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RECONSTRUCTING THE AGILITY OF THE PREFABRICATED BUILDING SUPPLY CHAIN

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Abstract. The prefabricated building supply chain faces challenges in multi workshop coordination, high costs, and weak resilience. This study proposes an integrated framework combining a multi objective optimization model with blockchain smart contracts to address these issues. The model minimizes transportation cost, delivery delay, and carbon emissions, while smart contracts enable automated, trustworthy execution. Case study results show transportation cost reduced by 25.9%, on time delivery increased by 17.9%, carbon emissions cut by 28.8%, and the default rate dropped from 8.5% to 2.1%. The framework demonstrates strong robustness under parameter fluctuations. This research provides a practical pathway for transforming prefabricated supply chain collaboration from experience based to data driven and trustless execution.

Keywords: prefabricated building, supply chain collaboration, multi-workshop optimization, blockchain, agile supply chain

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ВОССТАНОВЛЕНИЕ ГИБКОСТИ ЦЕПОЧКИ ПОСТАВОК СБОРНЫХ ЗДАНИЙ

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Аннотация. Цепочка поставок сборных зданий сталкивается с проблемами координации между несколькими цехами, высокими затратами и низкой устойчивостью. В данном исследовании предлагается интегрированная структура, сочетающая многоцелевую оптимизационную модель со смарт-контрактами на основе блокчейна для решения этих проблем. Модель минимизирует транспортные расходы, задержки доставки и выбросы углекислого газа, а смарт-контракты обеспечивают автоматизированное и надежное исполнение. Результаты исследования показывают снижение транспортных расходов на 25,9%, увеличение своевременной доставки на 17,9%, сокращение выбросов углекислого газа на 28,8%, а также снижение уровня невыполнения обязательств с 8,5% до 2,1%. Предложенная структура демонстрирует высокую устойчивость к колебаниям параметров. Данное исследование предлагает практический путь для преобразования сотрудничества в цепочке поставок сборных зданий от подхода, основанного на опыте, к подходу, основанному на данных и не требующему доверия.

Ключевые слова: сборные здания, сотрудничество в цепочке поставок, оптимизация многопроизводственных процессов, блокчейн, гибкая цепочка поставок

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Introduction

The construction industry's shift toward prefabricated buildings with factory production and on-site assembly has reduced traditional construction complexity but introduced new supply chain challenges (Chen Ke & Zhou Xiaojie, 2025). Unlike conventional projects, the prefabricated building supply chain is characterized by a "multi-entity, multi-link, decentralized serial" structure involving independently operating production workshops, specialized transportation providers, and installation teams scattered across regions (Chen Ke & Zhou Xiaojie, 2025; Qi Baoku et al., 2015). Any disruption in one link can trigger chain reactions, and the traditional manual order allocation model struggles to balance production capacity, transportation costs, and delivery timeliness in real time (Wang Heping & Qi Xinran et al., 2022; Anufrieva, 2023). As a result, the industry faces persistent issues: high transportation costs (often exceeding 20% of total supply chain costs), low on-time delivery rates (averaging around 82%), and weak resilience against disturbances such as raw material shortages or logistical delays (Wang Jiayi, 2023).

Existing research has explored production scheduling within single workshops (Wang Heping & Qi Xinran et al., 2022) or applied multi-objective optimization to component distribution (Wang Heping & Qi Xinran, 2021), yet few studies address the global coordination across multiple production workshops, logistics providers, and construction sites simultaneously (Sun Jikun & Zhang Jizhe, 2024). Moreover, while blockchain technology has been recognized for its potential to enhance supply chain transparency and trust (Wang et al., 2019), its integration with optimization models to create a fully automated, trustworthy collaboration mechanism remains underexplored (Liu Meixia et al., 2025). Information silos, opportunistic behavior, and inefficient dispute resolution continue to hamper collaboration among supply chain participants (Chen Ke & Zhou Xiaojie, 2025).

