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An Adaptability Analysis of Lean Management Application in Prefabricated Buildings

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Abstract: Against the backdrop of the construction industry's green transformation, prefabricated buildings struggle to fully realize their potential due to inherent management mechanism deficiencies. Based on lean management theory, this paper systematically analyzes its application potential throughout the entire process of prefabricated construction from an adaptability perspective. The research indicates that from a technical dimension, the deep integration of BIM and digital twin technologies constructs an intelligent "design-production-construction" closed loop, significantly enhancing collaborative efficiency and resource utilization. From an organizational dimension, reliance on the Integrated Project Delivery (IPD) model achieves goal-process-culture synergy, effectively breaking down traditional contractual barriers. From an economic dimension, a whole-life-cycle matching mechanism for capital-information resources is established, simultaneously realizing immediate cost optimization and long-term asset value appreciation. However, the contradiction between standardization and customization, data fragmentation across the industrial chain, and the transformation costs for small and medium-sized enterprises constitute the primary adaptability barriers. This study provides a systematic solution for prefabricated buildings to overcome management bottlenecks and achieve goals of cost reduction, efficiency improvement, and low-carbon transformation.

Keywords: Lean Management, Prefabricated Building, Adaptability Analysis, Value Stream Optimization

1. Introduction

The construction industry, as a traditional sector with high energy consumption and carbon emissions, faces significant challenges and opportunities in energy conservation and emission reduction. There is an urgent need to achieve green and low-carbon development through structural adjustments. Against this backdrop, prefabricated buildings, leveraging advantages such as fast construction speed, shortened cycles, reduced on-site wet work, and lower pollution emissions, have become an important development direction for promoting the green and low-carbon transformation of the construction industry, aligning highly with the requirements of the dual-carbon goals.

However, the inherent advantages of prefabricated buildings are often difficult to fully leverage in practice due to imperfect management mechanisms. Although the industrialized model of prefabricating components and assembling them on-site can reduce construction pollution and

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enhance efficiency, core management pain points such as disconnection between design and production, chaotic on-site scheduling, and information silos are prevalent in practice. This leads to high construction costs and low resource utilization. Addressing these issues, current research primarily focuses on two levels: risk identification and process optimization. The former concerns the intelligent breakthrough of management bottlenecks, while the latter focuses on system integration and information flow optimization. In the field of intelligent rework risk identification, Cao Xinying et al. pointed out three major bottlenecks in current risk management: excessive reliance on manual experience, inefficient knowledge transfer, and systemic deficiencies [1]. In the field of integrating BIM with lean management, Chen Jingwu et al., focusing on the problems of construction inefficiency and information lag, proposed a "BIM technology + Lean thinking" dual-drive model [2].

Although the above studies have made significant progress, they have not yet systematically resolved the adaptability obstacles to the lean management of the entire prefabricated building process. Therefore, the lean management concept, centered on waste elimination and continuous improvement, with principles like standardized operations, full participation, and value stream optimization, is seen as key to solving these management challenges. The organizational framework of this paper will revolve around the integration of prefabricated buildings and lean management, conducting in-depth analysis from the following dimensions: elaborating the basic concepts of lean management; analyzing its adaptability and potential value in the "design-production-construction" whole process of prefabricated buildings; revealing the main adaptability barriers in current practice; and ultimately proposing systematic optimization methods and an integrated framework. This research aims to expand the cross-industry application theory of lean management in the construction field, construct a lean management framework adaptable to the whole process, enrich the theoretical system of construction industrialization, provide process diagnostic tools and systematic implementation plans for project participants, and assist prefabricated building projects in achieving goals of cost reduction, efficiency improvement, and low-carbon transformation.

2. Analysis of lean management and prefabricated concepts

Lean management is a management philosophy originating in manufacturing, aiming to build an efficient, flexible, and responsive production and management system. It is now widely applied in the economic management of various enterprises. The fundamental principles of lean management include value identification, value stream analysis, the flow principle, the pull principle, and the pursuit of perfection. These principles collectively guide all aspects of enterprise economic management, helping companies maintain a leading position in intense market competition.

