

Challenges in the Development of Prefabricated Construction and Future Prospects

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Abstract. China's construction industry is currently accelerating its transition towards low-carbon and industrialised practices, with prefabricated construction becoming increasingly widespread within the sector. Compared to traditional construction methods, prefabricated construction offers unique advantages and represents one of the key pathways to achieving a green and low-carbon transformation of the industry. At present, the promotion and application of prefabricated construction in China face major constraints, including a shortage of specialised technical personnel, stringent requirements for the transport of prefabricated components, and difficulties in controlling manufacturing costs. In response to these issues, this paper proposes a series of measures, such as cultivating multi-skilled professionals, establishing a tripartite collaboration mechanism between design, production and construction, and optimising the management of the entire transport process using Building Information Modelling (BIM). It also analyses the future development directions of prefabricated construction from three dimensions: technological upgrading, industrial collaboration, and green and low-carbon development. The article aims to provide a reference for subsequent research in this field, as well as guidance for management optimisation in relevant enterprises and adjustments to talent development programmes in higher education institutions.

Keywords: Prefabricated Building, Development Challenges, Future Prospects, Low-Carbon Construction.

1. Introduction

As a pillar industry of the national economy, the construction sector has long faced prominent issues such as high energy consumption, high pollution and low efficiency. Against the dual backdrop of ongoing urbanisation and the establishment of the 'dual carbon' targets, traditional construction models are no longer able to meet the requirements of high-quality development. China's construction sector is accelerating its transition from traditional construction to prefabricated construction; compared with traditional construction, which is highly polluting and involves severe waste of resources, prefabricated construction is more in line with a green, low-carbon development model that prioritises energy conservation and emissions reduction. Prefabricated construction employs a model where components are prefabricated in factories and assembled on site. Its

structural types encompass a variety of forms, including prefabricated concrete structures, prefabricated steel structures, prefabricated timber structures and prefabricated hybrid structures. Characterised by standardised product design, factory-based production, assembly-based construction, integrated finishing, digitalised management and intelligent application, prefabricated construction has rapidly become a strategic choice for the nation in the urbanisation process and represents a modern industrialised production method [1]. Building components are manufactured and processed in workshops, where computerised systems precisely control material usage and ensure accurate production in accordance with design drawings. This significantly reduces the demand for manual labour, thereby achieving energy conservation and emissions reduction, lowering labour costs and improving component precision. Furthermore, noise, light pollution and wastewater pollution generated during the manufacturing process do not directly affect the construction site. Prefabricated construction demonstrates significant advantages over traditional construction in terms of energy conservation, emissions reduction, labour savings and work efficiency. However, as prefabricated construction in China started later than in other countries, many technologies have not reached the same level of maturity, and a comprehensive set of technical standards and collaboration systems for all stages has not yet been established. Although all the regions have gradually introduced policies on prefabrication construction and made some achievements in this field, limited technical capabilities and resource utilisation efficiency remain areas for improvement; thus, the application is still far from ideal.

2. Challenges in the development of prefabricated construction

2.1. Shortage of skilled technical personnel

At present, the integration of architectural design, construction technology, cost estimation and information management in construction projects remains insufficient. There is a lack of talent development platforms for roles across the industry chain, such as assistant designers, prefabricated construction technicians, cost estimators and Building Information Modelling (BIM) technicians, and thus, versatile and innovative technical and skilled personnel are unavailable [2]. It is difficult for professionals in the prefabrication construction industry to move directly from the traditional construction industry. Most practitioners of traditional construction have been involved in on-site construction and can determine the size and position of components by means of on-site survey; however, they generally lack the technical skills required for BIM modelling and digitalisation and are thus unable to meet the demands of these positions. Furthermore, as relevant degree programmes in higher education institutions have only recently been established and their curricula are still being refined, and while in-service training at the enterprise level lacks systematic and standardised approaches, the speed of talent development is unable to keep up with the expansion of the industry. Therefore, the development of talent in prefabrication construction urgently needs to be promoted.

2.2. Strict transport requirements for precast components

Some prefabricated components will not be transported to the construction site immediately after production and need to be stored in a warehouse temporarily. Fluctuations in temperature and humidity of the storage environment, poor stacking conditions, etc., can cause surface cracks or changes in the distribution of internal stress of components and thus reduce structural integrity. Therefore, all prefabricated components need to pass the final quality inspection before leaving the

factory [3]. A proper storage environment with suitable temperature and relative humidity should be maintained to preserve component quality.

At the same time, prefabricated components generally have the characteristics of large size and heavy weight; some beams, columns and wall panels can weigh several tons or even tens of tons each, and special supports and flatbed lorries are required for transport. The selection of transport vehicles must take into account the dimensions of the components, load limits and road conditions, whilst a survey of the transport route must identify factors such as bridge height restrictions, sharp bends, gradients and traffic restrictions in advance. Negligence at any stage may result in the components being knocked, overturned or exposed to moisture during transit, causing irreversible damage, which in turn delays the construction schedule and increases repair costs.

