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OPTIMIZING PREFABRICATED BUILDING INDUSTRY INTEGRATION: A STUDY OF CONSTRUCTION THROUGH INDUSTRIAL SUPPLY CHAIN DYNAMICS AND UPSTREAM/DOWNSTREAM ENTERPRISE ACCESS STANDARDS

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Abstract
This study examines the supply chain integration in the prefabricated building industry, focusing on the relationship between upstream and downstream enterprises. The research identifies critical risk factors across the project lifecycle using an Importance-Performance Analysis. Key findings reveal that major risks like high costs and policy changes, are more prevalent in the early project stages, while risk management is weakest in later stages, particularly in manufacturing and construction. The study highlights challenges in standardization, quality control, and technology adoption, emphasizing the importance of government policies and industry standards in shaping supply chain integration. Strategies for enhancing integration are proposed, including the development of industry-wide standards, investment in skills training, and adopting a lifecycle approach to project management.

INTRODUCTION

The prefabricated building industry has witnessed significant growth in recent years, driven by the need for efficient, cost-effective, and sustainable construction solutions. As urbanization accelerates and environmental concerns heighten, prefabrication has emerged as a viable alternative to traditional construction methods. However, the success of this industry hinges on the effective integration of its components within the broader industrial supply chain. The conventional construction method is slow and inefficient, placing a significant burden on the environment (e.g., visual intrusion, air and waste pollution), social welfare (e.g., noise and public health concerns), and sustainable development (Li, Shen, and Xue 2014).

Prefabrication involves the off-site production of building components, which are then transported to the construction site for assembly. This process offers several advantages over conventional construction methods, including reduced construction time, minimized waste, enhanced quality control, lower environmental impact, and improved social welfare (e.g., reduced noise and public health concerns). These benefits, however, can only be fully realized through seamless integration within the supply chain, which includes upstream suppliers of raw materials and downstream enterprises responsible for assembly and final delivery. While manufacturing supply chain management has reached a relatively advanced stage, prefabricated construction supply chain management has only recently begun to receive significant attention. The two are fundamentally different from each other in several key aspects. The production of prefabricated building components requires continuous processes, such as concrete pouring and curing, to maintain structural integrity (Sutrisna &

Goulding, 2019). Due to their substantial size and weight, these components necessitate specialized vehicles and meticulous logistical planning for safe and efficient transportation (Goulding et al., 2015). Furthermore, their installation demands strict adherence to detailed construction schedules, emphasizing precise coordination among all involved parties (Polat, 2010).

Supply chain dynamics play a crucial role in determining the efficiency and effectiveness of the prefabricated building industry. The integration of upstream and downstream enterprises involves complex interactions that need to be optimized to ensure timely material delivery, cost control, and maintenance of quality standards. This integration is not merely a logistical challenge but requires strategic alignment of objectives, standards, and processes across the entire supply chain.

Upstream enterprises in the prefabricated building industry typically include manufacturers of raw materials, components, and modules. These entities must adhere to strict quality standards and delivery schedules. On the other hand, downstream enterprises are responsible for the assembly, installation, and final delivery of the prefabricated buildings. They must work in close collaboration with upstream suppliers to manage the complexities of on-site construction, including scheduling, labor coordination, and adherence to safety regulations.

To achieve optimal integration within the supply chain, it is essential to establish robust access standards for both upstream and downstream enterprises. These standards should encompass quality control measures, logistical efficiency protocols, and compliance with industry regulations. Moreover, they should facilitate communication and coordination across the supply chain, ensuring that all stakeholders are aligned with the overall objectives of the construction project.

This study aims to explore the dynamics of the prefabricated building industry's supply chain, with a particular focus on the integration of upstream and downstream enterprises. By examining current practices and identifying potential areas for improvement, this research seeks to propose strategies for optimizing supply chain integration. The goal is to enhance the overall efficiency and effectiveness of the prefabricated building industry, ultimately contributing to its growth and sustainability. The prefabricated building industry represents a significant evolution in construction practices, offering enhanced efficiency, reduced waste, and faster project timelines. However, the integration of this industry within the broader construction ecosystem is complex, requiring a seamless connection between various stakeholders across the supply chain.