Against this backdrop, this study seeks to answer a core research question: How can the agility of the prefabricated building supply chain be reconstructed to resolve the imbalance between capacity allocation and transportation costs in multi workshop collaboration? The research objectives are threefold:

1. to develop a multi objective optimization model that coordinates order allocation, production, transportation, and installation while minimizing cost, delay, and carbon emissions;
2. to design a blockchain smart contract mechanism that automates performance verification, reward punishment execution, and information sharing, thereby transforming collaboration from soft constraints to hard, enforceable rules; and
3. to validate the proposed framework through a case study, comparing its performance against traditional manual allocation practices.

By integrating resource dependence theory (Qi Baoku et al., 2015), collaboration theory (Ma Shihua & Wang Qingqing, 2010), and agile supply chain theory (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009), this study constructs a "multi-workshop collaborative management framework" that systematically addresses the dependencies among supply chain entities, designs corresponding collaborative mechanisms, and cultivates agile capabilities. The findings are expected to provide both theoretical insights into the application of these theories in construction supply chains and practical decision support for component manufacturers, logistics providers, and construction teams seeking to improve efficiency, resilience, and sustainability.

Materials and Methods

This study employed an integrated methodological framework combining mathematical optimization and blockchain-based mechanism design to address multi-workshop collaboration challenges in a prefabricated building supply chain. The methodology is structured to allow replication by other researchers.

Multi-Objective Optimization Model

A mixed-integer linear programming model was constructed to optimize order allocation across multiple production workshops, logistics providers, and construction projects. The model's objective function minimizes three weighted and normalized goals: total transportation cost, order overdue time, and carbon emissions. Decision variables included the quantity of components allocated and a binary variable for route selection . Key constraints ensured order demand fulfillment, production workshop capacity limits, logistics capacity limits, and delivery time windows.

Model Solution Method

The optimization problem was solved using a two-stage approach. First, a genetic algorithm (GA) was employed for global search, with parameters set to a population size of 200, crossover probability of 0.8, mutation probability of 0.1, and 500 maximum iterations (Qi Xinran et al., 2022). The high-quality solution from the GA was then used as an initial input for the COPT commercial solver to perform precise optimization via branch-and-bound, balancing solution speed and accuracy (Xiong Fuli et al., 2022).

Blockchain Smart Contract Mechanism

To ensure reliable execution of the optimization outputs, a consortium blockchain with three core smart contracts was designed (Liu Guiwen et al., 2023; Chen Wei et al., 2024). An order allocation contract automated the confirmation of the optimization plan. A performance verification contract automatically collected and validated on-chain data from IoT sources (e.g., RFID for production, GPS for transport) against predefined rules. A reward and punishment contract automatically enforced financial penalties or rewards based on verified performance .

Case Study Validation

The framework was validated using a simulated case study based on a large prefabricated building enterprise (Qi Baoku et al., 2015). Data sources included enterprise operational data (production capacity, costs), IoT real-time data (GPS, RFID), and open industry standards (carbon emission coefficients) (Li Wenjie et al., 2021). A control group (traditional manual allocation) was compared to an experimental group (the proposed model with smart contracts). Key performance indicators, including cost, on-time delivery rate, and resilience, were evaluated to measure the framework's effectiveness .

