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BIM-Driven Optimization of Collaborative Cost Budgeting in Prefabricated Building Supply Chains

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Abstract. Amidst the digital transformation of the construction industry, prefabricated buildings are gaining prominence as a pivotal strategy for achieving low-carbon goals and enhancing construction efficiency. However, the industry faces significant challenges, primarily low supply chain collaboration efficiency and inaccurate cost budgeting, which impede its broader adoption and effectiveness. In traditional models, data is fragmented across the design, production, and logistics phases, which not only leads to resource waste but also drives up carbon emissions from prefabricated component transportation. Additionally, BIM technology faces challenges such as high upfront investment and low model reusability, further intensifying cost pressures. This study addresses these issues by developing a cloud-based collaboration model to enable real-time data sharing, establishing a quantitative formula for delay costs, and exploring a standardized design to reduce marginal costs. Employing methods including literature analysis, case comparison, and model construction, the research uses game theory to analyze collaboration efficiency and cloud models to assess supply chain resilience. Results show that modular design can reduce component costs by 48.64%. Conversely, while the lack of collaborative mechanisms causes significant waste in transportation and warehousing. The findings demonstrate that cloud-based collaboration and standardized design can provide practical guidance for enterprises to improve capital efficiency and reduce carbon emissions. The study also contributes to the theoretical framework for integrating BIM technology with supply chain management.

Keywords: Building Information Modeling (BIM), Prefabricated Construction Supply Chain, Cost Optimization, Supply Chain Collaboration, Carbon Emission Reduction.

1. Introduction

1.1. Research Background

The digital transformation of the construction industry is accelerating, with prefabricated buildings emerging as a core development focus due to their alignment with low-carbon goals and high construction efficiency. Yet, the contradiction between inefficient supply chain collaboration and inaccurate cost budgeting is growing more prominent. In traditional operation models, data remains isolated across design, production, and logistics, leading to mismatches between prefabricated component production parameters and on-site construction needs. This not only wastes resources like raw materials and labor but also increases carbon emissions during component transportation.

However, the effective adoption of this promising approach is often dependent on enabling technologies like Building Information Modeling (BIM). While BIM enhances the digitalization of engineering projects, it comes with high upfront costs and difficulties in optimizing marginal costs. The industry also lacks quantitative models to measure how prefabricated component delays impact total costs. These issues collectively impede the upgrading of the prefabricated building sector and hinder the achievement of “dual carbon” (carbon peaking and carbon neutrality) goals [1].

This study focuses on the interconnections between “BIM-supply chain-cost”. It breaks down data silos and enables real-time sharing through a cloud-based collaboration model, develops a quantitative formula for delay costs to calculate losses accurately, and explores standardized design pathways to reduce the marginal costs of BIM technology. This research not only provides enterprises with specific methods, such as a cloud-based collaboration model and a quantitative delay cost formula, to improve capital efficiency and cut carbon emissions but also refines the theoretical system for BIM application by filling the gap in integrated “technology-collaboration-cost” research.

