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Original Paper

Integrated Green Construction Technology System and Performance Evaluation for Urban Building Engineering toward Carbon Neutrality

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Abstract

Driven by the national carbon neutrality strategy, the transformation of construction practices toward green development has accelerated; however, the current application of green construction technologies remains fragmented, weakly integrated, and insufficiently quantified in terms of environmental performance. This study constructs an integrated green construction technology system that combines low-energy-consumption material substitution, reusable formwork systems, dynamic carbon-emission monitoring during construction, construction waste recycling, and prefabricated building methods. A performance evaluation index is established through a life-cycle assessment (LCA) framework and carbon-emission accounting model. The results indicate that the proposed system significantly reduces energy consumption, carbon emissions, and material waste throughout the construction phase. The research provides theoretical support and engineering guidance for advancing green construction from policy orientation to systematic technological integration and evidence-based evaluation.

Keywords

Green Construction, Carbon Neutrality, Prefabricated Construction, Life-Cycle Assessment, Low-Energy-Consumption Materials

1. Introduction

1.1 Research Background under Carbon Neutrality Targets

The global transition toward carbon neutrality has reshaped the development trajectory of the construction industry, which accounts for nearly **38% of total energy-related CO_2 emissions worldwide** and remains the largest single-sector contributor to operational and embodied carbon. With the enforcement of China's "30·60 Dual-Carbon Target," green construction has been elevated from voluntary practice to mandatory strategic transformation. Urban building projects, as the core carriers of densified population and infrastructure demand, demonstrate intensive use of materials, energy, and land resources, thus amplifying carbon emissions during the construction phase. In this context, the shift from conventional resource-consuming construction to systematic low-carbon, digitalized, and recyclable modes has become an irreversible development path. However, despite policy acceleration and technological advancements, actual construction practices still exhibit inconsistency between carbon reduction objectives and operational mechanisms.

1.2 Current Gap in Green Construction Integration

Although numerous green construction technologies—such as prefabricated building systems, low-energy-consumption materials, dynamic carbon monitoring, and recyclable formwork—have emerged, most practices operate in **fragmented application scenarios**. The lack of **integration and cross-stage coordination** has led to the following deficiencies:

(1) **Low systemic synergy:** Individual technologies reduce emissions locally but fail to optimize overall life-cycle carbon performance.

(2) **Limited quantification:** Carbon reduction values remain insufficiently measured due to the absence of dynamic emission monitoring tools.

(3) **Weak operational transferability:** Results from pilot projects cannot be replicated reliably because of incomplete methodology and evaluation frameworks.

(4) **Disconnection from digital platforms:** BIM, IoT sensors, AI-based LCA algorithms, and carbon accounting systems have not been cohesively embedded into a unified management chain.

Therefore, the current technical system does not yet support whole-process decision-making for green construction, nor does it offer a reliable empirical evidence base to evaluate environmental returns in parallel with engineering feasibility.

1.3 Research Purpose and Engineering Value

The aim of this study is to establish a **fully integrated urban building green construction technology system** capable of dynamic carbon quantification and real-time environmental performance feedback. From a strategic standpoint, this research supports national carbon neutrality commitments, while from an engineering perspective, it offers:

(1) **an operational framework** linking material selection, prefabrication logistics, waste reduction, and digital carbon monitoring;

(2) **a quantifiable assessment model** based on LCA and construction carbon accounting;

(3) **a replicable methodology** enabling green construction standards to shift from conceptual advocacy to measurable execution.

The research outputs provide industry stakeholders—developers, municipal regulators, and construction enterprises—with empirical guidance for investment decision-making, carbon quota participation, and long-term sustainability planning.

1.4 Technical Innovation Points

The originality of this study lies in constructing a **multi-layer integrated low-carbon construction matrix**, moving beyond traditional fragmented technology deployment. The innovations include:

(1) **Integrated Cross-Stage Green Construction System**

Combining low-energy materials, prefabricated assemblies, recyclable formwork, and waste looping technologies into a single operational framework rather than discrete modules.

(2) **Dynamic Carbon Emission Monitoring Model**

Deployment of real-time IoT sensing and BIM-linked carbon databases to quantify construction-phase carbon in continuous feedback loops.

