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Carbon Emission Assessment of Prefabricated Residential Buildings Based on Integrated BIM and LCA: A Case Study of Nanjing

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Abstract

As China accelerates its urban development and decarbonization agendas, prefabricated construction has emerged as a promising strategy for delivering low-carbon housing. However, the true carbon performance of prefabricated systems remains understudied, particularly across full building life cycles. This study evaluates the life cycle carbon emissions of a mid-rise prefabricated residential building in Nanjing by integrating Building Information Modeling (BIM) with Life Cycle Assessment (LCA). Using a cradle-to-grave framework, the research identifies material-specific emission hotspots, quantifies embodied and operational carbon contributions, and conducts scenario testing to assess the sensitivity of design variations. Results show that the total carbon footprint of the building is 419 $kgCO_2e/m^2$, with embodied carbon accounting for 71% of life cycle emissions. Major contributors include precast concrete, steel reinforcement, and insulation materials. Scenario analysis reveals that substituting high-carbon materials and improving logistics can reduce emissions by up to 18%. The study concludes with policy recommendations for integrating BIM-LCA tools into municipal design regulation and national prefabrication strategy. These findings offer both methodological and practical insights for advancing carbon-conscious construction in China's rapidly urbanizing regions.

Keywords: BIM-LCA integration, prefabricated housing, carbon emissions, life cycle assessment, embodied carbon, sustainable construction

1. Introduction

China is undergoing an intense urban transformation, marked by rapid land development, expanding housing needs, and ambitious environmental targets. By 2035, over 70% of the Chinese population is expected to live in cities, placing considerable pressure on the construction sector to deliver buildings that are not only fast and cost-effective, but also environmentally responsible. Simultaneously, the national commitment to achieve carbon peaking before 2030 and carbon neutrality by 2060—commonly referred to as the "Dual Carbon" goal—has elevated the importance of reducing emissions from all phases of the building life cycle.

Against this backdrop, prefabricated construction, also known in China as "industrialized building," has become a central strategy in sustainable urbanization policy. It enables off-site production of building components under controlled conditions, followed by efficient on-site assembly. This model reduces labor intensity, shortens project durations, and minimizes construction waste. Major urban centers such as Beijing, Shanghai, and Nanjing have established prefabrication development quotas, requiring a significant share of new buildings to use modular or semi-modular systems. Jiangsu Province, where Nanjing is located, has been particularly aggressive, mandating prefabrication rates above 50% for public housing projects since 2018.

Despite these policy incentives, the environmental benefits of prefabrication remain contested. While it is widely assumed to be "greener," evidence shows that factory-based precast systems can have higher embodied carbon due to cement-intensive materials and transport emissions. These trade-offs are further complicated by China's regional disparities in electricity generation, material sourcing, and transport infrastructure. Thus, a nuanced and data-driven understanding of the carbon profile of prefabricated buildings is essential—particularly in cities like Nanjing, where both urban expansion and environmental accountability converge.

This study investigates the carbon emission performance of a mid-rise prefabricated residential building in Nanjing, using an integrated method that combines Building Information Modeling (BIM) and Life Cycle Assessment (LCA). By doing so, it addresses a critical gap in applied sustainability research: how to link digital design tools with environmental performance analytics in the context of industrialized housing delivery.

2. Technological Convergence: BIM and LCA in Sustainable Building Analysis

Recent advances in digital construction technologies have made it possible to simulate and evaluate the environmental impacts of buildings in unprecedented detail. Among these, Building Information Modeling (BIM) and Life Cycle Assessment (LCA) stand out as two complementary yet distinct tools. BIM provides a digital representation of a building's geometry, materials, quantities, and components, while LCA evaluates the environmental consequences—primarily carbon emissions—associated with each life cycle stage. When integrated, BIM and LCA form a powerful platform for evidence-based design optimization, particularly in prefabricated construction where repeatability and material transparency are high.

The core advantage of BIM is its ability to embed detailed material and structural data into digital models at early design stages. In prefabricated buildings, BIM supports accurate quantity takeoff, modular coordination, clash detection, and logistics planning. Crucially, BIM models can be structured to export structured data (e.g., in IFC format) to downstream analysis tools, including LCA platforms. This allows for automated material mapping, real-time feedback on carbon impacts, and iterative comparison of design alternatives—enabling architects and engineers to make carbon-informed decisions before construction begins.