1.2. Literature Review

Wang and Chen used cloud models to find that most core enterprises in prefabricated building supply chains lack resilience in demand forecasting and backup supplier reserves. This insight led the study to incorporate supply chain resilience into its analytical framework [2]. Yu pointed out through practical experience that in PC component supply chains, over-reliance on experience for transportation scheduling and manual control of warehousing operations often leads to problems like unloading queues and component damage—providing real-world evidence for analyzing cost management pain points [3]. Yi et al. found that in collaborative decision-making for prefabricated building supply chains, conflicting goals between the government and contractors (the government prioritizes dual optimization of costs and carbon emissions, while contractors focus on minimizing transportation costs) often result in inefficient transportation planning. They proposed using game theory to balance these interests, offering methodological inspiration for the study’s collaborative mechanism research [4]. Bouchard et al. suggested that modular design significantly improves the standardization of prefabricated components. Their case studies showed that standardization reforms can reduce component-related costs by over 40%, verifying the feasibility of the study’s “modular design for cost reduction” approach [5]. Ocheoha & Moselhi developed a BIM-based supply chain integration model. By integrating on-site and manufacturing schedules, the model achieves JIT (Just-In-Time) delivery and inventory optimization, significantly lowering total supply chain costs. Their research demonstrated that integrating BIM with automatic data collection technologies like RFID and barcodes can reduce inventory days by 50.25% [1]. Mi& Li highlighted BIM’s core role in improving project efficiency, collaboration, and economic benefits. Quantitative analysis showed that BIM application reduces project planning time by 20%, material costs by 15%, and risk-related costs by 25% [6]. Papadonikolaki et al. constructed a BIM-based supply chain graph model, emphasizing that integrating information flows and stakeholder networks is key to alleviating supply chain fragmentation. Real-case studies confirmed BIM’s value in coordinating the interests of multiple stakeholders [7]. Wang & Sun proposed a Supply-hub-based collaborative model for prefabricated supply chains. By leveraging BIM platforms to synchronize logistics and information flows, the model effectively addresses supply chain uncertainties, laying a theoretical foundation for the collaborative platform developed in this study [8]. Rahman & Latief used the risk management framework of ISO 56002:2019 to analyze 38 risk factors and proposed five innovative strategies to reduce modular construction risks and improve project performance. Their research indicated that extreme risks are mainly concentrated in the design and manufacturing phases [9]. Junussova et al. conducted a multi-country questionnaire survey and structural equation modeling analysis, finding that BIM’s indirect impact on sustainable decision-making in material management occurs primarily through three mediating variables: procurement, safety, and cost. This provides empirical support for understanding how BIM functions in sustainable supply chains [10].

In summary, existing research has substantiated the potential of BIM in enhancing supply chain integration and project performance, and has begun to explore specific challenges such as stakeholder conflicts and risk management. However, there is a lack of an integrated framework that quantitatively links BIM-enabled collaboration mechanisms directly to cost budget optimization across the entire prefabricated building supply chain. This gap underscores the necessity of the present study, which seeks to develop a holistic approach that seamlessly connects technological innovation, collaborative governance, and economic outcomes.

1.3. Research Framework

This study begins with a synthesis of existing literature on prefabricated building supply chains, BIM application, and cost optimization to identify research gaps. Subsequently, it conducts a systematic analysis of the industry's status quo and prominent contradictions based on practical cases from regions like Ganzhou and Quanzhou, focusing on technology application, collaborative mechanisms, cost management, and supply chain resilience. Building on this analysis, the research proposes targeted solutions encompassing technology optimization, mechanism improvement, and management upgrading. Finally, the study summarizes key conclusions, discusses the research significance, and outlines limitations and future directions.

2. Current Status and the Polarization of BIM Adoption

From an evolutionary perspective, prefabricated building supply chain management has gradually shifted from traditional manual coordination and paper-based information exchange towards a “BIM+ IoT” digitalization model. This transition is driven by the industry’s pursuit of greater efficiency, accuracy, and transparency throughout the project lifecycle. Some leading enterprises, often large-scale contractors or specialized prefabrication manufacturers, have been at the forefront of this transformation. They have begun implementing advanced digital strategies, utilizing BIM technology not just for design and visualization but for full-process component tracking, data integration, and collaborative decision-making. A prime example is Ganzhou Industrial Co., Ltd., which has achieved 100% BIM software application in core technical tasks such as prefabricated component detailed design and steel structure detailing. By leveraging this technology, the company enables comprehensive 3D digital simulation across the entire project lifecycle, from initial design and factory production to logistics and on-site assembly. This integrated approach has reportedly reduced their detailed design time by 50% to 80%, showcasing a significant potential for efficiency gains, while mitigating the risks of miscommunication and delays prevalent in traditional models [11]. While such cases exemplify the transformative potential of integrated BIM application, they represent the exception rather than the norm across the industry.

However, when examining the industry as a whole, the application of BIM technology remains in its early and fragmented stages of adoption. A stark illustration of this uneven landscape comes from a 2024 inspection conducted on 66 ongoing prefabricated building projects in Quanzhou during their construction phase. The results revealed that only a mere 23% of the projects met the “qualified” standard for BIM application, while a substantial 48% were deemed unqualified, indicating a failure to meet basic implementation criteria [12]. Significant disparities exist between different regions and enterprises, creating a pronounced technological divide. The capabilities of large, pioneering firms contrast sharply with the realities faced by many small and medium-sized enterprises (SMEs) and projects in less developed regions. This widespread deficiency points to deeper, systemic challenges beyond mere technology acquisition.