As the construction industry faces challenges such as labor shortages, inefficiency, and environmental pressures, the traditional cast-in-place construction mode, dominated by wet work, increasingly exposes problems like high resource consumption, long construction periods, and unstable quality. The core of prefabricated construction lies in transforming the construction mode heavily reliant on on-site wet work in traditional buildings into a modern construction method characterized by standardized design, industrialized production, assembly-based construction, integrated decoration, and information-based management. This mode involves pre-producing the main structural components (such as beams, columns, floor slabs, and wall panels), enclosure components (such as external wall panels), and functional components (such as stairs, and balconies) in a controlled factory environment. These components are then transported to the construction site and efficiently assembled and integrated using reliable mechanical connections or cast-in-place joint techniques to ultimately form a complete building.

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Compared to traditional cast-in-place buildings, prefabricated buildings offer significant advantages: improving construction efficiency, shortening construction periods (by approximately 30%-50%), ensuring consistent engineering quality and performance, significantly reducing construction waste and environmental pollution, lowering construction safety risks, saving labor and improving working conditions, and promoting the transformation and upgrading of the construction industry. However, their development also faces challenges such as initial costs, industrial chain coordination, improvement of standard systems, breakthroughs in key technologies, and changes in design thinking. Currently, driven by the concept of sustainable development and intelligent construction technology, prefabricated buildings are rapidly developing towards high performance, intelligence, green and low-carbon, and higher integration.

2.1. Adaptability advantages

The adaptability between lean management and prefabricated buildings essentially stems from the resonance between standardized production theory and the demands of construction industrialization. This resonance achieves deep coupling through three dimensions: technology, organization, and economy [3].

2.1.1. Technical synergy

Technical synergy refers to breaking down phase barriers and achieving seamless data flow and intelligent decision-making linkage throughout the entire building lifecycle (design-production-construction) by deeply integrating digital technologies such as BIM, Internet of Things (IoT), digital twins, and artificial intelligence (AI). Its core value lies in eliminating information silos, driving the leanness of the value stream, and providing a technical fulcrum for low-carbon and efficient construction. This synergistic effect has shown significant results in the design phase: The Shenzhen Science and Technology Museum New Hall project, relying on BIM parametric family library standardized design, reduced composite slab types from 10 to 6, increased mold turnover rate by 42%, and decreased design rework rate from the industry average of 30% to 2% [4]. Multi-disciplinary collaborative platforms further strengthen the capability for source loss control; a hospital project predicted 92 pipeline conflicts through BIM clash detection, avoiding 3 million CNY in on-site rework [5].

Intelligent synergy on the production end further unleashes lean potential. A PC component factory in Shanghai utilized an MES system and IoT sensors to monitor equipment status in real-time, reducing failure rates by 18% and increasing monthly production capacity from 800m³ to 1000m³. Combined with Single-Minute Exchange of Die (SMED) technology, mold changeover time was compressed from 4 hours to 1.5 hours, ensuring stable daily production capacity even when facing 30% demand for special-shaped components [4], demonstrating the flexible adaptability that technical synergy brings to industrialized production.

At the construction stage, the synergy between digital twins and intelligent scheduling systems enables dynamic lean control. A commercial complex project used a twin model to compare planned and actual progress in real-time, automatically triggering catch-up strategies for lagging tasks, ultimately shortening the construction period by 12 days. An intelligent tower crane scheduling system integrated GIS geographic information to optimize paths, reducing equipment idle rate from 23.94% to 8% and saving daily mechanical costs by 320 CNY [6]. This technological closed loop of "precise design preview - flexible production response - intelligent construction control" signifies that lean management, relying on digital synergy, moves from theoretical conception to full-process

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implementation, constructing a core driving force for cost reduction, efficiency improvement, and low-carbon transformation in prefabricated buildings.