2.3. High production cost of precast components

Prefabricated components for modular construction face dual constraints of process and cost during the production stage. Firstly, there is the cost of moulds: these must be custom-made to the shape of the component, require high precision, but offer poor versatility, with a typical service life of only 30 to 50 cycles; amortisation costs account for 5% to 10% of total production costs [4]. For irregularly shaped or non-standard-sized components, moulds are often scrapped after a single use, further driving up the unit cost. The low versatility of moulds leads to higher production costs for prefabricated components; if moulds capable of precise dimensional adjustment could be developed, this would enable significant cost reductions and improve mould utilisation rates.

Secondly, there is the issue of raw material costs. The direct raw material costs of prefabricated components account for over 50 per cent of total production costs, with reinforcement steel accounting for approximately 55 per cent [5]. The prices of bulk building materials such as steel and cement are highly susceptible to market fluctuations, whilst prefabricated component manufacturers lack bargaining power during the raw material procurement process, leaving them with limited control over costs.

3. An analysis of strategies for addressing the challenges of prefabricated construction

3.1. Talent development for prefabricated construction

Based on the analysis of the current situation of industrialisation in construction at home and abroad, and a comparison with architectural education, it can be seen that fostering students' interest and good study habits is a prerequisite for their all-round development. Therefore, it is necessary to help college students keep up with the changes in the industry at present and, from a conceptual level, learn fundamental skills and key technologies, as well as advanced equipment [6]. Highly skilled professionals in prefabricated construction need to have deep theoretical knowledge in building structures and material properties, and also possess all-round abilities to convert design ideas into component solutions that are both manufacturable and installable. The construction of a theoretical training curriculum for prefabricated construction centres on architectural projects as its primary medium and is process-oriented. According to the analysis of market demand for prefabricated construction professionals and the required competencies at all levels, a knowledge system and professional quality standards have been established to build a theoretical training program. Among them, the first basic theory module covers the interpretation of architectural drawings and general conditions for prefabricated buildings, and the second is a practical training module that teaches operating skills such as BIM modelling and component breakdown design. At present, the Smart

Construction Engineering programme has added prefabricated construction as one of its modules, and in terms of curriculum content, it covers topics such as drawing interpretation and drafting, BIM modelling, etc., to help students gain a deeper understanding of the transport process and practical application of prefabricated building components [7].

3.2. End-to-end collaborative cost control

In light of the problems of the absence of source control and poor collaboration of prefabricated components for modular construction during the design stage, collaborative management at all times in the process can be reinforced as follows.

At the design stage, design teams should cooperate with suppliers and contractors early on to consider the feasibility of the following stages before drawing finalisation and thus avoid a lack of collaboration between design and construction that would lead to resource wastage.

With regard to information transfer, a cloud-based BIM collaborative design system should be established, thereby avoiding errors, omissions, clashes and missing elements caused by version inconsistencies. The components, along with the encoded information, are then delivered to the site; the contractor can scan the quick response (QR) code or radio-frequency identification (RFID) chip to obtain installation details.

By building the above cooperation system, rework of components caused by information delay or misinterpretation of drawings can be reduced, and the costs of extra design modifications and on-site rectifications will be lowered; thus, the overall cost control capacity of prefabricated construction will be improved.

3.3. Strategies for managing the transport of prefabricated components

A three-dimensional geographical model of the transport route can be constructed in BIM to simulate topographical features, load restrictions on roads and bridges, and the distribution of obstacles along the route, and thus identify a shorter transport route with smoother passage. Algorithms are employed to compare multiple candidate paths automatically and select the one that can be travelled in a short time with low fuel consumption, while ensuring safety. In the event of severe weather, such as heavy rain or a heat wave, an all-weather contingency plan will be prepared in advance. Based on the actual dimensions of the components and the installation sequence at the construction site, a suitable loading plan can be designed, and the vehicle's loading space should be used to its fullest extent to increase loading efficiency and reduce the number of return trips; thus, space and time costs can be saved.

The transport process of components consists of three stages: loading, transit and unloading. During loading, components need to be arranged properly according to their individual stress characteristics, and additional cushioning and protection should be added to areas more likely to be damaged by impact. As vehicle jolts are inevitable during transit, routes must be planned sensibly; in extreme conditions, measures to prevent water ingress and moisture must be put in place. During unloading, workers must handle components with care; for specialised components, their unique load-bearing characteristics must be taken into account to prevent damage during handling.

Through the coordination of route optimisation, loading optimisation and process protection, the rate of component damage and the risk of delays during transport can be significantly reduced.