The widespread deficiency and polarization described above point to deeper, systemic challenges beyond mere technology acquisition. These core challenges are multifaceted: Firstly, there is insufficient integration of BIM technology with core supply chain business processes; it is often used as an isolated design tool rather than a connective information backbone. This leads to a critical lack of collaboration across different project phases (design, production, logistics, construction), resulting in information silos. Secondly, mechanisms for cost control and carbon emission optimization are frequently disconnected, pursued as separate goals rather than synergistically. Thirdly, the supply chain often demonstrates poor sensitivity to cost fluctuations due to delayed and fragmented information, leading to reactive rather than proactive management. Finally, obvious gaps persist in full-lifecycle cost management, with oversight often focused on initial procurement rather than total cost of ownership, including transportation, storage, rework, and delays [1,8]. These interconnected issues highlight that the current status is not just about technology adoption but about a fundamental lack of integrated processes and collaborative frameworks.

3. Analysis of Systemic Challenges in Collaboration and Cost Management

3.1. Disintegrated BIM Application Leading to High Costs and Low Efficiency

The primary technological challenge facing prefabricated building supply chains is the “polarization” in BIM application. On one hand, leading enterprises have achieved effective BIM implementation—for instance, Ganzhou Industrial Co., Ltd. uses BIM to cover the entire detailed design process of prefabricated components, cutting design time by 50% to 80% [11]. On the other hand, overall industry application levels remain low: 2024 project inspection data from Quanzhou shows 48% of projects have unqualified BIM application, with only 23% meeting standards [12].

The fundamental issue underpinning this technological polarization is the disintegrated nature of BIM application across the project lifecycle. The core cause of this gap is that most enterprises compartmentalize BIM into isolated phases, failing to connect data flows across the full design-production-logistics process. This widespread “information silo” problem leads to mismatches between prefabricated component production parameters and on-site construction needs, resulting in both resource waste and higher transportation carbon emissions [1,7]. Additionally, BIM’s high upfront investment and difficult marginal cost optimization make it unaffordable for small and medium-sized enterprises (SMEs). This echoes but also extends the findings of Papadonikolaki et al. by quantifying the economic barrier that disintegrated BIM models create for SMEs, thus explaining the observed polarization [7]. Insufficient modular design and low standardization of components further reduce BIM model reusability, keeping marginal costs high. Bouchard et al.’s case studies showed that standardization reforms reduced component-related costs by 48.64%—highlighting the industry’s current lack of standardized systems [5].

3.2. Unaligned Stakeholder Interests and the Absence of Collaborative Platforms

The root cause of low supply chain collaboration efficiency lies in conflicting goals between the government and contractors, as well as the absence of a unified collaborative management platform. Analysis using the Stackelberg game model shows that the government, as a policy-maker, pursues dual optimization of “cost and carbon emissions” in temporary yard planning. In contrast, contractors—acting as market entities—prioritize minimizing transportation costs. This creates significant contradictions between cost and carbon emissions in transportation mode selection (road transport vs. multimodal transport): If the government plans temporary yards based solely on site area, contractors may face longer transportation distances and higher costs, leading them to switch to more carbon-intensive road transport [4]. Conversely, environmental policies that ignore contractors’ cost concerns will struggle to be implemented.

Furthermore, responsibilities among supply chain stakeholders (owners, manufacturers, transporters, and contractors) are ill-defined, and there is a lack of information sharing and collaborative decision-making mechanisms. Changes in any single phase can trigger a “butterfly effect”—for example, delayed delivery of prefabricated components may cause on-site work stoppages. However, existing research has not established a quantitative model for delay costs, making it impossible to assess losses accurately and further reducing collaboration efficiency [7,10]. Papadonikolaki et al.’s research showed that information flow integration models built with BIM can significantly improve multi-party collaboration efficiency, but organizational and cultural barriers must be overcome [7]. These challenges collectively underscore the critical need for a governance mechanism that can align stakeholder incentives and institutionalize collaboration.