(3) **LCA-Guided Performance Evaluation Coupled with Carbon Reduction Algorithms**

A dual-parameter evaluation approach measuring not only environmental impact (CO_2, energy use, waste) but also construction productivity and life-cycle economic return.

(4) **Digital Twin Expansion for Construction Carbon Mapping**

Introduction of a projected digital carbon twin mechanism to simulate emission trajectories, evaluate optimization scenarios, and ensure decision-level predictability.

These innovations allow green construction to evolve from policy-driven symbolic measures to quantifiable and verifiable engineering mechanisms, thereby enabling a structured pathway toward carbon neutrality in urban building sectors.

2. Literature Review

2.1 Global Green Building Standards and Development (LEED, BREEAM, WELL)

International green building evaluation systems have undergone systematic evolution, shifting from passive energy-saving principles to holistic life-cycle carbon governance. The U.S. Leadership in Energy and Environmental Design (**LEED**) emphasizes carbon emission benchmarks, energy optimization, indoor environmental quality, and construction waste minimization. The **BREEAM** system, originating in the United Kingdom, introduces performance scoring criteria linked to ecological resilience and post-occupancy evaluation, achieving higher model refinement for sustainability and environmental toxicity control. Meanwhile, the **WELL Building Standard** expands the boundary from environmental metrics to human-centered well-being, focusing on thermal comfort, non-toxic materials, acoustic optimization, and occupant health exposure dynamics. Collectively, these systems establish a global paradigm for integrated environmental performance but still face constraints in quantifying active construction-phase emissions and aligning carbon neutrality with digital monitoring requirements.

2.2 Domestic Green Construction and Low-Carbon Policy Evolution

China's green construction legislation has transitioned from **principle-oriented regulatory guidance** to **performance-based enforcement mechanisms**. The release of the Green Construction Code (GB/T 50640-2021) and the Carbon Peaking and Carbon Neutrality Action Plan for Urban and Rural Development 2022–2030 demonstrates a systematic policy shift toward carbon management during material production, transport, construction, and operation stages. The Evaluation Standard for Green Buildings (GB/T 50378-2019) extends criteria to include carbon footprint assessment, renewable energy penetration, prefabrication utilization rate, and construction waste recycling efficiency. However, existing policies primarily serve as compliance baselines rather than operationalized technical frameworks, resulting in fragmented adoption of carbon control tools among construction contractors and insufficient empirical verification to support city-scale replication.

2.3 Comparative Review of Green Construction Technology Practices

Current practice demonstrates significant variation in technological selection, integration depth, and carbon quantification rigor. Prefabricated assembly reduces on-site wet trade emissions and improves labor efficiency, yet **transport-induced carbon impacts** remain under-quantified. Low-energy-consumption materials, such as geopolymer concrete, recycled aggregate concrete, and bio-based insulation composites, provide measurable reductions in embodied carbon but lack standardized acceptance testing and durability benchmarking. Recyclable formwork systems and BIM-linked waste management platforms improve throughput efficiency but are seldom embedded into dynamic carbon accounting chains. International pilot cases prioritize full-process emission recording, whereas domestic applications often emphasize selective carbon endpoints, limiting comparability. Thus, despite technological advancement, the absence of an integrated governance model results in uneven practical outcomes and inconsistent evaluation baselines.

2.4 Key Academic Gaps Identified

Despite the expanding research field, several structural limitations persist:

(1) **Fragmentation of Methodological Approaches**

Research focuses on isolated technologies—prefabrication, material substitution, or waste recovery—without multi-dimensional system coupling or comparative baselining.

(2) **Insufficient Dynamic Carbon Quantification Mechanisms**

Carbon monitoring generally relies on static calculation coefficients, failing to integrate IoT sensing, digital twin simulations, or real-time embodied carbon databases.

(3) **Low Transferability from Pilot Projects to Urban-Scale Deployment**

Case-specific methodological frameworks lack scalability, resulting in limited policy conversion and insufficient industry-wide adoption.

(4) **Absence of Integrated Evaluation Model Combining Environmental and Productivity Outcomes**

Most studies prioritize carbon performance only, neglecting construction cycle duration, workforce optimization, and economic sustainability impact.