The dynamics between upstream suppliers, including material producers and component manufacturers, and downstream enterprises, such as construction firms and project managers, play a critical role in the successful implementation of prefabricated building projects. Establishing standardized access criteria and optimizing these interrelationships is essential to maximize the benefits of prefabrication. By examining industrial supply chain dynamics, this study aims to uncover the challenges and opportunities that exist in aligning the objectives and processes of different actors involved. Understanding these dynamics is key to enhancing collaboration, improving quality, and achieving cost-effective outcomes in the prefabricated building industry. Prefabricated structures are a new kind of modern building model that has emerged as the main option for the traditional construction sector looking to reinvent itself thanks to advancements in technology. Prefabricated buildings, as opposed to typical cast-in-place structures, are those whose prefabricated parts are manufactured in a factory and then transported to the construction site for installation and connection. They have the advantages of minimal labor requirements, quick construction, and reduced resource waste. To further encourage the rapid growth of prefabricated structures, capacity building in terms of integrated management and flexible supply chains must be strengthened. Significant risks have emerged in the supply chain as a result of the growing number of factors influencing the prefabricated building supply chains upstream and downstream in recent years. The supply chain's lack of resilience is becoming more and more obvious, and this has a big effect on how long engineering projects can be built on time and how competitively engineering contracting businesses can operate. Thus, it's imperative to develop a scientifically sound evaluation system for assessing and analyzing the prefabricated construction supply chain's resilience and raising its current level of resilience.

1. Literature Review

2.1 Industrial Dynamics

Industrial dynamics is concerned with problem solving in living systems which bring together machines, people and organizations. It therefore links together hard control theory typified by Tustin with soft system theory. The latter originated in biology and philosophy and at present is best summarized via the work of Check land. Industrial dynamics needs to be aware of the relevant tools as viewed from both ends of the systems spectrum. These include basic control theory but equally require the ability to understand and model situations where there is no single unique viewpoint but merely some consensus among the various "players" as to what appears to happen in practice. Industrial dynamics in China involve a complex interplay of factors that have shaped the country's rapid economic development and ongoing transformation. China's industrial sector has experienced several key phases. China's industrial dynamics are shaped by a mix of historical legacies, strategic government interventions, and global economic trends. The country continues to evolve, aiming to become a leader in high-tech industries while addressing challenges related to sustainability and demographic shifts.

2.2 Industrial Dynamics and Supply Chain

Supply chains are complex, dynamic network systems that evolve over time and change their size, shape and configurations (Gross et al. 2018, MacCarthy et al. 2016). Supply chain structural dynamics theory studies change in network design and topology and develops methods to manage and optimize the supply chain processes when experiencing structural changes (Ivanov et al. 2010). Supply chain structural dynamics can be considered in light of both positive and negative changes, such as new disruptive technologies (e.g., blockchain) or disruption risks (e.g., natural disasters and the ripple effect (Dolgui et al. 2018)), respectively.

A firm's competitive advantages strongly depend on the adoption of new disruptive technologies, such as Industry 4.0, Blockchain, Internet of Things, development of supply chain sustainability, and increasing resilience in light of more and more frequent and severe disruption risks. As such, new research is needed to advance our understanding of the place, role, and impacts of new technologies in the further development of digital and resilient supply chains with efficient and sustainable resource utilization (Dubey et al. 2019a,b, Ivanov et al. 2019, Ivanov and Dolgui 2019, Babich and Hilary 2020).

2.3 Supply Chain Structural Dynamics

It is important that the industrial dynamicist should not confuse the relevance of utilizing those hard system tools which greatly assist the modelling process with any assumption on his part that people within the system behave in machine-like ways. This is a distinction which some critics of ID believe we tend to overlook, and which is largely rebuffed if we concentrate on generating simulation models which allow for significant variability for both human and machine performance. One must always keep to the forefront the fact that at best an industrial dynamics model is a simplified description of the real world. It is derived in the reasonable expectancy that in a complex situation One should be able to make predictions which are 80 per cent correct and to minimize the chance of making predictions which are 100 per cent wrong! Compared with the modeling and design of hardware systems, ID models require a markedly different distribution in effort during the phases of problem identification, synthesis of possible solutions, and implementation of the preferred solution. Industrial dynamics modeling has potential uses in the following three distinctive phases of supply chain re-engineering:

1. Planning
2. Implementation
3. Control

Industrial experience suggests that the planning (and by implication design) and implementation roles are the most powerful of the foregoing. Real-time control applications we expect to be a bonus, since the latter should already be present in existing physical situations.