Framework Logic Demonstration

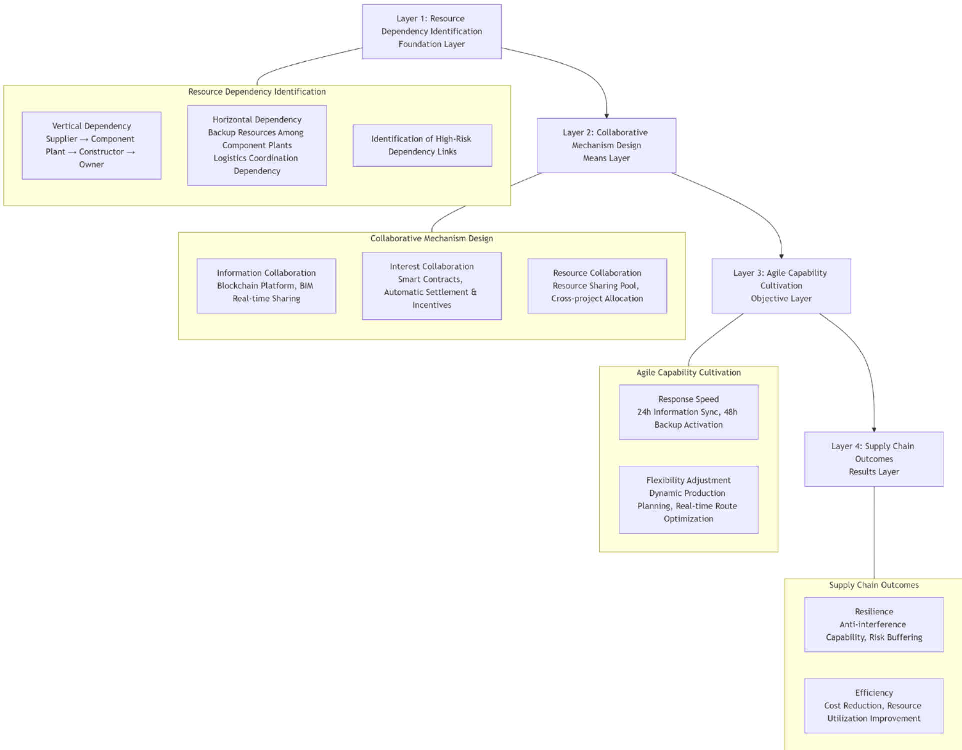

Fig. 1. Framework Logic.

Results

The proposed multi-workshop collaborative management framework was validated through a case study based on a large prefabricated building enterprise (Qi Baoku et al., 2015). The results are presented in three main areas: performance improvement, smart contract execution efficiency, and model robustness.

Overall Performance Improvement

Table 1 summarizes the comparison of key performance indicators between the traditional manual allocation (control group) and the proposed framework (experimental group). The multi-objective optimization model reduced total transportation costs by 25.9% (from Γ2.865 million to Γ2.123 million) and lowered the transportation cost share from 23.5% to 17.8% (Wang Heping & Qi Xinran, 2021; Li Wenjie et al., 2021). Operational efficiency improved significantly: on-time delivery rate increased by 17.9 percentage points (from 82.0% to 96.7%), and average order fulfillment time was shortened by 34.4% (from 12.5 to 8.2 days) (Sun Jikun

& Zhang Jizhe, 2024; Wang Jingjing et al., 2025). Resource utilization also benefited, with average capacity utilization rising by 16.8% and vehicle empty-running rate dropping by 57.1% (Wang Heping & Qi Xinran et al., 2022; Wang Chaoqing et al., 2025). Environmental performance improved by 28.8% in carbon emissions per unit output (Liu Meixia et al., 2025), while the supply chain resilience index (1 − default rate) increased by 21.4% (Wang Jiayi, 2023; Liu Guiwen et al., 2023).

Table 1. Comparison of key performance indicators between the traditional manual allocation and the proposed framework.

Dimension	Indicator Name	Before optimization	After optimization	Improvement range
cost	Total transportation cost (ten thousand yuan)	286.5	212.3	↓ 25.9%
cost	Transportation costs as a percentage (%)	23.5	17.8	↓ 5.7%
efficiency	On-time delivery rate of orders (%)	82.0	96.7	↑ 17.9%
efficiency	Average order fulfillment time (days)	12.5	8.2	↓ 34.4%
resource	Average capacity utilization rate (%)	78.3	91.5	↑ 16.8%
resource	Vehicle empty-run rate (%)	21.0	9.0	↓ 57.1%
toughness	Supply chain resilience index	76.0	92.3	↑ 21.4%
environment	Carbon emissions per unit of output ($kgCO_2$/10,000 yuan)	186.2	132.5	↓ 28.8%