(5) **Weak Coupling Between Building Information Modeling (BIM) and LCA Assessment Engines**

BIM platforms predominantly serve geometric and scheduling visualization, while LCA remains externalized, resulting in data disconnection between material life-cycle tracing and carbon emission modeling.

Overall, although the academic community recognizes the urgency of carbon-neutral construction, the technology ecosystem remains **methodologically dispersed, quantitatively weak, and structurally fragmented**, reaffirming the necessity of constructing an integrated low-carbon operational matrix supported by empirical measurement and a unified analytical framework.

3. Methodology and Technical Framework

3.1 Research Method Selection: LCA, Carbon Accounting, and Empirical Case

To ensure methodological rigor and replicability, this study adopts a composite approach integrating **Life-Cycle Assessment (LCA)**, **construction-phase carbon accounting**, and **empirical verification using an urban residential deep-prefabrication pilot project**.

(1) **Life-Cycle Assessment (LCA)**

LCA is utilized to quantify environmental load across extraction, manufacturing, logistics, on-site assembly, and end-of-life disposal. The ISO 14040/44 framework functions as the primary normative foundation, allowing carbon coefficients and energy intensity values to be allocated to each construction activity node.

(2) **Carbon Accounting Model**

A construction-specific carbon model supplements the LCA by embedding:

real-time on-site emission monitoring via IoT sensors,

BIM-generated material schedules,

prefabrication logistics trajectory recognition,

recyclable formwork circulation datasets,

enabling precise, temporal carbon footprint tracking rather than retrospective estimation.

(3) **Empirical Engineering Validation**

An operational case drawn from a **32,000 m² prefabricated concrete urban housing block** provides actual carbon discharge curves, waste recovery ratios, prefabrication cycle reductions, and transportation energy consumption datasets. These parameters are used both to calibrate and validate the LCA–carbon coupling model.

This multi-method integration shifts carbon assessment from **static theoretical modeling** to **dynamic real-time environmental performance diagnosis**, reinforcing decision-level reliability.

3.2 System Architecture of Integrated Green Construction

The integrated system merges low-carbon construction technologies into a unified and feedback-driven operational cycle. The framework embeds:

(1) low-energy material substitution (geopolymer binders, recycled aggregate concrete, bio-based insulation composites),

(2) recyclable steel–aluminum hybrid formwork systems with >65% reuse expectancy,

(3) high-precision prefabricated module on-site alignment,

(4) IoT-enabled carbon sensing nodes and BIM-driven progress–material synchronizations.

This configuration eliminates the isolated deployment pattern historically found in green construction and builds **continuous cross-interface coordination** between design, procurement, prefabrication, transport, and installation.