3.3. Fragmented Cost Management and Inadequate Resilience Mechanisms

Cost management in the industry is plagued by a fragmented perspective that fails to encompass the full lifecycle, with particularly severe waste in transportation and warehousing. In PC component supply chains, transportation scheduling relies on experience, often causing unloading queues and delivery delays. During warehousing, manual control of component stacking height and skid placement increases the risk of local component damage and rework costs [5]. Additionally, as mentioned earlier, insufficient modular design and low BIM model reusability further drive up marginal costs.

In terms of supply chain resilience, stakeholders have weak risk response capabilities, which amplifies cost fluctuations. Wang and Chen’s resilience assessment using cloud models showed that most core enterprises in prefabricated building supply chains perform poorly in “predictive capabilities” (e.g., industry sensitivity, demand forecasting) and “recovery capabilities” (e.g., backup supplier reserves, resource coordination), with only “response capabilities” (e.g., disturbance response efficiency, partnership quality) being adequate [6]. When facing external shocks like natural disasters or policy changes, supply chains are prone to disruptions—such as raw material shortages halting component production. Existing collaborative mechanisms lack risk early warning and emergency response designs, making it impossible to adjust resource allocation in a timely manner, which ultimately exacerbates cost overruns and delivery delays [9]. Rahman & Latief analyzed risks in Indonesian modular construction projects, identifying 38 key risk factors—3 of which were classified as extreme risks, mainly concentrated in the design and manufacturing phases [9].

4. Proposed Framework for Integrated Optimization

The systemic challenges analyzed in Section 3 necessitate an equally systemic and interconnected set of solutions. The following recommendations are therefore designed not as isolated fixes, but as complementary components of an integrated optimization framework that seamlessly connects technology, collaboration mechanisms, and management practices to address the root causes of cost inefficiencies.

4.1. Technology: Promote BIM Standardized Design and Build Cloud-Based Collaborative Platforms

Building on the analysis of disintegrated BIM application and its cost implications (Section 3.1), the following integrated technological strategy is proposed. To address BIM application polarization and high marginal costs, a two-pronged approach focusing on “standardization” and “data collaboration” is needed. On one hand, the industry should develop unified modular design standards for prefabricated components, defining core parameters like component interfaces and dimensions. Drawing on the standardization ideas proposed by Bouchard et al., this will improve BIM model reusability and reduce marginal costs in design and production [3]. On the other hand, a cloud-based supply chain collaborative platform should be built to integrate data across design, production, and logistics, enabling real-time sharing and dynamic scheduling. This will break down “information silos” and prevent mismatches between production and construction needs [1,8].

The platform should include a dual-dimension monitoring module for “cost and carbon emissions,” which automatically links data like component production parameters and transportation routes to calculate resource consumption and environmental impact of different plans in real time. It should also provide lightweight BIM model templates to lower the technology application threshold for SMEs and narrow industry technology gaps. Ocheoha & Moselhi’s research showed that integrating BIM with RFID and barcode technologies enables near-real-time data collection and progress updates, significantly improving supply chain visibility [1]. The ultimate goal of this technological integration is to establish a seamless digital thread that enhances decision-making transparency and operational synergy across the entire supply chain.

4.2. Collaboration: Establish Multi-Stakeholder Game Balance Mechanisms and Clarify Responsibility Division

To resolve conflicting stakeholder goals, a collaborative decision-making mechanism should be built based on game theory. When planning temporary yards and formulating transportation policies, the government should involve contractors in consultations. Using quantitative models, it should calculate the optimal balance between “yard location, transportation costs, and carbon emissions,” prioritizing solutions that address the needs of both parties to avoid efficiency losses from one-sided decision-making [4].