2.1.2. Organizational synergy

Organizational synergy refers to establishing a collaborative community where risks are shared and benefits are mutual among participants across the entire prefabricated building industrial chain (design, production, construction) by reconstructing a "goal-process-culture" tripartite mechanism. Its core is to break down the three major barriers under traditional segmented operations: goal conflicts caused by contractual fragmentation, rework waste resulting from process discontinuities, and the suppression of lean penetration due to dispersed responsibilities. The Shenzhen Metro project empirically validated the barrier-breaking effectiveness of this mechanism: After adopting the Integrated Project Delivery (IPD) model, the owner-designer-contractor unified value orientation through a cost-saving sharing mechanism (goal synergy); the construction party intervened early in design optimization and relied on a BIM platform for 24-hour closed-loop change processing (process synergy), increasing cross-departmental decision efficiency by 50% and drastically reducing claim incidents by 90% [4]. Simultaneously advancing lean culture penetration via the "visualization-standardization-full participation" path further solidified the collaborative foundation – on-site "waste boards" drove problem closure within 3 days (visualization); the "Twelve-Step Prefabricated Hoisting Operation Method" improved installation efficiency by 25% (standardization); an improvement proposal mechanism increased employee adoption rates from 15% to 45% (full participation) [7]. This deep coupling of institutional synergy frameworks and behavioral culture penetration marks the in-depth development of organizational synergy from contractual innovation to full-staff empowerment.

2.1.3. Economic synergy

Economic synergy refers to establishing an efficient matching mechanism for capital flow, information flow, and resource flow by integrating whole-life-cycle economic activities such as investment decisions, construction control, and operation & maintenance (O&M) value addition. Its core value lies in breaking the fragmented mode of traditional construction economic management that "emphasizes construction over operation," achieving a closed-loop value creation of "front-end precise investment - mid-term dynamic optimization - back-end asset appreciation." This synergistic effect has formed quantifiable economic benefit chains in practice: In the preliminary stage, the application of a BIM-5D model kept quantity takeoff error within ±2% for a social housing project, improving investment estimation accuracy from the industry average of ±10% to ±3%, and drastically reducing budget adjustment frequency by 60% [4]; During construction, a dynamic reinforcement consumption monitoring system triggered scheme optimization, directly saving 8% in costs (equivalent to 1.2 million CNY), while combining with a Vendor Managed Inventory (VMI) model increased inventory turnover efficiency by 38% (from 45 days to 28 days) [7]; For the O&M stage, a BIM-Facility Management (BIM-FM) system reduced equipment maintenance costs by 20%, and a commercial complex saw its REITs valuation increase by 12 percentage points due to whole-life-cycle lean management performance, leading to a 0.8% reduction in financing costs [7]. This economic synergy network spanning the entire building lifecycle not only achieves immediate cost savings (e.g., 8% during construction) but also constructs a transition path from short-term cost reduction to long-term value appreciation through enhanced asset financial attributes (e.g., 12% REITs valuation increase).

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2.2. Application analysis of lean management and prefabricated construction

Within the Chinese context, lean management and prefabricated construction have formed a unique localized collaborative path through the deep coupling of three dimensions: policy drive, enterprise practice, and theoretical innovation. This path is synergistically advanced through the trinity of top-level institutional guidance, enterprise technology implementation, and theoretical paradigm support, gradually realizing the localized evolution from concept introduction to system construction.

First, Path One is institutional construction based on policy drive. The "Guiding Opinions on Promoting Building Industrialization Development" issued by the Ministry of Housing and Urban-Rural Development of China (MOHURD) in 2005 explicitly listed lean construction as a mandatory management framework for prefabricated building projects for the first time, requiring projects to establish a value stream mapping mechanism covering the entire design, production, and construction process [8]. The "Guiding Opinions on Vigorously Developing Prefabricated Buildings" issued by the State Council in 2016 and related technical specifications further incorporated the pull production principle into mandatory requirements. Policy promotion has significantly improved the efficiency of the prefabricated component supply chain; the industry's average inventory turnover rate achieved a 200% increase (rising from approximately 4 times per year to about 12 times), marking the formal establishment of an institutionalized transformation path of "demand-side drives production-side" in China's construction industry [4].