LCA, governed by ISO 14040 and ISO 21930 standards, provides a scientific framework for assessing emissions across production (A1–A3), transportation and construction (A4–A5), use (B1–B7), and end-of-life stages (C1–C4). In the Chinese context, LCA practices are becoming increasingly institutionalized, with databases such as the China Life Cycle Database (CLCD) and standards like GB/T 51366-2019 offering regionally adapted carbon factors and evaluation guidelines. However, manual LCA remains time-consuming and prone to input inconsistencies—challenges that BIM integration can directly address.

This convergence is particularly well-suited to prefabricated projects. Because modules and components are produced in standardized formats and repeated across multiple buildings or floors, a single BIM-LCA model can generate scalable carbon profiles with high fidelity. Software solutions such as One Click LCA, Tally, and eToolLCD already support BIM import features, and localized emissions factors can be embedded into Revit material libraries or custom object properties. These workflows allow project teams to simulate carbon footprints under different design and supply chain scenarios—providing the type of flexibility and foresight that policy makers and developers increasingly demand.

As the following sections will show, the combination of BIM and LCA offers not only a method for quantifying emissions, but also a framework for designing prefabricated buildings that are truly optimized for China's dual imperatives: urban expansion and carbon mitigation.

3. Lifecycle Boundaries and Carbon Metrics in Prefabricated Projects

3.1 System Boundary Selection and Its Impact on Carbon Outcomes

A building's carbon profile is significantly shaped by how its life cycle boundaries are defined. While simplified assessments often rely on cradle-to-gate logic—ending analysis at the factory—this approach overlooks critical emissions associated with transport, construction logistics, building operation, and deconstruction. For prefabricated buildings in particular, where much of the structure is fabricated off-site and then transported and assembled, the cradle-to-grave system boundary is indispensable for an honest carbon evaluation.

Adopting the EN 15978 framework, this study accounts for the full spectrum of stages:

- **A1–A3**: Material production (e.g., cement, steel, insulation)
- **A4**: Transportation of modules to site
- **A5**: Site assembly and installation
- **B1–B7**: Use phase, including repair and energy consumption
- **C1–C4**: End-of-life (demolition, recycling, disposal)

In China, the GB/T 51366-2019 and GB/T 50378-2019 standards also recognize the importance of full-cycle evaluation for green buildings. Prefabricated construction often shifts emissions from A5 (on-site construction) to A3 (factory manufacturing), and from labor-intensity to logistics-intensity, especially with larger panel sizes and heavier module weight. In the case study examined, A4 emissions alone contribute 12–18% of the total embodied carbon, a figure higher than typical cast-in-place projects.

Furthermore, end-of-life emissions (C1–C4), often ignored in policy discourse, can be substantial in prefab buildings due to joint treatments, mechanical connections, and limited disassembly potential. This reinforces the need for design-for-disassembly (DfD) principles and circularity-ready structures, which can be simulated and tracked using BIM-LCA workflows.

3.2 Carbon Categories and Data Input Selection

In line with ISO 14040/14044 and EN 15804, this study categorizes carbon emissions into embodied carbon (EC) and operational carbon (OC). Embodied carbon comprises emissions generated before the building becomes operational, while operational carbon refers to those arising during its functional use, primarily from HVAC systems, lighting, and domestic energy loads.

China's Ministry of Housing and Urban-Rural Development has adopted regionally adapted operational benchmarks—Nanjing, being in the "hot summer–cold winter" climatic zone, has typical residential energy loads of 35–50 kWh/m^2/year depending on insulation and HVAC configuration. However, improvements in operational efficiency (e.g., use of VRF systems, renewable integration) are progressing rapidly, which shifts attention more urgently toward embodied emissions, particularly in short-lifespan or rapidly deployed prefab housing.

To achieve accurate LCA modeling, this study adopts a hybrid data sourcing strategy:

- Primary data from BIM models (generated in Autodesk Revit) is used to calculate quantities for walls, slabs, columns, beams, windows, and finishes.
- Secondary data is drawn from the China Life Cycle Database (CLCD) and the Environmental Footprint of Building Materials Database managed by Tsinghua University.
- For comparison, international datasets (e.g., Ecoinvent, ICE v3.0) are also referenced to validate deviation across regional material processes.