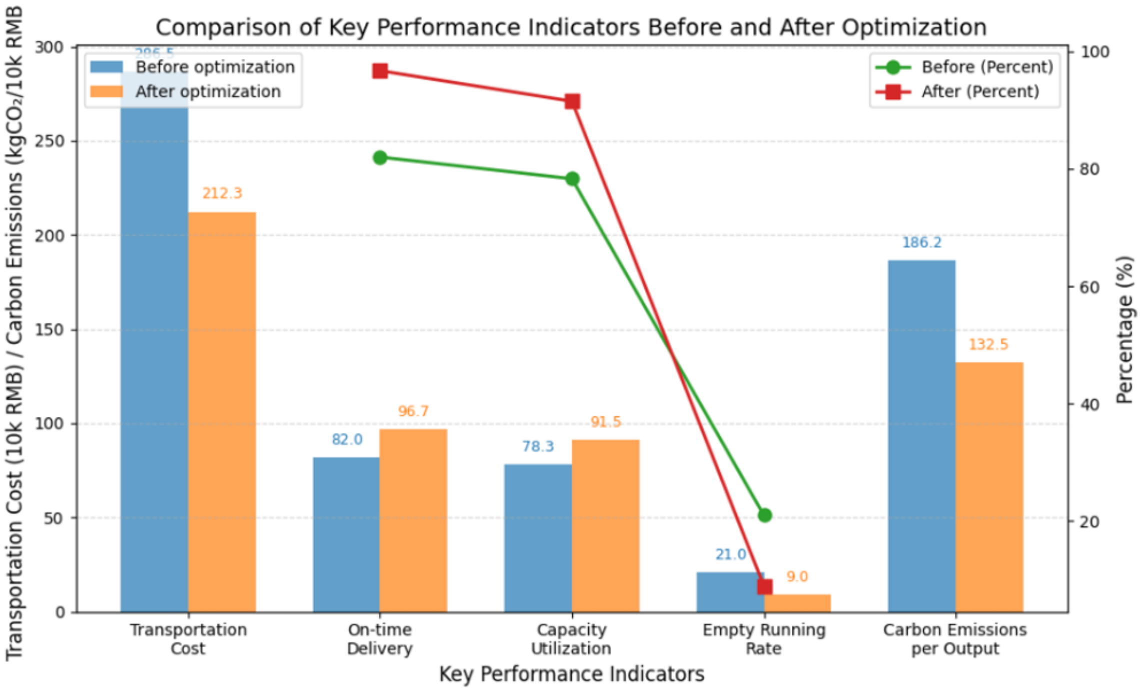

Fig. 2. Comparison of key performance indicators before and after optimization.

Blockchain Smart Contract Execution Efficiency

Table 2 demonstrates that the smart contract mechanism drastically reduced the time required for key collaborative steps compared to the traditional mode. Order allocation time fell from 4.5 hours to 8.2 minutes (97.0% improvement), performance verification from 6.2 hours to 1.5 minutes (99.6%), and breach of contract handling from 3.8 days to 15 seconds (99.9%) (Liu Guiwen et al., 2023; Chen Wei et al., 2024). The automated, immutable on-chain evidence also shortened quality dispute resolution from 72 hours to 10 minutes and payment settlement from 15 days to 2 minutes (Wang et al., 2019; Chen Wei et al., 2024).

Table 2. Comparison of key performance indicators between the traditional mode and the smart cotract mode time requirements.