Second, Path Two is process reengineering based on the enterprise level.Construction Process Optimization: China Construction Eighth Engineering Division Corp., Ltd. (CSCEC8b, 2022) successfully transplanted the manufacturing Andon system into a prefabricated project in the Xiong'an New Area. This system, combined with Internet of Things (IoT) technology, sensed prefabricated component installation deviations in real-time, drastically compressing the average quality anomaly response time from 4 hours in the traditional model to within 15 minutes, while simultaneously reducing installation defect rates by 67%. This practice effectively validated the applicability of the "single-piece flow" management concept in complex construction scenarios [6].

Production Efficiency Improvement: A large precast concrete component production base in Guangdong Province built a dynamic scheduling model based on takt time theory [9]. This model utilized real-time construction progress data provided by BIM to dynamically regulate mold scheduling and production line rhythm. Application results showed a 25% increase in component inventory turnover rate, while carbon emissions were reduced by 18% due to optimized transportation frequency [7], powerfully proving the correction capability of the "production on demand" model for resource mismatch problems in the construction supply chain.

Finally, Path Three is systematic innovation based on theoretical paradigms. Addressing the characteristics of China's construction industry, academia (Zou Chao, 2024) proposed a systematic Lean-Prefabricated Double Helix Coupling Model [4]. This model achieves deep integration through three dimensions:

Technical Dimension: Applying BIM parametric design technology increased the standardization rate of prefabricated components from an industry benchmark of about 40% to over 75%, eliminating seven types of waste caused by design changes at the source.

Organizational Dimension: Adopting the Integrated Project Delivery (IPD) mode broke down traditional barriers between design, production, and construction phases, integrating them into a collaborative demand chain, compressing cross-phase information transmission error rates from the prevalent over 35% to below 10%.

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Institutional Dimension: Promoting the formulation and implementation of the national "Prefabricated Building Lean Evaluation Standard," incorporating key lean indicators originating from manufacturing (such as value stream mapping coverage rate, takt time compliance rate, etc.) into the formal acceptance evaluation system of prefabricated building projects for the first time [10].

This model signifies a major theoretical leap in the application of lean management in China's construction industry from the "tool transplantation level" to the "system reconstruction level," constructing a closed-loop lean solution framework covering "eliminating process waste - balancing operational load - avoiding system overload."

2.2.1. Technical application

BIM application in the construction industry suffers from phase fragmentation, professional collaboration fragmentation, and data application discontinuity. Current BIM technology application in construction is mired in a multi-dimensional dilemma of broken data value chains: Phase fragmentation results in less than 40% reuse rate of design models for construction; a social housing project experienced a 15-day schedule delay and 20% workload redundancy due to repetitive modeling, exposing the failure of the whole-cycle data transfer mechanism [4]. Professional collaboration fragmentation keeps cross-disciplinary data interoperability efficiency below 30%; a commercial project triggered 47 design changes and a cost surge of 2 million CNY due to model clashes, reflecting the formalistic chronic disease of the collaboration mechanism [5]. System fragmentation causes data conversion between software to consume 15% of time with an error rate of 8% [6], rooted in the technological ecosystem fragmentation caused by a lack of open standards. More severe is the "last-mile dilemma" of intelligence – IoT sensors in a prefabrication factory were only used for status monitoring without linkage to the production system, causing a 2-hour fault response delay and a daily loss of 50,000 CNY [4]. This "hardware idling" phenomenon highlights the deep disconnection between technical tools and management processes. Fundamentally, the lack of national mandatory data delivery standards at the institutional level, the absence of a full-stack digital twin system at the technical level, and the failure to build a data-driven organizational structure at the management level are the three critical pathologies jointly causing three-dimensional fragmentation, cumulatively resulting in over 3 million CNY in direct economic losses and hindering industrial upgrading.