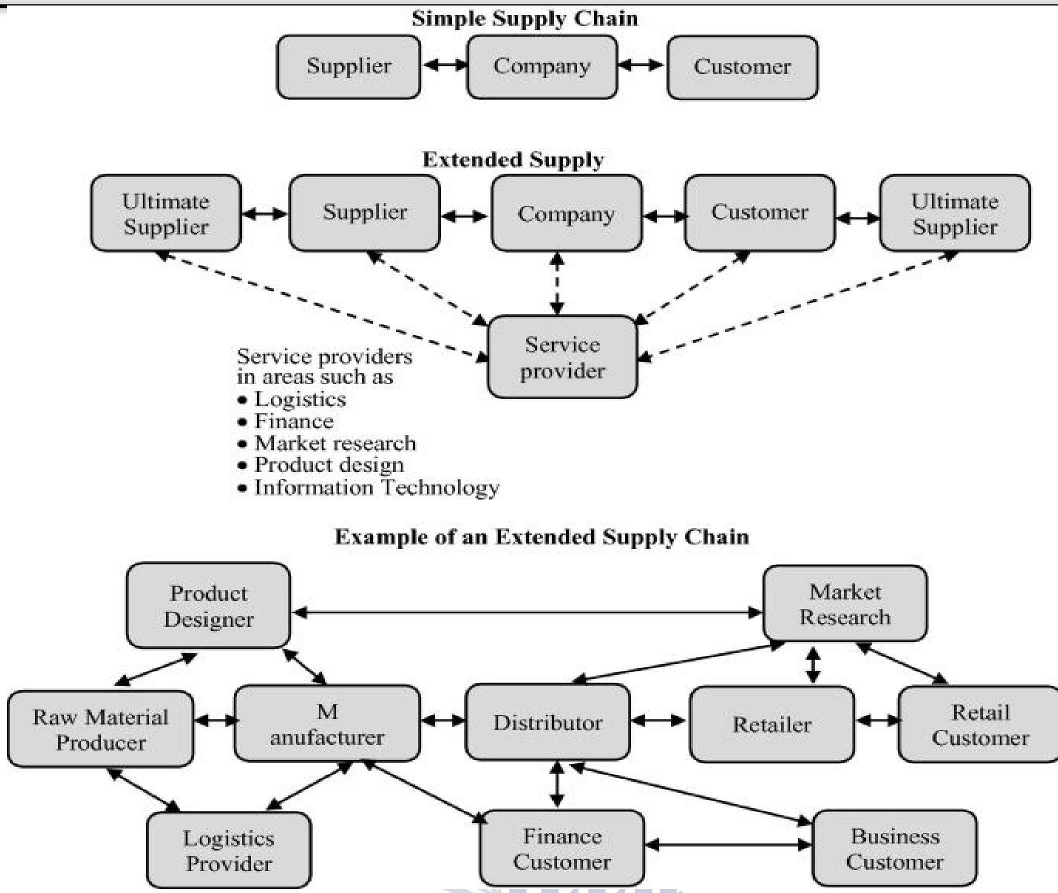

Figure 1: Illustration of the supply chain structure, depicting the flow of materials and information from suppliers to customers

2.4 Upstream Enterprise Access Standards in Prefabricated Building Industry

Upstream and downstream enterprise access standards refer to the protocols, practices, and guidelines that govern how companies interact with their supply chain partners, both before (upstream) and after (downstream) the production process. Upstream refers to the processes and interactions that occur before the manufacturing stage, typically involving suppliers and raw material providers. Developing strong supplier relationships and implementing standardized processes are essential strategies for optimizing the upstream supply chain (Blismas & Wakefield, 2009). Upstream enterprise access standards are the rules and practices that govern how an organization interacts with these suppliers. Key aspects include:

- *Supplier Qualification and Selection:* Standards for evaluating and selecting suppliers based on criteria such as quality, cost, reliability, and compliance with regulations.
- *Data Exchange Protocols:* Guidelines for how information is shared with suppliers, including product specifications, forecasts, orders, and delivery schedules. This may involve secure electronic data interchange (EDI) systems or supplier portals.
- *Security and Compliance:* Requirements for data security, intellectual property protection, and compliance with industry regulations or standards. This ensures that suppliers adhere to necessary legal and ethical standards.
- *Quality Assurance:* Standards for monitoring and ensuring the quality of materials and components provided by suppliers, often including inspections, audits, and certifications.
- *Sustainability and Ethical Sourcing:* Guidelines for ensuring that suppliers adhere to environmental and social responsibility practices, such as sustainable sourcing and fair labor practices.

2.5 Downstream Enterprise Access Standards in Prefabricated Building Industry

Downstream refers to the processes and interactions that occur after the production stage, typically involving distributors, retailers, and end customers. Digital tools, such as Building Information Modeling (BIM), are increasingly used to enhance communication and coordination in the downstream supply chain (Eastman et al., 2011). Downstream enterprise access standards govern how an organization manages these relationships. Key aspects include:

- *Customer Relationship Management (CRM):* Standards for managing interactions with customers, including data handling, communication protocols, and service level agreements (SLAs).
- *Distribution and Logistics:* Guidelines for the distribution of finished goods, including warehousing, transportation, and delivery. This may involve collaboration with logistics providers to ensure timely and accurate deliveries.
- *After-Sales Support:* Standards for providing post-sale services, such as warranties, repairs, returns, and customer support. This ensures customer satisfaction and builds brand loyalty.
- *Data Privacy and Security:* Protocols for protecting customer data, especially in compliance with data protection regulations like GDPR or CCPA. This includes secure data sharing and storage practices.
- *Product Traceability:* Standards for tracking products through the supply chain to ensure that they can be traced back to their origin. This is crucial for quality control, recalls, and regulatory compliance.
- *Customer Feedback and Improvement:* Processes for collecting and analyzing customer feedback to drive continuous improvement in products and services.

2. Integration Challenges

Integrating the supply chain in the prefabricated building industry is fraught with challenges. One of the primary obstacles is the misalignment between upstream and downstream activities, which can result in delays, cost overruns, and quality issues (Arif et al., 2012). Technological barriers, such as the lack of interoperability between different software systems used by various stakeholders, further complicate the integration process (Lu & Korman, 2010). Additionally, economic factors, such as fluctuations in material costs and supply chain disruptions, pose significant risks to project outcomes (Vrijhoef & Koskela, 2000). Regulatory challenges, including the need to comply with varying building codes and standards, add another layer of complexity to supply chain integration (Goulding et al., 2015).

3. Technological Innovation and Tools

Technological advancements are playing an increasingly important role in optimizing supply chain integration in the prefabricated building industry. Digital tools such as BIM, the Internet of Things (IoT), and Artificial Intelligence (AI) are being adopted to improve coordination, reduce errors, and enhance decision-making (Eastman et al., 2011). BIM, in particular, allows for detailed planning and visualization of the construction process, facilitating better collaboration among stakeholders (Lu & Korman, 2010). IoT technologies enable real-time tracking of materials and components, ensuring that they are delivered and installed as planned (Gbadamosi et al., 2020). AI can be used to analyze data from various sources to optimize scheduling, resource allocation, and risk management (Pan & Goodier, 2012). The integration of Industry 4.0 principles, which involve the digital transformation of manufacturing and construction processes, is also seen as a key enabler of supply chain optimization in the prefabricated building industry (Huang et al., 2019). Companies that have adopted these technologies report significant benefits, including faster project completion times, reduced costs, and improved quality (Kamar et al., 2011).

4. Global Perspective and Comparative Studies

The integration of supply chains within the prefabricated building industry displays considerable variation across different regions, reflecting the influence of local regulatory frameworks, industry standards, and the adoption of innovative practices. Comparative studies provide valuable insights into how different countries approach supply chain integration, with significant lessons to be drawn from the successes and challenges observed in various contexts.

5.1 Success in Developed Markets: The Cases of Japan and Sweden

Countries like Japan and Sweden serve as exemplary models in the integration of prefabricated building supply chains. Both nations benefit from well-established regulatory frameworks and a long history of innovation in construction practices, particularly in prefabrication.