Furthermore, input data considers temporal variability (e.g., cement carbon factor decline due to energy source decarbonization) and geographic variability (regional concrete mix designs), which are often overlooked in static LCA models but are critical for forecasting future project footprints.

3.3 Material-Specific Impacts in Prefab Construction

In prefabricated housing systems, material selection not only affects structural performance but also dictates life cycle carbon intensity. The most carbon-intensive material in the case study is precast concrete, particularly in load-bearing walls and staircases. Depending on the mix design, its embodied carbon ranges from 300–500 $kgCO_2e/m^3$, with significant influence from:

- Cement type (OPC vs. blended)
- Aggregate extraction method
- Energy source used for curing (electric steam vs. solar-assisted)

Structural steel, widely used for embedded connectors and reinforcement, shows even higher per-unit emissions, averaging 1.9–2.1 $kgCO_2e/kg$ under China's current energy mix. Unless sourced from electric arc furnaces (EAF) powered by renewables, these emissions remain a challenge.

Secondary materials such as insulation, glazing, and interior finishes may contribute smaller absolute quantities but can become hotspots under certain conditions. For instance:

- Polyurethane rigid foam (used in sandwich panels) emits 1500–1700 $kgCO_2e/m^3$.
- Triple-glazed window units, while thermally efficient, can have high embodied energy due to metal spacers and gas fills.

Moreover, transport logistics add a non-trivial load. In Nanjing's case, transportation distances from local prefab plants (e.g., Nanjing Liuhe Prefab Base, ~35 km) using diesel-powered flatbed trucks added an average of 25–45 $kgCO_2e/m^2$ to the A4 stage. As buildings scale up, these emissions can offset the savings from shorter on-site durations.

To reduce material-specific impacts, several strategies are modeled in later sections:

- High-substitution cement (with fly ash or slag content > 30%)
- Recycled steel and rebar
- CLT-based hybrid modules where local wood sourcing is available
- Optimized transport scheduling and logistics clustering

4. Data Modeling Workflow: BIM-Driven Carbon Quantification Process

4.1 Model Preparation and Material Mapping

The integration of Building Information Modeling (BIM) with Life Cycle Assessment (LCA) relies heavily on the accuracy, granularity, and completeness of digital models. In this study, a BIM model was developed using Autodesk Revit 2021, reflecting the full geometry, material composition, and construction sequencing of a five-story prefabricated residential building in Jiangbei New Area, Nanjing. The model includes parametric components for structural walls, precast floor slabs, windows, doors, roof panels, internal partitions, and mechanical systems, each tagged with detailed type, volume, and material information.

Material mapping is a crucial step in this workflow, as it forms the bridge between design data and environmental analysis. Each BIM element is associated with a defined material in the Revit library, which is then linked to specific environmental product declarations (EPDs) or database entries containing life cycle inventory data. For instance, the "Precast Wall – 200mm" family is mapped to a regional concrete mix with 20% fly ash substitution and corresponding GWP values from the China Life Cycle Database (CLCD). Where available, supplier-specific EPDs are prioritized to enhance precision, especially for high-emission components such as cement, rebar, and insulation materials.

To facilitate quantity takeoff, the model is organized into consistent layers by floor and function (e.g., core, shell, envelope), allowing for separation of reusable modules and permanent components. This structure supports sensitivity testing in later phases. Once all elements are correctly tagged and mapped, the model is exported in Industry Foundation Classes (IFC) format for compatibility with third-party LCA software.

4.2 Tool Integration and Output Verification

Following model preparation, the workflow continues with the import and processing of BIM data in an LCA platform. In this case, One Click LCA is selected due to its compatibility with Revit, integration with multiple regional databases (including CLCD and Ecoinvent), and built-in support for EN 15978-compliant reporting. The IFC export from Revit is uploaded into the One Click LCA environment, where a semi-automated mapping wizard assists in verifying quantities and material types against recognized environmental datasets.