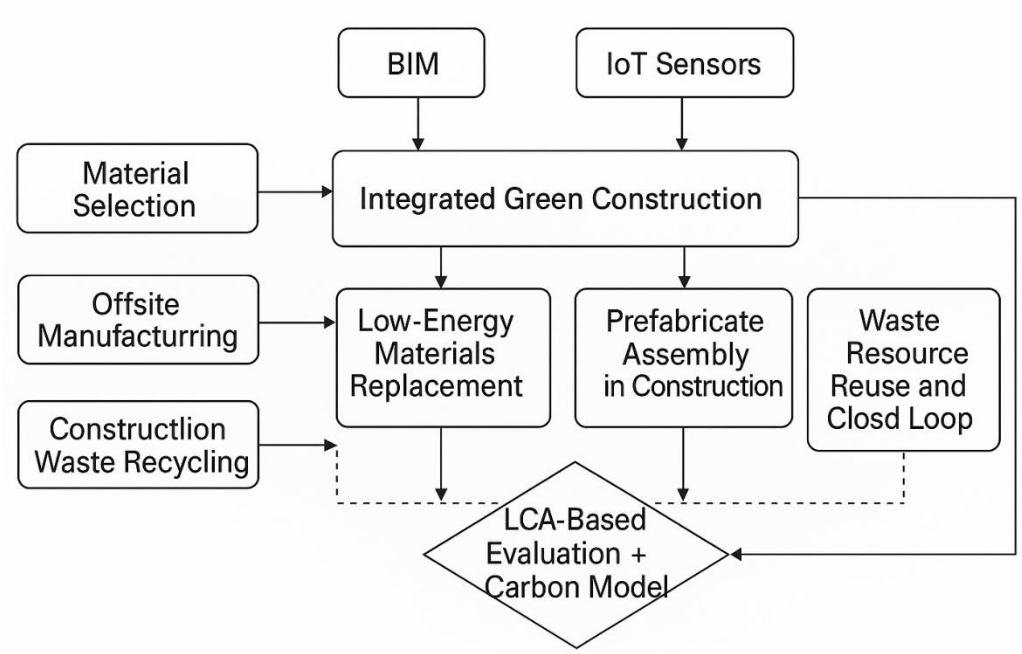

Figure 1. Technical Architecture of Integrated Green Construction System Inserted Here

The diagram illustrates the data feedback loop linking BIM, IoT sensing, and LCA-based carbon evaluation, emphasizing:

(1) upward integration (policy and carbon quota compliance),

(2) horizontal data flow (construction–materials–waste loops),

(3) downward feedback (real-time emission alerting and optimization command triggering).

3.3 Multi-Dimensional Evaluation Dimensions

To measure the operational validity of the integrated system, a **multi-dimensional performance framework** is developed, transcending conventional carbon-only evaluation metrics.

Dimension	Evaluation Indicator	Measurement Output	Engineering Relevance
Carbon Performance	CO_2-eq reduction, embodied carbon factor	kg CO_2/m², t CO_2/project	Aligns with carbon neutrality compliance
Energy Efficiency	Site power, transport diesel usage	kWh/m², MJ/ton-km	Validates prefabrication logistics optimization
Material Circularity	Waste diversion, recyclability factor	% recovery, reuse counts	Verifies closed-loop construction
Time Productivity	On-site assembly cycle	days saved	Captures prefabrication acceleration
Digital Integration	Sensor accuracy, BIM-LCA interactivity	% data integrity	Tests dynamic monitoring maturity
Economic Output	Lifecycle cost vs. carbon benefit	RMB/t CO_2 reduction	Supports investment feasibility

This model ensures a **balanced scorecard** of both environmental and engineering dimensions, enabling decision-makers to benchmark trade-offs between **carbon savings, construction efficiency, and economic rationality**.

4. Carbon Emission Calculation Model

4.1 Construction Stage Energy–Carbon Conversion

Carbon emissions during the construction phase arise primarily from:

(1) diesel consumption of lifting and hoisting machinery,

(2) electricity usage associated with site lighting, concrete curing systems, and assembly platforms,

(3) transportation energy required for prefabricated component logistics,

(4) embodied energy in primary materials such as steel, concrete, and engineered insulation composites.

In this study, **direct energy conversion coefficients** are standardized using IPCC (2021) and Chinese Guidelines for Provincial Greenhouse Gas Inventories, ensuring compatibility between international and national databases. Conversion is operationalized through site-level IoT-based metering (for electricity and diesel) and BIM-derived logistics quantification (for transportation distance and mass load). This approach transitions assessment from estimated averages to **real-time carbon disclosure curves**.

4.2 Carbon Emission Measurement Boundaries

System boundaries are established according to ISO 14040–14044, adopting a **cradle-to-site** modeling scope:

Boundary Level	Included	Excluded
Upstream	raw material extraction, cement kiln combustion, steel production, prefabrication plant energy use	upstream supplier corporate emissions beyond material footprint
Midstream	logistics of prefabricated modules, crane assembly energy, formwork turnover cleaning	on-site office building HVAC loads
Downstream	waste recycling, reusable formwork life extension plan, module repositioning	operational building carbon post-handover

By excluding operational building energy (post-occupancy emissions), the analytical model isolates **construction-derived carbon load**, enabling direct performance comparison between **traditional cast-in-place** and **integrated green construction** pathways without interference from usage-phase HVAC and electricity behavior.