In Japan, the construction industry has long embraced prefabrication as a means to address challenges such as labor shortages, high land costs, and the need for rapid urban development. The Japanese government's strong regulatory framework has been pivotal in promoting standardization across the industry. This includes the widespread use of quality assurance standards for prefabricated components, which ensures consistency and compatibility across the supply chain (Goulding et al., 2015). Additionally, Japan has fostered a culture of collaboration among various stakeholders in the construction industry, from manufacturers to contractors, which has further streamlined the supply chain integration process. The result is a highly efficient system where components are produced with precision and delivered just-in-time for assembly, minimizing waste and reducing project timelines.

Similarly, Sweden has demonstrated significant success in the integration of its prefabricated building supply chain, driven largely by its commitment to sustainability and innovation. Swedish construction firms have been at the forefront of adopting digital tools and technologies, such as Building Information Modeling (BIM) and automation in manufacturing processes. The Swedish government has also played a crucial role in setting stringent environmental and quality standards that have pushed the industry towards greater efficiency and sustainability (Tam, 2007). These policies encourage the use of renewable materials and energy-efficient practices, which have become integral to the Swedish approach to prefabricated construction.

5.2 Challenges in Developing Markets: Learning from Advanced Economies

In contrast, many regions with less developed regulatory frameworks and fragmented supply chains struggle to achieve similar levels of integration. In these areas, the prefabricated building industry often faces significant hurdles, including inconsistent quality standards, poor coordination among supply chain partners, and limited adoption of advanced technologies. These challenges are compounded by economic constraints and a lack of government support, which can hinder the development of a robust and integrated supply chain.

However, these regions have the opportunity to learn from the experiences of more advanced markets like Japan and Sweden. By adopting best practices, such as establishing clear regulatory frameworks that promote standardization and quality assurance, developing collaborative industry networks, and investing in digital technologies, developing markets can enhance their supply chain integration (Vrijhoef & Koskela, 2000). For example, introducing policies that incentivize the use of BIM and other digital tools can help improve coordination and communication across the supply chain, leading to better project outcomes.

Furthermore, developing markets can benefit from international collaboration and knowledge exchange. Engaging with global industry leaders and participating in international construction forums can provide valuable insights into the latest trends and innovations in prefabrication. This, in turn, can help these regions accelerate their adoption of best practices and technologies, ultimately leading to more efficient and integrated supply chains.

5.3 The Role of Globalization and International Standards

Globalization has also played a significant role in shaping the supply chain dynamics of the prefabricated building industry. The increasing interconnectedness of markets has led to the cross-border flow of materials, components, and expertise, creating opportunities for greater integration. International standards, such as ISO certifications, have facilitated this process by providing a common framework for quality assurance and process management across different regions (Goulding et al., 2015). These standards help ensure that prefabricated components produced in one country can be seamlessly integrated into construction projects in another, thus enhancing global supply chain efficiency.

Nevertheless, the reliance on global supply chains also introduces new challenges, particularly in the face of geopolitical instability, trade restrictions, and supply chain disruptions. For instance, the COVID-19 pandemic highlighted the vulnerabilities of global supply chains, as disruptions in manufacturing and transportation led to significant delays in construction projects worldwide. This has prompted many regions to re-evaluate their supply chain strategies, with a growing emphasis on local sourcing and the development of more resilient supply chains.

5. Research Methodology and Findings

In this study, a critical review was conducted with literature related to prefabrication. Academic databases were searched using keywords such as: prefabrication, prefabricated building, module construction, off-site manufacturing, etc. As a result, a list of critical factors associated with prefabrication is identified.

6.1 Research Methodology

Semi-structured interviews with prefabrication industry professional are common text. These interviews are intended to help refine the list of important variables derived from the analysis of important literature. Table 1 lists the ten experts who were interviewed. In the first instance, they were shown the preliminary list of risk factors that came from the literature review. As a result, they were questioned about:

1. Are these risks related to the implementation of prefabrication in China?
2. Are there any other risks that are not included in this list?
3. Is the expression of each risk factor clear?