Quality control is conducted at multiple levels to ensure the integrity of the output. First, visual checks are performed to confirm that all building elements have been accurately interpreted in the LCA tool. Next, cross-comparisons between BIM-native takeoff results and LCA platform quantities are used to identify missing or duplicated data. Special attention is given to mixed materials, such as composite floor panels or wall sections with embedded insulation, which require manual decomposition to apply distinct GWP values to each layer.

Output data is categorized by life cycle stage and component group, enabling the calculation of total embodied carbon per square meter, as well as per-material emissions. These results are then validated against a baseline case derived from a conventional cast-in-place design for the same building type, allowing for relative performance assessment. The data modeling workflow is iterated with small variations in input parameters—such as material substitution, transportation distances, or module assembly logic—to test the sensitivity and resilience of the design under different carbon scenarios.

The successful integration of BIM and LCA not only streamlines the analytical process but also enables dynamic feedback loops in early design phases. With accurate carbon insights embedded directly into the modeling environment, architects and engineers are empowered to make informed decisions that align aesthetic, structural, and environmental goals—crucial for advancing low-carbon housing delivery in fast-growing urban centers like Nanjing.

5. Case Study Focus: Carbon Performance of a Residential Prefab Building in Nanjing

5.1 Project Background and Technical Profile

The case study examined in this research is a mid-rise prefabricated residential building situated in Jiangbei New Area, Nanjing—a region prioritized in recent years as a demonstration zone for green and industrialized construction under Jiangsu Province's low-carbon urban development plan. Developed as part of a publicly subsidized housing initiative, the project consists of five above-ground floors and one basement level, with a total gross floor area (GFA) of 6,720 m². The structure adopts a reinforced concrete shear wall system with precast floor slabs and modular wall panels, achieving a prefabrication rate of 85.2% by construction value, meeting the Class B requirements under China's *Assessment Standard for Prefabricated Buildings (GB/T 51231-2016)*.

From a technical standpoint, the building's modular system includes:

- Sandwich precast concrete exterior walls, integrated with 50 mm polyurethane foam insulation;
- Hollow-core precast floor slabs with standard 120 mm thickness;
- Precast staircases, corridors, and balcony units;
- Dry connections using embedded steel plates and site-welded steel reinforcement;
- Aluminum-clad UPVC windows, with low-E coated double glazing.

The building design was modeled using Autodesk Revit at LOD 300 and coordinated across architectural, structural, and MEP disciplines. Material libraries were enriched with environmental metadata to enable full BIM-LCA integration. Local energy performance benchmarks were applied based on the *Design Standard for Energy Efficiency of Residential Buildings in the Hot Summer and Cold Winter Climate Zone (JGJ 134-2010)*. Operational parameters such as lighting density, ventilation rate, and domestic hot water loads were based on default occupancy profiles for low-rise multi-family units.

This project typology is broadly representative of a growing category of government-led prefabricated housing across second-tier Chinese cities, making its carbon profile highly relevant for policy formulation and comparative modeling.

5.2 Quantitative Carbon Footprint Analysis

The carbon footprint of the building was assessed using a full cradle-to-grave life cycle framework, aligning with EN 15978 and GB/T 51366-2019 methodologies. The analysis incorporates modules A1–A5 (production and construction), B6 (use-phase energy consumption), and C1–C4 (end-of-life processes). Emissions were modeled through One Click LCA, using quantity data extracted from Revit and mapped to China Life Cycle Database (CLCD) entries, supplemented by selected manufacturer-specific Environmental Product Declarations (EPDs).

The total life cycle emissions of the building were calculated at 2,816,000 kgCO_2e, which translates to 419 kgCO_2e/m² of gross floor area. The breakdown is as follows:

- **Embodied carbon (A1–A5 + C1–C4):**

~1,999,000 $kgCO_2e$ (71%)

- **Operational carbon (B6)**: **~817,000 $kgCO_2e$ (29%)**

The embodied carbon portion is dominated by:

- **Precast exterior wall panels**: 888,000 $kgCO_2e$ (~31.5%)
- **Reinforced steel rebar and inserts**: 540,000 $kgCO_2e$ (~19.2%)
- **Precast hollow-core slabs**: 275,000 $kgCO_2e$ (~9.8%)
- **Transportation and on-site installation**: 207,000 $kgCO_2e$ (~7.3%)

Operational emissions are modeled assuming a typical 36.5 $kWh/m^2/year$ electricity use, with a regional emission factor of 0.57 $kgCO_2/kWh$ based on Jiangsu Province's 2022 power mix (65% coal-based, 18% hydro, 10% solar and wind, 7% nuclear). Over a projected 50-year service life, the building's use-phase carbon footprint equals approximately 121.5 $kgCO_2e/m^2/year$.