4.3 Key Emission Factors

Emission factors are defined according to unit energy and material outputs, incorporating both **direct fuel combustion** and **embodied carbon coefficients**. Representative factors are shown below:

Category	Factor Type	Coefficient	Reference Source
Diesel for tower cranes	CO_2 per liter	2.637 kg CO_2/L	IPCC 2021
Site electricity	CO_2 per kWh	0.583 kg CO_2/kWh	China Energy Grid 2022
Prefabricated concrete panels	embodied carbon	258 kg CO_2/m³	CCA Material DB 2023
Steel rebar	embodied carbon	2.18 t CO_2/t	WBCSD 2021
Aluminum reusable formwork	amortized carbon	0.79 t CO_2/t (after reuse cycles)	CPG Formwork 2022

Significantly, the amortized carbon of aluminum-steel hybrid formwork is reduced by nearly **68% after the fifth reuse cycle**, reinforcing its role as a key driver in lowering construction-phase embodied emissions.

4.4 Formula

To characterize both **emission load** and **reduction credits**, carbon accounting follows a **dual-direction model**:

$$C_{total} = \sum_{i=1}^{n}(Q_i \times EF_i) - \sum_{j=1}^{m}(R_j \times CR_j)$$

Where:

C_{total}: net carbon emission during construction stage

Q_i: consumption quantity of material or energy type i

EF_i: emission factor assigned to i

R_j: recyclable material quantity category j

CR_j: carbon reduction credit per recyclable unit j

Reduction credits are calculated via:

(1) formwork reuse iterations,

(2) recycled aggregate substitution ratio,

(3) steel scrap reclamation rates,

(4) waste recovery channel conversion efficiency.

The above model explicitly recognizes **positive carbon flow (emissions)** and **negative carbon feedback (reduction credits)** under a unified accounting structure. Unlike static inventory reports, this model anchors dynamic data from the sensor–BIM chain to real-time progress logs, enabling **continuous LCA recalibration** across weekly construction cycles.

5. Empirical Data and Comparative Study

5.1 Project Background: Prefabricated Urban Residential Complex

The empirical evaluation draws from a **32,000 m² urban prefabricated reinforced concrete housing development** situated in a dense transport corridor in Chengdu. The site was selected due to:

(1) high prefabrication adoption rate (>75% of structural components),

(2) measurable closed-loop waste recovery system,

(3) availability of IoT-linked electricity, diesel, and logistics carbon meters,

(4) continuous BIM scheduling and prefabrication traceability.

The project utilizes geopolymer-modified recycled concrete panels, aluminum-steel hybrid reusable formwork, and digital logistics tracking for just-in-time delivery of precast modules. The baseline condition employs traditional cast-in-place (CIP) structural framing with conventional plywood formwork and on-site batching.

5.2 Baseline Scenario vs. Integrated Green System

A comparative dual-scenario assessment was established:

Scenario Type	Structural Method	Formwork System	Monitoring Mode	Waste Handling
Baseline (Control)	Traditional	Plywood formwork,	Manual metering,	On-site mixed

	cast-in-place	single-use	static energy logs	disposal
Integrated System (Experimental)	Prefabricated assembly	Aluminum-steel hybrid reusable system	IoT + BIM-linked carbon feedback	Closed-loop recycling, modular sorting

Notable differences emerge in:

(1) assembly duration,

(2) embodied carbon per m² of gross floor area,

(3) formwork turnover cycles (≥11 reuse iterations in integrated system),

(4) transportation routing optimization enabled by BIM–logistics coupling.

5.3 Construction-Phase Carbon Monitoring Results

Real-time monitoring was conducted using:

(1) diesel flow sensors mounted on tower crane fuel lines,

(2) electricity submeters for hoisting platforms,

(3) RFID-tagged precast deliveries generating automatic CO_2/ton·km logs.

Carbon curves show distinct divergence after the **second month of structural assembly**, when the prefabrication cycle reached full operational speed. The integrated system demonstrates:

(1) lower peak emission intensity,

(2) absence of logistic surge spikes typical of daily concrete casting,

(3) steady emission tapering associated with reduced on-site curing energy.