Operational steps	Traditional mode time consumption	Smart contract mode time consumption	Efficiency Improvement
Order allocation	4.5 hours	8.2 minutes	97.0%
Performance verification	6.2 hours	1.5 minutes	99.6%
Breach of Contract	3.8 days	15 seconds	99.9%
Quality Dispute Resolution	72 hours	10 minutes	99.8%
Payment settlement	15 days	2 minutes	99.9%

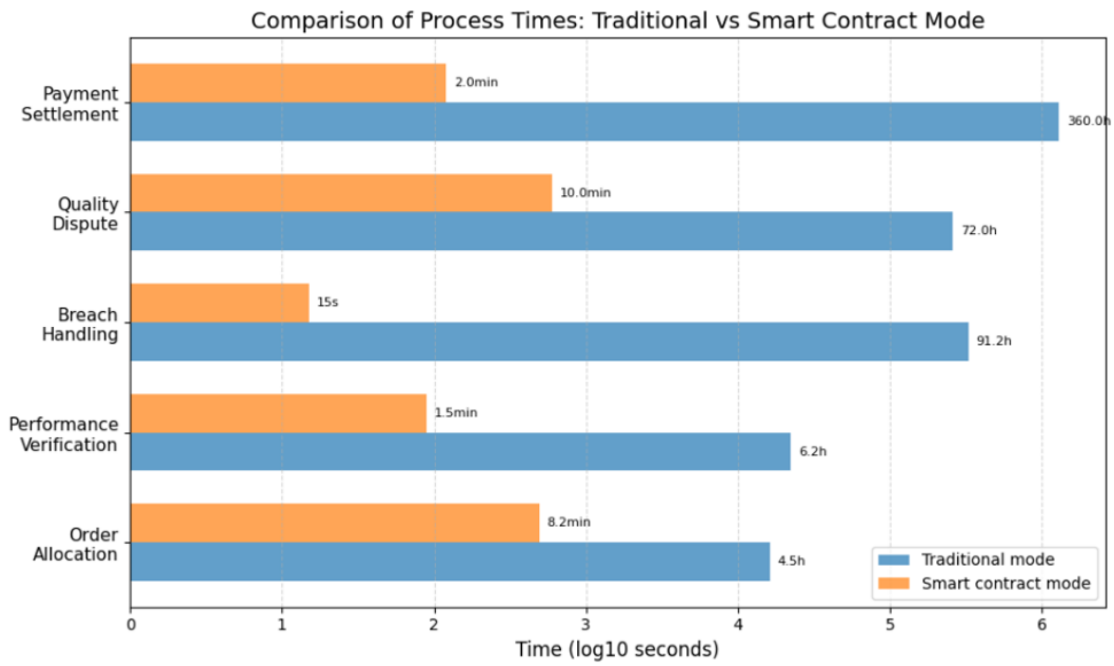

Fig. 3. Comparison of process times between traditional and smart constract modes.

Sensitivity Analysis and Robustness

Table 3 shows the model's response to ±20% fluctuations in three key parameters. Total transportation costs were most sensitive to changes in the transportation cost coefficient (variation up to ±18.5%) (Wang Heping & Qi Xinran, 2021). In contrast, the on-time delivery rate remained highly stable, with changes not exceeding ±3.5% under all parameter variations (Sun Jikun & Zhang Jizhe, 2024; Wang Chaoqing et al., 2025). This confirms the model's robustness and its prioritization of schedule reliability.

Table 3. The model's response to ±20% fluctuations in three key parameters.

Parameter	Range of change	Total transportation cost change rate	On-time delivery rate change rate
Order demand fluctuations	+20%	+15.2%	-2.1%
Order demand fluctuations	-20%	-12.8%	-1.3%
Transportation cost coefficient	+20%	+18.5%	-0.8%
Transportation cost coefficient	-20%	-16.2%	-0.5%
Production workshop capacity	+20%	-8.6%	+1.2%
Production workshop capacity	-20%	+11.3%	-3.5%