Emphasis was placed on getting interviewees to consider potential risks at each stage of the prefabricated building life cycle, such as the design, manufacture and transportation, construction, operating, and feasibility study stages. Every interviewee attested to the fact that the initial inventory of risk indicators supplied during the interview accurately reflects the overall state of prefabricated buildings in China. They also affirmed that the term does not have any ambiguity issues. Furthermore, respondents proposed a few novel risk variables that aren't addressed in the body of current research.

Table 1. Profile of Interviewees

Interviewees	*Organization*	*Prefabrication Related Experience (Years)*
A	Contractor	8
B	Contractor	7
C	Contractor	6
D	Design institute	8
E	Design institute	8
F	Modular manufacturer	7
G	Modular manufacturer	6
H	Developer	7
I	Government	8
J	Government	6

The questionnaire survey was conducted with professionals in the prefabrication sector to gauge their expert opinion of how those critical factors are applicable in the Chinese market. Meanwhile, the Importance-Performance Analysis was conducted to develop corresponding strategies. Importance-Performance Analysis was proposed by Martilla and James for the purpose of developing strategies based on identified critical factors. The Importance-Performance Analysis consists of following steps:

1. A list of critical factors is identified.
2. Each critical factor is evaluated from two dimensions, i.e., level of importance and level of performance.
3. All factors are classified into four groups according to their level of importance and level of performance, i.e., concentrating here, keeping up the good work, low priority, and possible overkill.

The entire research process is shown in Figure 1. A five-point Likert scale was employed in this study to measure the importance and performance levels of the management of each individual risk perceived by industry practitioners. Each survey participant was required to evaluate the relative importance of the measure the performance of the management of every single risk associated with prefabrication management of every single risk associated with prefabrication, i.e., from 1 (“very unimportant”) to 5 (“very important”). Similarly, a 5-point Likert scale from 1 (“very insufficiently”) to 5 (“very sufficiently”) was used to measure the performance of the management of every single risk associated with prefabrication.

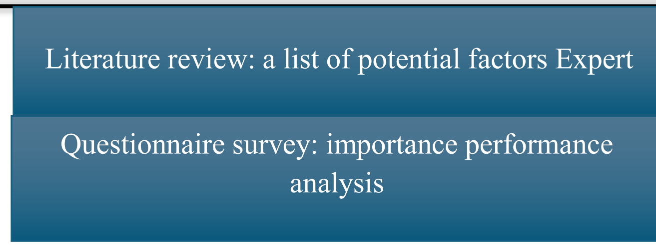

Figure 2. Research Process

6.2 Results Overview

It is well-recognized that a life cycle approach needs to be employed to evaluate benefits and costs of prefabricated buildings. Life cycle stages of prefabricated buildings include feasibility study, design, manufacturing and transportation, construction, and operation. Therefore, the identification of risks associated with prefabricated buildings is according to these life cycle stages. A total of 154 valid responses were received. Nearly 60% of these respondents were aged 26 – 40. Most survey respondents have more than five years of experience related to prefabricated buildings (Table 2). Therefore, these respondents provide valid and valuable input for this research.

Table 2. Respondent Demographics

Respondents	***Distributions***
Gender	*Male and Female*
Age	-
Organization	*Construction Design Modular manufacturer: Developers Government and others*
Prefabricated related experience	-

6.3 Study Stage

Risks exist in the feasibility study. According to Jiang, top-down policy support plays a crucial role in the promotion of prefabricated construction. These include preferable taxes, subsidy, and loan. The mandate policy on the adoption of prefabrication in certain sectors also encourages the implementation of prefabricated construction. Consequently, changes to these preferable policies will present a significant risk to the prefabricated construction. Similarly, changes to related laws and market condition may pose severe risks to prefabricated construction. The other risk during the feasibility study stage is the lack of market and social acceptance. This is mainly due to the negative public perception of prefabrication and the general risk-averse attitude of the construction industry. In addition, previous studies have reported concerns of potential high capital cost or even high overall cost in prefabricated building projects. The capital cost is high because the specialized factory has to be established to manufacture the required components as well as the associated production and maintenance cost. Interviewees suggested two extra risk factors during the feasibility stage. These two risks are: lack of appropriate transport and environmental support around the site, and lack of appropriate planning of production capacity of prefabricated components. For instance, some interviewees highlighted the high concentration of air pollutants in the prefabrication factory environment.