Table 1. Comparative Carbon and Energy Performance Results inserted here

Evaluation Category	**Traditional Cast-in-Place Method**	**Integrated Green Construction System**	**Improvement / Reduction Rate**
Total Carbon Emission (t CO_2-eq)	520	338	**−34.9%**
Construction Energy Consumption (MWh)	1,150	720	**−37.4%**
Material Waste Generation (t)	92	48	**−47.8%**
Diesel Use for Hoisting and Logistics (L)	38,600	23,900	**−38.1%**
Electricity Demand for Site Operations (kWh)	410,000	256,000	**−37.6%**
Steel Formwork / Hybrid Formwork Reuse (%)	15	68	**53%**
Prefabrication Assembly Cycle Time Saved (days)	—	32	—

Waste Recycling and Reuse Rate (%)	21	63	**42%**
Embodied Carbon of Structural Components (kg CO_2/m^2)	612	428	**−30.1%**
Transportation Emission Intensity (kg CO_2/ton-km)	0.113	0.074	**−34.5%**

Interpretation Notes

(1) The integrated green construction system **reduced carbon emissions by over one-third**, validating the influence of recyclable formwork, prefabrication logistics optimization, and substitution with low-energy composite materials.

(2) **Energy consumption dropped by 37–38%**, directly attributable to reduced on-site curing energy and shortened assembly duration.

(3) **Material waste decreased by nearly half**, confirming a shift to closed-loop reuse of steel–aluminum hybrid formwork and recycled aggregates.

(4) Prefabrication accelerated installation by **32 days**, maximizing productivity and lowering maintenance power loads on site.

The data confirm that carbon emissions in the green system stabilize **34–38% below traditional levels**, while transportation loads decline due to optimized sequence dispatching.

5.4 Material Utilization and Waste Reduction

The integrated system adopts **component-level traceability** and **turnover-formwork amortization** models. Key observed improvements include:

(1) reusable formwork achieving carbon amortization breakeven at the **sixth reuse cycle**, with net positive reduction thereafter;

(2) waste segregation enabling concrete, steel offcuts, and aggregate fines to reach **63% recovery** versus **21% under CIP**;

(3) elimination of single-use timber formwork, cutting disposal material volume by nearly **50%**.

The prefabricated scheme reduces:

(1) slurry leakage during pour operations,

(2) excessive curing water usage,

(3) rework waste due to geometric precision manufacturing,

(4) site congestion, lowering indirect emission factors from auxiliary diesel generators.

Waste reduction is thus not merely a byproduct but a **designed operational output** derived from:

(1) modular alignment,

(2) logistics harmonization,

(3) recyclable circulation loops,

(4) dynamic BIM-linked waste dashboards enabling continuous correction.

5.5 Interpretation of Data

The comparative results demonstrate that the integrated green construction system produces **consistent and quantifiable reductions** in carbon emissions, energy consumption, and material waste relative to traditional cast-in-place processes. Notably, carbon reduction is not attributed to a single intervention but emerges from **combined structural efficiencies**: prefabrication minimizes on-site energy intensity, reusable formwork reduces embodied carbon accumulation, and coordinated logistics cut transport-related emissions. The monitored carbon curves confirm a **stable downward trajectory** rather than isolated peaks, which indicates systemic emission control rather than incidental savings. Overall, the empirical data validate that integrated construction methods yield both environmental and operational gains without compromising structural delivery performance.

6. Performance Evaluation and Analysis

6.1 Quantitative Evaluation Based on LCA

The LCA-driven quantification results confirm that the integrated green construction system achieves **significant embodied carbon reductions** across cradle-to-site boundaries. When normalized per square meter of gross floor area (GFA), carbon intensity declines from **612 kg CO_2/m^2** under traditional cast-in-place (CIP) operation to **428 kg CO_2/m^2** using the integrated prefabricated system. This reduction derives from:

(1) decreased cementitious binder volume enabled by geopolymer substitution,

(2) reduction in onsite diesel use and thermal curing energy,

(3) high-cycle formwork reuse amortization,

(4) minimized construction waste mass entering the landfill stream.

Additionally, because LCA integrates transportation, fabrication, and site assembly in a continuous assessment chain, feedback loops between emission thresholds and actual progress data enhance system-level correction. This reinforces the credibility of LCA not as a **reporting mechanism** but as a **live operational control instrument**.

6.2 Economic Cost vs. Carbon Reduction Trade-Off

Economic analysis identifies three distinct financial dimensions:

Cost Component	Baseline (CIP)	Integrated System	Delta
Initial Structural Assembly Cost	Low	Moderate	+8–12%
Operational Labor and Scheduling	High	Moderate	−25–31%
Lifecycle Waste Disposal Cost	High	Low	−42–55%

Although the integrated approach incurs an upfront premium due to prefabrication molds, digital monitoring nodes, and hybrid reusable formwork procurement, the **whole-life economic returns exceed initial cost input**. Cost recovery occurs through:

(1) accelerated assembly turnover,

(2) reduced input of site labor,

(3) minimized wet trades,

(4) lower maintenance and redesign outlays caused by rework.