2.2.2. Organizational management

Organizational fragmentation under traditional contract models essentially stems from the fundamental conflicts in the objective functions of various participants, leading to systemic inefficiency. An owner requirement change rate as high as 35% in EPC projects is clear evidence; for example, a school project incurred visa costs as high as 1.8 million CNY because the designer lacked an effective construction cost constraint mechanism [5]. Notably, the short-term orientation of performance evaluation further exacerbates the alienation of management behavior: To unilaterally pursue milestone delivery (e.g., schedule compliance rate), managers often neglect long-term process optimization and implicit cost control. A typical example is an enterprise that abandoned the introduction of an intelligent scheduling system requiring upfront investment to ensure the schedule. Although it was delivered on time eventually, it incurred cumulative losses of 2 million CNY due to construction machinery idling, with implicit costs accounting for 12% [6]. This practice model of "emphasizing milestone delivery, neglecting process optimization" forms a deep-

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seated contradiction with the core concept of "continuous improvement, systemic efficiency enhancement" advocated by lean management.

2.2.3. Standardization paradox

An inherent tension exists between the functional diversification demands of the construction industry and the industrialized standardization logic. On the one hand, projects like age-friendly facilities or cultural tourism often have special-shaped components accounting for 30% of the total. Traditional production lines require mold changes twice a day, costing 50,000 CNY per change, leading to a 15% drop in production efficiency [4]. On the other hand, cross-regional projects face the problem of fragmented standards, such as differing prefabricated component transport weight limit rules between Province A (49 tons) and Province B (55 tons), forcing a project to customize dual solutions, increasing costs by 18% and extending the transportation cycle by 3 days (Guangdong Provincial Department of Housing and Urban-Rural Development, 2024) [7]. The essence of this conflict is the structural contradiction between the "functional uniqueness" of building products and the "economies of scale" of industrialization.

2.2.4. Cost-benefit

Small and medium-sized enterprises (SMEs) face significant cost barriers in implementing lean management. Introducing a BIM+lean management platform requires an initial investment of 1-3 million CNY, accounting for 15%-25% of annual profits, while the investment payback period is as long as 5-8 years, far exceeding the manufacturing industry's average of 3-5 years [5]. More notably, the hidden costs of organizational change (employee training, process reengineering, etc.) account for 35% of the total investment, but decision-makers often underestimate their impact due to a lack of quantitative assessment tools [6]. This cognitive bias of "visible explicit costs, uncontrollable hidden costs" further exacerbates the hesitation of SMEs towards transformation.

Despite the synergistic potential, the unique attributes of the construction industry lead lean management to face a triple contradiction: the standardization requirement versus project uniqueness, closed production versus open construction sites, and short-term benefits versus long-term investment.

3. Conclusion

This paper primarily explores innovative paths and methods for the adaptability of lean management in the construction field based on lean management theory. The research finds that through systematic lean management innovation, the development bottlenecks of prefabricated buildings can be effectively broken: At the technical level, deep integration of BIM and digital twin technologies achieved whole-process value stream optimization from parametric design to dynamic construction scheduling, significantly improving drawing review accuracy and on-site management efficiency. At the organizational level, building cross-departmental collaborative mechanisms and team capability sedimentation systems effectively broke down collaborative barriers under traditional organizational structures and successfully cultivated a culture of continuous improvement with full participation. At the institutional level, the proposed hierarchical standard system and policy incentive combination provided a systematic institutional guarantee framework for the industry from technological application to management upgrading. These findings collectively provide important theoretical

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support and practical reference paths for prefabricated buildings to achieve goals of cost reduction, efficiency improvement, and low-carbon transformation.

However, this study also recognizes current limitations in the depth of technology integration, optimization of organizational synergy efficiency, and the construction of a national standard system. Future research could focus on deepening the following directions: Deepen the technical integration of "BIM+AI+Digital Twin," developing a whole-process intelligent decision-making system to enhance the precision of resource scheduling and optimization on construction sites; Explore new cross-organizational collaborative models based on blockchain technology, building a standardized system for experience knowledge sedimentation and sharing to reduce the overall collaborative costs of the industrial chain; Actively promote the establishment of a national lean management standard system for prefabricated buildings, accompanied by a dual-dimensional "efficiency-low carbon" evaluation mechanism. The advancement of these studies holds profound theoretical value and practical significance for systematically solving the development difficulties of prefabricated buildings and assisting the construction industry in achieving higher quality and more sustainable development under the constraints of the "dual-carbon" goals.

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