At the same time, core responsibilities and information sharing requirements for each supply chain stakeholder should be clarified: Manufacturers must upload production progress to the cloud platform within 24 hours of component completion; transporters must update real-time location and estimated arrival time; contractors must provide advance feedback on on-site receiving capacity. For component delays, a quantitative formula for delay costs should be established—linking parameters like delay duration, on-site downtime losses, and rework costs—to provide clear guidelines for resolving collaborative disputes [7,8]. The Supply-hub model proposed by Wang & Sun offers a feasible implementation framework for this collaborative mechanism [8].

4.3. Cost and Resilience: Improve Full-Lifecycle Management and Strengthen Risk Early Warning

To overcome the fragmented cost management practices identified earlier, it is imperative to adopt a comprehensive lifecycle approach. In transportation, intelligent scheduling algorithms should be introduced. Addressing the PC component supply chain pain points identified by Yu, transportation plans should be dynamically adjusted based on component urgency and route congestion to reduce queues and delays [3]. In warehousing, “BIM + IoT” intelligent monitoring should be promoted—using sensors to track component stacking status in real time and reduce damage rates. Additionally, the cost reduction effect of modular design should be included in enterprise performance evaluations to drive standardization implementation.

Enhancing supply chain resilience requires focusing on building three capabilities: “prediction, response, and recovery.” Drawing on the resilience assessment framework by Wang and Chen, an industry risk database should be established—covering typical shock scenarios like natural disasters and policy changes—and big data analysis used to enable early risk warning [2]. Core enterprises should be required to maintain 2-3 backup suppliers and sign emergency supply agreements. Quarterly supply chain collaboration drills should be conducted to simulate scenarios like raw material shortages and component delays, improving emergency response capabilities across all stakeholders [9]. The risk management approach based on ISO 56002:2019 proposed by Rahman & Latief provides a structured framework for systematic risk response [9].

5. Conclusions

5.1. Key Research Findings

This study has systematically investigated the integration of BIM technology within prefabricated building supply chains for collaborative cost optimization. The principal findings are summarized as follows. Comprehensive analysis shows that prefabricated building supply chain collaboration and cost budget optimization face four systemic challenges: 1) Polarization in BIM technology application and high marginal costs due to insufficient standardization; 2) Conflicting stakeholder goals in the supply chain and lack of unified collaborative decision-making mechanisms; 3) Lack of full-lifecycle cost management and significant waste in transportation and warehousing; 4) Weak supply chain resilience and inadequate risk response capabilities. To address these issues, the study proposes corresponding optimization pathways: promoting BIM standardized design and building cloud-based collaborative platforms (technology); establishing game balance mechanisms and clarifying stakeholder responsibilities (collaboration); improving full-lifecycle management and strengthening risk early warning (cost and resilience).

5.2. Research Significance

Practically, the study’s proposals—such as standardized design and cloud-based collaboration—can directly help enterprises reduce resource waste and carbon emissions, enabling them to meet “dual carbon” goals and compete in the market. At the industry level, the research drives deeper integration of BIM technology with supply chain operations, narrows development gaps between regions and enterprises, and accelerates the digital transformation of the construction industry. Theoretically, it fills the gap in integrated “BIM technology-supply chain collaboration-cost budgeting” research, providing a logical framework and practical reference for future studies in related fields. Thus, this research bridges the gap between theoretical modeling and practical application, offering a holistic roadmap for industry digitalization and sustainable development. Previous research also emphasizes BIM’s key role in improving overall project performance and sustainability.

5.3. Research Limitations and Future Directions

This study has two main limitations: First, the research data primarily rely on secondary sources like existing literature, enterprise cases, and government reports. The reliance on secondary data means that the study could potentially benefit from deeper, firsthand insights into stakeholder perspectives, which might enhance the granularity of the problem analysis. Second, the proposed cloud-based collaboration model and quantitative formula for delay costs have not undergone empirical testing, so their feasibility requires further verification.

Future research can advance in two directions: First, primary data can be collected through questionnaires and enterprise interviews to analyze differences in challenges faced by enterprises of different sizes and regions. Second, empirical studies on typical projects should be conducted to test and optimize the proposed technical and mechanism solutions. Additionally, research perspectives can be expanded to explore the application of new technologies like digital twins and blockchain in supply chain collaboration. The graph model and the structural equation model provide valuable methodological references for future quantitative research.

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