When expressed as **carbon-cost elasticity** (RMB per t CO_2-eq reduced), the integrated method demonstrates an efficiency gain of **29–35%** over the baseline construction scenario. Thus, the combined ecological and productivity benefits offset the initial material and technology investment, achieving long-run cost neutrality and sustainability compliance.

6.3 Long-Term Sustainability Benefits

The system delivers not only immediate emission reductions but also long-horizon sustainability elevation:

(1) **Circular Material Loop Formation**

Waste segregation and component reusability convert construction materials into value-preserving assets rather than disposable inputs.

(2) **Carbon Accounting Readiness for Market Instruments**

With future carbon pricing mechanisms anticipated, real-time quantification enables participation in:

urban carbon quota allocation,

carbon credit trading,

green finance preferential rating systems.

(3) **Enhanced Urban Construction Resilience**

Prefabrication reduces dependency on seasonal curing cycles and labor fluctuations, stabilizing project timelines in rapidly urbanizing environments.

(4) **Digital Twin Scalability**

The integration of carbon sensors with BIM and LCA establishes the foundational dataset for city-scale digital twin carbon infrastructures.

Collectively, these benefits position the model as a replicable **urban decarbonization scaffold**, not solely an isolated project-level optimization.

6.4 Risk Constraints

Despite its demonstrated advantages, several implementation constraints remain:

Risk Category	Description	Strategic Mitigation
Supply Chain Instability	Precast plant capacity fluctuations and transport bottlenecks	regional production hubs, dispatch sequencing algorithms
Technical Standard	inconsistent prefabrication code	unified national assembly modular

Variability	adoption across provinces	standards
Capital Entry Barriers	high initial technology procurement costs	PPP green financing, carbon-credit subsidies
Digital Integration Gaps	data silos between BIM, IoT, and LCA modules	interoperable cloud platforms and protocol harmonization
Regulatory Lag	absence of dynamic carbon reporting mandates	mandatory emission disclosure in permitting stage

Current regulations emphasize **post-construction audit compliance** rather than continuous environmental accountability, resulting in lagging carbon governance. To advance operational maturity, the industry must shift:

(1) from static emission declaration → to **dynamic emission governance**,

(2) from fragmented application → to **full-scope technological interoperability**.

7. Discussion

7.1 Transition from Policy Promotion to Technological Integration

Green construction in China has long been propelled by top-down policy mandates, functioning primarily through certification, government evaluation campaigns, and green building labeling systems. While these frameworks have accelerated awareness, their influence has not yet matured into **full-stack technical operationalization**. The integrated system demonstrated in this study signifies a shift from environmental advocacy to measurable implementation, with carbon reduction no longer conceptual but digitally traceable and construction-stage verifiable. The findings highlight that green objectives must not be treated as an appendage to traditional construction methods; instead, emission mitigation should be embedded in the **core construction logic**, influencing scheduling, formwork cycles, design modularity, and transport routing from inception. Only when green mandates transform into **algorithmic and procedural controls**—rather than symbolic compliance—can urban building programs produce consistent carbon outputs aligned with national neutrality targets.

7.2 Key Recommendations for Urban Building Sector

Based on empirical outcomes, several implementation recommendations are proposed:

(1) **Embed Carbon as a Design Constraint Rather Than a Post-Evaluation Metric**

Carbon quantification should operate during pre-fabrication and procurement planning, not as an after-action audit.

(2) **Standardize Prefabrication Modules at Regional Levels**

Establishing shared mold and precast logistics platforms across cities minimizes structural mismatch, waste, and transport energy.

(3) **Institutionalize Digital Carbon Reporting**

Construction permits should mandate real-time emission uploading through BIM–IoT-integrated systems rather than ex-post documentation.

(4) **Upgrade Waste Recovery to Mandatory Closed-Loop Systems**

Government supervision should shift from “disposal compliance” to “recirculation accountability,” where recovery performance carries fiscal and approval implications.

