation carbon of building materials reduced by 12% and 9%, respectively.

- Low-Carbon Technologies in the Production and Construction Phases

Low-carbon technologies in the production phase focus on the application of green building materials and the substitution of clean energy. Xi'an requires that by 2025, the application rate of green building materials in new constructions exceed 50%[4]; Broad Group can deploy energy-saving equipment, achieving a comprehensive energy consumption of 69 kgce per 10,000 yuan of output value in 2023, reaching an industry-leading level. The China State Construction First Bureau East China Headquarters project applies a new type of concrete system, with a prefabrication rate exceeding 40% and carbon emissions reduced by 34.9%[9]; factory photovoltaic systems and waste heat recovery can further reduce carbon emissions. Inner Mongolia has clearly defined full-process requirements for production carbon emission accounting.

- Low-Carbon Technologies for the Operation and Demolition Phases

During the operational phase, carbon emissions are reduced by 69.8% through energy-saving equipment, intelligent operation and maintenance, and renewable energy integration: Broad's 'Living Building' achieves 90% energy savings through smart temperature control and heat recovery, CSCEC's AI platform achieves comprehensive energy savings of 15%-25%; Suzhou farmhouses use 'photovoltaic + energy storage' to reduce emissions by an average of 11.9 tons per year, and Wuhan mandates rooftop photovoltaics, while BIM and IoT further extend equipment lifespan by 20%. The demolition phase focuses on resource utilization and harmless treatment: BIM archiving improves material recycling rates, with metals yielding the highest recovery benefits; China's coal science fly ash carbon sequestration technology sequesters 30,000 tons of carbon annually, and data from Portugal show that recycling one ton of construction waste can reduce carbon by 2.6 tons, providing both economic and environmental benefits.

4 BIM Building Carbon Emission Calculation and Carbon Reduction Design

4.1 Core Application of BIM in Building Carbon Emission Calculation

Multi-Stage Carbon Emission Dynamic Calculation.

BIM technology, by constructing a 'digital twin of buildings,' integrates carbon emission calculations throughout the entire lifecycle, enabling a shift from 'post-event accounting' to 'pre-event prediction and in-process control. Its core value lies in dynamism, accuracy, and collaboration. During the building materials production phase, BIM's built-in carbon emission factors automatically calculate embodied carbon. For example, a project in Wuhan optimized reinforcement based on this data, reducing the carbon emissions from material production by 8.7%. In the construction phase, BIM combined with 4D simulation allows real-time control of process-related carbon emissions. The

Shanghai Rainbow Inn project reduced emissions by 24.9 tCO_2, achieving a 38.8% reduction through optimization. In the operation phase, BIM integrates parameter simulation to model energy consumption. The Suzhou Photovoltaic Farmhouse project predicted power generation with an error margin of only 3.2% compared to actual output, demonstrating high accuracy.

Comparison of BIM Carbon Emission Calculations with Traditional Methods. To intuitively demonstrate the advantages of BIM technology, Table 3 summarizes the computational application data of three typical prefabricated building projects:

Table 3. Comparative Study on the Carbon Reduction Effects of BIM Technology in Typical Construction Projects.

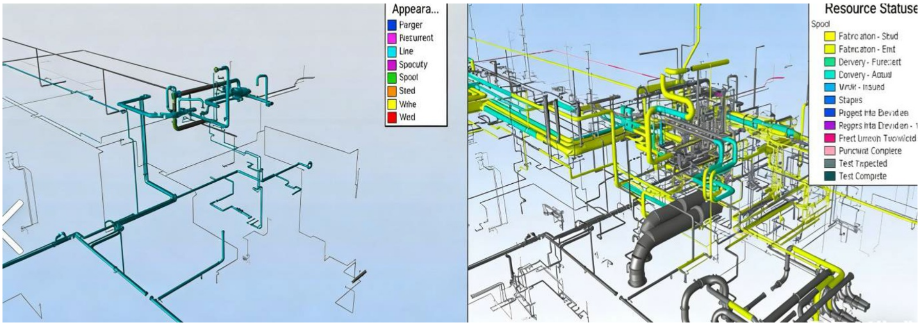
Project name	Application phase	Core BIM Functions	Improved Accuracy in Carbon Emission Calculation	Correlation reduction effect (compared to traditional methods)
New Construction Project of Yinchuan No.45 Middle School	design and construction	Digital pre-assembly and collision detection of templates	Increased from 72% to 95%	Material loss reduced by 20%, construction waste decreased by 30%, and total carbon emissions lowered by 15%.
A Prefabricated Residential Project in Wuhan	Design and Production	Carbon Factor Embedding in Component Library and LCA Integration	Increased from 68% to 93%	Pipeline conflicts reduced by 70%, carbon emissions from design changes decreased by 42%, and prefabrication rate increased by 18%.
Shanghai Rainbow Station	Full-stage coordination	Modular Modeling and Photovoltaic Energy Consumption Simulation	Increased from 75% to 96%	Duration reduced by 60% (completed in 45 days), with annual CO_2 emission reduction of 10,000 kg from photovoltaic systems

4.2 Key Pathways for Carbon Reduction Design Driven by BIM

The core value of BIM technology lies not only in its accuracy, but also in enabling visual, simulative, and collaborative construction management by optimizing upfront emission reduction goals through design, as shown in the image in Figure1, thereby reducing the carbon reduction pressure in subsequent stages from the source. Based on project practice, its carbon-reduction design paths can be summarized into four major directions:

- Modular and Parametric Design: Reducing Carbon Emissions in Transportation and Construction
- Material Selection Optimization: Reducing Hidden Carbon Emissions in Building Material Production

- Construction Plan Rehearsal: Reducing Process Energy Waste
- Operation and Maintenance Plan Pre-Control: Extending the Emission Reduction Cycle During the Operational Phase



(a) (b)

Fig. 1. Visual Comparsion Diagram.

4.3 Existing Issues and Optimization Directions

Furthermore, the current findings are contingent on specific regional conditions and project scales. Although BIM technology has achieved significant results in carbon emission calculation and low-carbon design, in practice it still faces three major bottlenecks: insufficient collaboration between BIM and LCA, gaps in full lifecycle data, and inconsistent regional standards. These issues need to be addressed through breakthroughs in technology, policy, and market mechanisms. Technologically, BIM-LCA integrated tools should be developed; from a policy perspective, standards for cross-stage data sharing should be established; and in the market, the application of BIM in low-carbon design should be incentivized. Leveraging its "dynamic calculation—front-loaded optimization—full-cycle control" capabilities, BIM has become the digital hub for carbon reduction in prefabricated buildings, with practical applications confirming its effectiveness. Future research should shift towards longitudinal tracking of operational data to validate these models across diverse climatic zones.

5 Conclusion

Future research should focus on three aspects: first, the development of lightweight component materials to address the high carbon emissions during the transportation stage; second, the establishment of a full life-cycle carbon footprint tracking platform; and third, the exploration of a "zero-carbon building and carbon trading" business model. Through the dual drive of technological innovation and institutional innovation, prefabricated buildings can transition from "low-carbon construction" to "full life-cycle net zero," laying a solid foundation for achieving the construction industry's carbon peak and carbon neutrality goals.

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