4. Future development trends in prefabricated construction

4.1. Technical basis

BIM technology is already being used to some extent in the design stage at present, but its full technical potential for prefabricated construction has not yet been realised. Digital design can integrate information from multiple disciplines—such as architecture, structure, and mechanical, electrical and plumbing (MEP)—into a single model, thus increasing accuracy and reducing material costs [8]. At the same time, intelligent systems extend the BIM model to the production stage, building automated component scheduling and processing models, thereby reducing labour costs and improving efficiency. The two approaches can be integrated to form an automated production line based on BIM models. Deep learning and big data analysis are used to identify problems in production by the system, and at the same time, manual adjustments to the data can be made in real time for human-machine collaboration. Meanwhile, the machine proactively detects and records any abnormalities in equipment operation, and technical staff improve the performance by addressing error codes. The artificial intelligence (AI) model can be continuously trained with historical production data to recognise abnormal fluctuations in equipment operating parameters and issue an early warning before a fault occurs; thus, switch from reactive to proactive maintenance. In the future, digital twin technology will be used to build virtual models of physical components in a virtual space, and the production process and quality status can be updated in real time for visualised support of management decisions. Ultimately, BIM, the Internet of Things (IoT) and AI will be integrated more deeply to drive the intelligent transformation of the entire prefabricated construction process—design and production, construction, operation and maintenance.

4.2. Industrial standardisation and collaboration

Standardisation and collaboration at the industrial level provide support for the large-scale application of prefabricated construction. In the future, a standardised component library for the main types of components should be built based on a national modular standard to reduce the duplication of mould development and waste of resources caused by inconsistent regional standards. Standardised design is a method based on basic modules that expands by combining multiple modules and functional modifications; it has good replicability and can also create multi-category, multi-functional architectural spaces. Based on this, collaboration will be implemented through standardisation, and for components with a high utilisation rate, the principle of fewer specifications, more combinations will be applied to improve efficiency across the entire supply chain [9]. The establishment of a standard component library will promote the further specialisation of the industrial chain: design firms can directly use component parameters from the library in scheme design; manufacturers can carry out mass production with standard moulds; and construction firms can standardise the installation process according to this, reducing collaboration costs at all links in the chain. In the future, cross-regional information platforms for the supply and demand of components will be able to realise real-time matching of production capacity surpluses and shortages, avoid the problem of idle capacity in some areas due to new factory construction elsewhere, and improve the efficiency of resource allocation across the entire industry. At the same time, standardised BIM models will integrate component information at all times during design, production, transport, installation and operation and maintenance to enable management of the entire life cycle of prefabricated buildings.

4.3. Green and low-carbon initiatives

In terms of green and low-carbon development, the factory-based production model of prefabricated construction demonstrates notable advantages [10]. Factory production can achieve high-precision components and reduce material waste at the construction site through off-site cutting; at the same time, centralised production of prefabricated components will lower water consumption and dust emissions at the construction site. Prefabricated construction can reduce both the quantity of construction waste and carbon emissions over the entire life cycle compared with traditional in-situ casting, thus meeting China's dual carbon targets.

The green development of prefabricated construction will have the following trends in the future. First, a system of carbon emission accounting will be gradually established to set unified carbon emission measurement standards at all stages—including component production, transportation, installation and operation—thereby quantifying and comparing the carbon reduction benefits of prefabricated construction. Second, the proportion of renewable energy and recyclable materials used will continue to increase; for instance, recycled aggregates will be incorporated into prefabricated components, and rooftop solar power generated at the factory will be used to reduce the carbon footprint of the production process further. Through the above measures, prefabricated construction is expected to shift from providing green advantages to driving carbon reduction and efficiency gains, and will become one of the primary paths for the construction industry to achieve carbon peaking and carbon neutrality goals.

5. Conclusions and outlook

5.1. Conclusions

This paper systematically examines the main constraints that prefabricated construction faces at present in terms of talent development, component transportation and cost control, and proposes corresponding countermeasures. A lack of specialist staff limits the cooperation among all links of the prefabrication construction chain from design to construction; difficult transportation conditions increase the risk of damage to components and project delays; and poor mould versatility and high raw material costs reduce the profit margins for enterprises. To address these issues, the following measures have been proposed in this paper: strengthening the talent development system, establishing a tripartite collaboration mechanism for design-production-construction, and optimising the entire transport process through BIM. The analytical system built in this paper for problem identification and the design of countermeasures can serve as a reference for future research, provide directions for improving management in prefabrication construction companies, and offer guidance for adjusting talent development programmes in higher education institutions.

5.2. Outlook

Although this paper has established an analytical framework for the problems and policy responses, it is a macro-level analysis of these issues and policy discussions, drawing mainly from existing literature and policy documents, and has not yet been quantitatively verified through specific engineering case studies or empirical data. In the future, typical prefabricated construction projects will be selected for empirical analysis to quantify the cost-effectiveness and carbon-reduction advantages of prefabricated buildings under different circumstances. With empirical data, reliable evidence can be offered to help the government design differentiated promotion policies and assist

enterprises in selecting suitable project types and technical paths, thus promoting a shift in the development of prefabricated construction from a policy-driven model to a data-driven and refined development model. In the longer term, with the continued penetration of digital technologies such as BIM, the IoT and AI, prefabricated construction is expected to achieve systemic breakthroughs in intelligent design, flexible production, visualised transport and modular construction, thereby becoming a key driver of the construction industry's green transition and high-quality development.

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