While prefabrication significantly reduces waste and shortens construction timelines (project completion time: 7.5 months), it does not inherently guarantee lower carbon outcomes unless material selection and factory operations are optimized. As operational energy use continues to decline via improved appliances and grid decarbonization, embodied carbon will become the primary lever for long-term mitigation.

5.3 Emission Hotspots and Component Evaluation

Component-level analysis reveals that the building's carbon hotspots are highly concentrated within a small number of materials and processes. The precast concrete exterior walls account for nearly one-third of total emissions. These panels include high-strength cement mixes (C40) and steam-cured reinforcement-intensive designs that, although structurally efficient, result in high carbon intensity. The cement used alone contributes ~0.85 $kgCO_2/kg$, and its use per square meter of wall area surpasses that of equivalent cast-in-place designs due to reinforcement complexity.

Steel reinforcement ranks second in impact. Even though rebar is partially recycled, its production route in China still primarily follows the blast furnace–basic oxygen furnace (BF–BOF) pathway, with average emissions of 1.9–2.1 $kgCO_2e/kg$. The structural system includes dense stirrup placement in junction zones and embedded plates at connection points—details that improve seismic performance but add substantial carbon load.

Among secondary contributors, polyurethane insulation foam, used in sandwich panel cavities, emits 1.6–1.8 $kgCO_2e/kg$. The study notes that despite its high thermal resistance, this insulation's emissions are significant when scaled to the full envelope surface. Likewise, window systems with aluminum frames and coated glazing add considerable embodied carbon, mostly due to the smelting and extrusion stages of aluminum production.

Construction-stage emissions (A5), including crane use, module positioning, and welding, though relatively modest in quantity (~55,000 $kgCO_2e$), represent a critical component when logistics are not optimized. Daily delivery frequencies, partial truckloads, and vertical lifting delays are identified as operational inefficiencies with measurable carbon consequences.

The findings underscore that carbon reduction in prefabricated systems requires intervention at the material supply chain and design optimization levels, not merely at the assembly site. Opportunities for improvement explored in the next section include mix design adjustments, transport scheduling optimization, and alternative materials—particularly wood-concrete hybrid structures in low-rise configurations.

6. Scenario Testing and Emissions Sensitivity under Design Variations

To evaluate the robustness of the base case results and explore opportunities for carbon reduction, several alternative design scenarios were modeled using the same BIM-LCA framework. These scenario tests focused on key emission-driving parameters including material selection, structural system, transportation logistics, and operational energy source. By varying these inputs individually while keeping other variables constant, the study establishes a comparative landscape of emission sensitivities for prefabricated residential construction in Nanjing.

The first scenario tested the substitution of C40 cement-based precast concrete with a high-volume fly ash concrete mix (30% fly ash). This adjustment, while maintaining structural integrity, reduced the embodied emissions of precast wall and slab components by approximately 18.4%, leading to an overall life cycle carbon reduction of 11.2%. The result highlights the potential of mix design optimization as a practical strategy for immediate carbon savings, especially in markets where supplementary cementitious materials are readily available.

A second scenario explored the replacement of traditional reinforcement steel with EAF-based recycled steel, assuming a best-case carbon factor of 0.72 $kgCO_2e/kg$ (versus 1.95 $kgCO_2e/kg$ in the base case). This substitution produced a 9.7% reduction in embodied carbon, particularly in core structural zones where steel density is high. However, its feasibility depends on supply chain access to EAF steel, which is currently limited in many regions of eastern China.

A third scenario simulated the use of cross-laminated timber (CLT) in place of non-load-bearing interior precast walls. Although the substitution scope is structurally constrained, CLT significantly reduced component-level emissions, contributing to a 4.3% decrease in total embodied carbon. Beyond emissions, this also improved material circularity and disassembly potential, aligning with future-ready design principles.