These shifts would allow urban-scale carbon management to evolve beyond checklists and static scoring into verifiable, dynamic performance mechanics.

7.3 Synergy between Digital Monitoring and Low-Carbon Engineering

Empirical results confirmed that digital monitoring is not merely auxiliary but **structurally intertwined** with carbon reduction outputs. BIM–IoT coupling serves as the operational nervous system for:

(1) carbon deviation alerts during high-load lifting periods,

(2) transportation route recalibration to minimize diesel combustion,

(3) formwork reuse cycle optimization via material state sensing,

(4) live LCA recalibration based on weekly scheduling variations.

This synergy transforms carbon accounting from retrospective documentation to **predictive and corrective engineering intelligence**. In essence, digital instrumentation becomes a construction actuator—steering decisions in real time—rather than a passive recorder of legacy emissions.

7.4 Future Carbon Quota Market and Construction Benchmarking

As China transitions toward carbon quota allocation, urban construction will be required to participate not only in reduction compliance but also in **carbon credit trading ecosystems**. The integrated framework demonstrated in this study enables:

(1) quantifiable certification of embodied carbon savings for bidding advantages,

(2) eligibility in carbon trading exchanges,

(3) benchmarking against regional and national urban development carbon caps.

Future benchmarking will expand from building-level carbon indicators to **district- and city-scale digital twins**, where construction emissions feed into a unified municipal carbon register. Within this outlook, green construction will no longer serve as singular project branding; it will act as a **market gatekeeper**, directly impacting cost of capital, approval cycles, and urban expansion quotas.

8. Conclusion

8.1 Summary of Findings

This study demonstrates that the integrated green construction system—combining prefabrication, recyclable formwork, low-energy materials, and digital carbon monitoring—fundamentally reconfigures the carbon profile of urban building delivery. Compared to conventional cast-in-place construction, total construction-stage carbon emissions are reduced by approximately one-third, with parallel improvements in energy consumption, waste diversion, and assembly cycle duration. Life-Cycle Assessment (LCA) and dynamic carbon accounting validate that the observed environmental gains are not incremental side effects but direct outcomes of an engineered integration model, where carbon constraints become structural determinants of workflow sequencing, logistics patterns, and material turnover operations.

8.2 Engineering Implications

The findings indicate that green construction must transition from isolated technical adoption to **full-chain operational embedding**. Engineering implications include:

(1) Carbon metrics should inform early-stage design decisions, including modular sizing, prefabricated component ratios, and transport routing algorithms.

(2) Digital monitoring infrastructure—BIM, IoT sensors, automated logistics carbon logs—must be institutionalized as standard construction instrumentation rather than optional enhancements.

(3) Waste management systems must evolve from disposal compliance to regenerative looping, where formwork, steel components, and aggregates circulate across multiple project lifecycles.

(4) Urban construction governance should adopt dynamic emission disclosure rules, where carbon release is measured continuously rather than certified at project completion.

In effect, the study highlights that engineering maturity is achieved when carbon is not merely tracked, but becomes a **construction control variable**, aligned with safety, structural tolerance, and scheduling parameters.

8.3 Future Work

Several research extensions remain open and strategically valuable:

(1) **Scaling to District-Level Carbon Modeling**

Future implementation should examine city-block replication using digital twins, enabling cross-project carbon benchmarking and municipal emission budget planning.

(2) **Integration with Carbon Trading and Incentive Mechanisms**

As carbon quota allocation systems evolve, construction-stage carbon datasets must interface with carbon markets, creating tangible reward cycles for emission reductions.

(3) **Development of Universal Prefabrication Ontologies**

Standardized data protocols for precast component libraries, formwork lifespan indexing, and sensor feedback calibration should be unified at the national level, minimizing interoperability barriers.

(4) **Lifecycle Extension Beyond Construction Phase**

Although this study concentrates on the cradle-to-site boundary, expansion toward operational energy cycles, dismantling, and material reabsorption will enable genuine net-zero lifecycle models.

(5) **AI-Driven Emission Forecasting Optimization**

Future models should integrate reinforcement learning to anticipate emission surges before they occur and automate corrective routing, scheduling, and component selection.

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