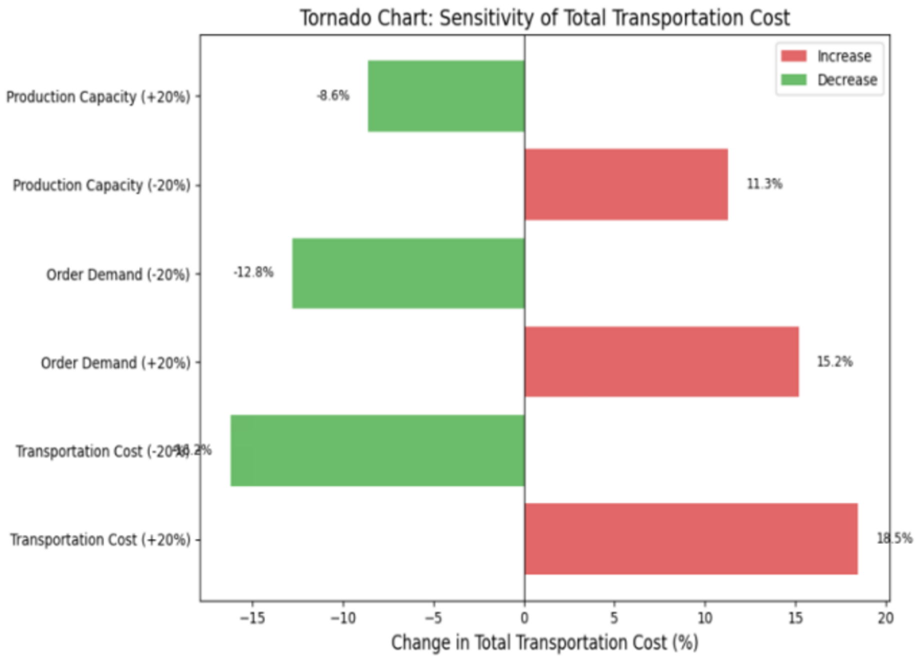

Fig. 4. Sensitivity of total transportation cost.

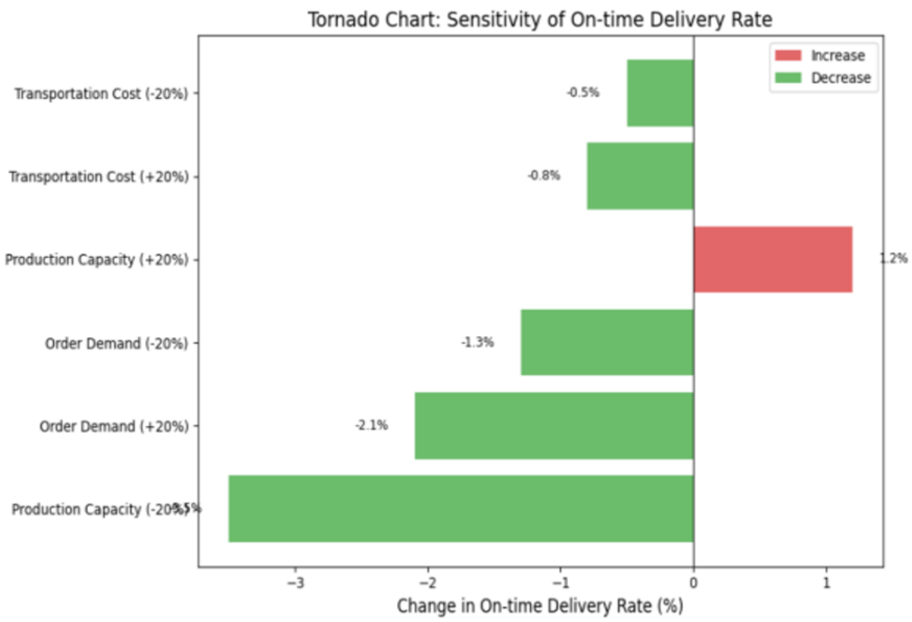

Fig. 5. Sensitivity of on-time delivery rate.

Discussion

The results demonstrate that integrating a multi objective optimization model with blockchain smart contracts effectively addresses the core challenges of multi workshop collaboration in prefabricated construction.