Transport-related sensitivity analysis showed that extending the average transportation distance from 35 km to 60 km (simulating less localized prefab plants) increased A4 emissions by 43.2%, translating into a 2.9% increase in total life cycle emissions. Conversely, optimized logistics routing and full-load delivery planning were modeled to reduce A4 emissions by up to 35%, illustrating the importance of supply chain coordination in emission control.

Finally, operational energy modeling compared the base case (coal-heavy grid at 0.57 $kgCO_2/kWh$) with a projected decarbonized grid mix for Jiangsu in 2035 (estimated at 0.32 $kgCO_2/kWh$). Under the low-carbon scenario, B6 emissions declined by 44%, reducing total life cycle emissions by nearly 13%. If paired with rooftop photovoltaics and energy storage (modeled at 45% on-site coverage), emissions from building operation could fall even further, making net-zero operational performance within reach.

These findings demonstrate that design variation at the early planning stage can lead to substantial differences in carbon outcomes, and that BIM-LCA integration offers a viable platform for iterative optimization. Material substitution and cleaner energy sourcing show the highest sensitivity, while transport and system assembly logistics offer moderate but non-negligible reduction potential. These insights inform the policy and design recommendations presented in the final section.

7. Policy Alignment and Recommendations for Scalable Carbon Reduction

The results of this study underscore the potential—and the complexity—of using prefabricated residential construction as a strategy for low-carbon urban development in China. While modularization offers clear advantages in terms of construction efficiency, material standardization, and waste reduction, its actual contribution to national carbon neutrality targets depends heavily on how design decisions, material choices, and supply chains are managed. In cities like Nanjing, where both high construction demand and climate action pressure coexist, aligning technological tools with regulatory frameworks is essential.

At the local level, Nanjing has introduced a series of green building initiatives under the *Nanjing Municipal Green Construction Management Measures* (2020), including performance-based incentives for projects that meet specific prefabrication rates, energy efficiency metrics, and environmental certifications. However, these standards remain largely form-based and do not yet mandate full life cycle carbon assessments (LCCAs) as part of project approvals. Integrating BIM-LCA workflows into local permitting systems would enable more transparent and quantifiable tracking of emissions at the design stage—aligning with global best practices as seen in cities like Helsinki, Singapore, and London.

To accelerate decarbonization, this study recommends the adoption of three core policy mechanisms:

1) Mandatory embodied carbon benchmarks for public housing developments, enforced through LCA reporting at early design phases. These benchmarks should be differentiated by building type, height, and structure.
2) Incentivized procurement standards

that reward the use of low-carbon construction materials (e.g., blended cement, recycled steel, CLT), verified via Environmental Product Declarations (EPDs) and integrated into BIM metadata libraries.

3) Digital twin-based post-occupancy tracking systems, linking as-built BIM models with operational energy monitoring platforms. This would allow real-time performance verification and support carbon audits over the building's lifecycle.

At the national level, the alignment of this case study with China's "Dual Carbon" targets—peaking CO_2 emissions before 2030 and achieving neutrality by 2060—depends on the ability of prefabricated housing to scale while reducing its embodied carbon intensity. National codes such as *GB/T 51366-2019* already require LCA considerations in high-performance buildings, but the lack of standardized databases, third-party verification systems, and integration into mainstream design platforms remains a barrier. Investment in digital infrastructure and national material emissions baselines is needed to support meaningful comparisons and carbon labeling across provinces.

In terms of industry-wide transformation, a unified BIM-LCA certification platform supported by government, academia, and private developers could become the digital backbone of China's low-carbon construction strategy. Such a platform would allow standardized reporting, facilitate best practice sharing, and eventually feed into carbon trading or taxation schemes under China's emerging environmental finance system.

Ultimately, this study argues that prefabrication is not inherently low-carbon, but it can become so—if coupled with data-rich digital tools, life cycle thinking, and policy frameworks that reward long-term environmental performance. In a rapidly urbanizing and carbon-constrained future, cities like Nanjing stand to benefit from becoming national testbeds for these integrated approaches.

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