6.4 Design Stage

There are several risks during the design stage. It can be understood that many of these factors are associated with design professionals. Indeed, there are several design issues associated with prefabricated buildings. These include lack of uniqueness or customization in prefabricated building design and poor consideration of geological conditions. To enhance the constructability, it is necessary to use information technologies such as Radio-frequency identification (RFID) and Building Information Modelling (BIM). This will help to clearly understand the information flow associated with the entire process and assist the material selection. Interviewees revealed that it is a common practice in China that a design institute is engaged in the project to undertake the design of prefabricated buildings. It is not unusual that the design is not conducted according to prefabrication principles. This is attributed to the fact that many design institutes lack deep design capability and experience in integration design of prefabricated building. Rather, traditional design is performed and consequently a specialist design consultant is engaged by the client to decompose the original design into various prefabricated components.

6.5 Manufacturing and Transport Stage

Prefabricated components need to be manufactured in the factory and then transported to the site for assembly. A few risks are involved in this process. However, these upstream processes are largely overlooked in existing studies. The manufacturing and transport of prefabricated components require a highly skilled workforce. For instance, a number of machineries and devices are used in a prefabrication factory. These machineries and devices include Computer Numerical Control (CNC) marking machine, concrete distributor, vibrator, concrete conveyor, remolding machine, etc. The operators of these machineries and devices have to be highly skilled to keep up the efficiency of the operation. This could be a result of a low level of factory management. In terms of transportation, a lot of risk factors have been reported in existing studies such as: improper stacking of components, lack of professional stacking tools, and lack of professional transportation tools. Interviewees revealed many risk factors during the manufacturing and transport stage of prefabricated building projects. These include deviation in component sizes, and deviation in specification of prefabricated components. They also suggested potential strength issues, e.g., insufficient strength of prefabricated concrete components and insufficient strength when lifting the prefabricated concrete component.

6.6 Construction Stage

Some studies have been undertaken to identify potential risks in the construction stage. As many workforces and machinery are involved in the construction stage, a lack of related resources will pose a significant challenge to the prefabricated building. Insufficient radius of crane operation and insufficient lifting capacity of lifting machinery are critical issues, especially in volumetric prefabricated buildings. There are safety risks during the construction process such as failure of lifting connection and lifting operation error. Interviewees suggested other risks during the construction stage such as: lack of quality inspection methods, lack of technologies to test the quality of connections, lack of quality acceptance method and standard system, and lack of catalogue of building parts and components. Some interviewees also revealed that in some cases, materials and accessories used for component installation have not been tested. Similarly, there have been some concerns about insufficient coordination between prefabricated construction and other components of construction, and insufficient concrete strength after in-situ cast of joint connections.

6.7 Importance-Performance Analysis: Critical Risks and Corresponding Strategies

In terms of importance, all risks listed in Table 1 received a score higher than 3. This indicated that the list developed from the literature review and tested in interviews is valid. All risks listed in Table 1 are applicable in the context of China. The identification of risk factors was conducted through a comprehensive literature review and validated by expert evaluations. The top ten identified risks are:

- High overall cost (A10)
- Changes to preferable policies (A1)

- Lack of uniqueness or customization in prefabricated building design (B1)
- High capital cost (A9)
- Lack of related standards (A6)
- Shortage of industrial technology management personnel during construction (D3)
- Insufficient training for industrial workers (C18)
- Changes to related laws (A4)
- Insufficient coordination between prefabricated construction and other components of construction (D1)
- Lack of appropriate planning of production capacity for prefabricated components (A12)

Half of these top ten risks are associated with the feasibility study stage (Stage A), highlighting industry professionals' concerns about potential risks from the very early stages of prefabrication projects. Respondents expressed apprehensions not only about associated costs but also about the lack of supportive policies and standards. Notably, the policy mandating the implementation of prefabricated buildings has significantly facilitated the development of the prefabrication sector in China. As the volume of prefabricated buildings increases, costs can be reduced. Additionally, resource-related risks, such as shortages in human resources, machinery, and production facilities, have been identified as critical. Given China's vast geography, proper planning is essential to ensure adequate production capacity of prefabricated components in each region, thereby avoiding excessive transportation and its associated environmental impacts, such as increased energy consumption and greenhouse gas emissions. Interviewees noted that current production capacity is concentrated in a few cities and suggested developing additional production bases in rapidly urbanizing regions.