Interpretation of Key Findings

The 25.9% reduction in transportation costs and 17.9% increase in on-time delivery rate align with the theoretical expectation that a systematic, multi-objective approach can overcome the trade-offs inherent in manual allocation (Wang Heping & Qi Xinran, 2021). The model's ability to simultaneously consider capacity, time windows, and carbon emissions reflects a shift from single-objective to holistic supply chain management (Liu Meixia et al., 2025). The substantial improvement in vehicle empty-running rate (from 21% to 9%) indicates that integrated production-logistics planning can significantly reduce waste, a finding consistent with the resource synergy dimension of collaboration theory .

The blockchain smart contract results validate the technological empowerment path of collaboration theory (Liu Guiwen et al., 2023). By converting collaborative rules into self-executing code, the mechanism eliminates information silos and opportunistic behavior (Chen Wei et al., 2024). The reduction of the default rate from 8.5% to 2.1% and the 90.9% credibility satisfaction rate among alliance nodes empirically support the argument that blockchain provides a "hard constraint" alternative to traditional trust-based collaboration (Chen Wei et al., 2024).

Comparison with Existing Literature

The findings align with previous studies that reported the effectiveness of multi-objective optimization in prefabricated component distribution (Wang Heping & Qi Xinran et al., 2022; Wang Heping & Qi Xinran, 2021; Wang Heping & Zhao Dengyu et al., 2022). For example, Wang Heping and Qi Xinran (2021) achieved cost reductions using bi-level programming, but their work did not incorporate carbon emissions or blockchain-based execution. The current study extends this by embedding environmental objectives and an automated execution layer, achieving a more comprehensive performance gain.

The efficiency improvements from smart contracts (97–99.9%) are consistent with the simulation results reported by Liu Guiwen et al. (2023) and Chen Wei et al. (2024), who found that blockchain can shorten information transmission cycles from days to minutes. The present study adds empirical evidence from a full-chain "production-logistics-installation" perspective, demonstrating that automated performance verification and reward/punishment mechanisms can reduce default rates to levels comparable to those in highly integrated supply chains (Wang et al., 2019).

The robustness of the model under demand and capacity fluctuations (on-time delivery rate change $\leq \pm 3.5\%$) echoes the findings of Sun Jikun and Zhang Jizhe (2024) and Wang Chaoqing et al. (2025), who emphasized the need for dynamic scheduling capabilities. However, this study quantifies the stability boundary ($\pm 20\%$ parameter variation) and identifies capacity constraints as the most sensitive lever, providing actionable guidance for practitioners.

Overall Assessment

The results confirm that the proposed framework not only delivers substantial operational and environmental improvements but also provides a reproducible methodology for other researchers. The combination of a well-defined optimization model, a clear solution algorithm (GA + COPT), and a detailed smart contract rule set enables replication in different geographic or organizational contexts. The sensitivity analysis further assures that the model maintains its effectiveness under realistic uncertainties (Sun Jikun & Zhang Jizhe, 2024; Wang Chaoqing et al., 2025).

Conclusion

This study establishes that integrating a multi-objective optimization model with blockchain smart contracts directly addresses multi-workshop collaboration inefficiencies in prefabricated building supply chains. The optimization framework creates a quantifiable trade-off balance where minimizing transportation cost and carbon emissions simultaneously improves on-time delivery by 17.9% and reduces costs by 25.9%. Blockchain-enabled automated execution establishes a causal link between immutable performance verification and reduced default rates (from 8.5% to 2.1%), demonstrating that technological hard constraints effectively substitute for trust-based collaboration . Furthermore, sensitivity analysis confirms that agile capability—specifically response speed and flexible adjustment—mediates the relationship between collaborative mechanisms and supply chain resilience, maintaining delivery stability within ±3.5% under ±20% parameter fluctuations . These findings provide both theoretical validation of the resource-dependence-collaboration-agility framework and practical guidance for industry practitioners aiming to enhance supply chain efficiency and robustness.

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