The survey also gathered respondents' professional judgments on the effectiveness of current risk management practices in China. The following risks were identified as being less effectively managed:

- Insufficient strength of prefabricated concrete components (C2)
- Insufficient lifting capacity of lifting machinery (D14)
- Insufficient strength during the lifting of prefabricated concrete components (C3)
- Insufficient radius of crane operation (D13)
- Violation of design specifications (B3)
- Poor consideration of geological conditions, resulting in failure to put into use (B5)
- Untested materials and accessories used for component installation (D12)
- Insufficient concrete strength after joint pouring (D15)
- Rebar corrosion (D16)
- Impact of climate factors (D17)

Interestingly, while most of the top ten risks are associated with early project stages (e.g., feasibility study and design stages), respondents reported that risk management performance is comparatively poorer in later stages (e.g., manufacturing and construction stages). Numerous risks are present in the factory environment during manufacturing and in the transportation of prefabricated components to construction sites for assembly. The majority of these risks are technical issues related to prefabricated concrete components, such as their strength and, consequently, the structural integrity. Notably, there is concern about the lack of testing mechanisms for all materials and accessories used in component installation. Interviewees suggested that current practices predominantly rely on quality control efforts.

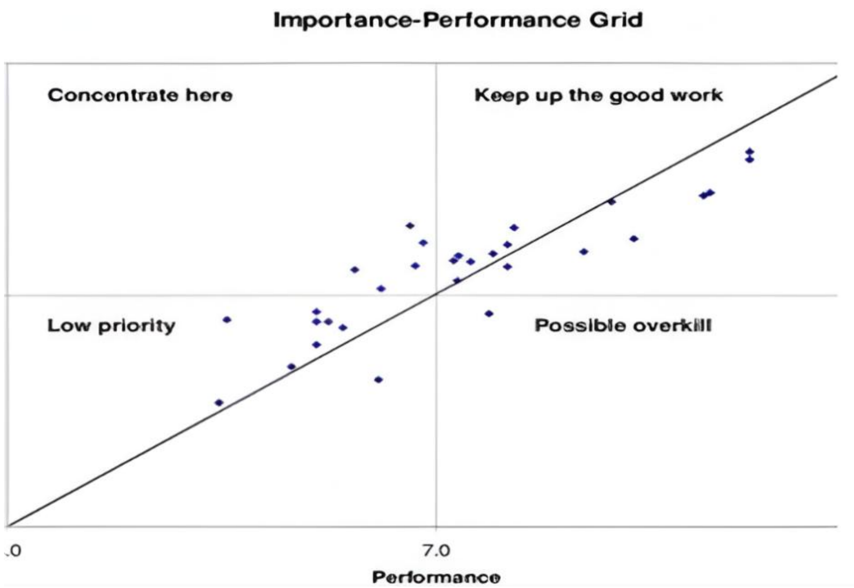

Figure 2. Importance-Performance Analysis (IPA) matrix

The IPA matrix presented in Figure 2 was generated using survey data collected from industry professionals. Respondents rated the importance and performance of various attributes associated with prefabrication risks on a Likert scale, typically ranging from 1 to 7. The data was analyzed using the IPA framework, where attributes are plotted on a two-dimensional grid. The x-axis represents the performance score, and the y-axis represents the importance of the score. The IPA model employs a quadrant-based classification system:

- High importance but low performance, requiring immediate attention.
- High importance and high performance, indicating strengths to be maintained.
- Low importance and low performance, requiring minimal resources.
- Low importance but high performance, suggesting potential resource optimization.

This matrix was created using Python, using libraries such as Matplotlib for visualization and Pandas for data processing. A diagonal line was included to enhance interpretability, distinguishing attributes that require focused improvement from those already performing well.

Interviewees revealed that it is a common practice in China that traditional non-modular design is undertaken even in those projects using prefabrication methods. As a result, a special consultant is employed by the client to perform decomposition of a traditional non-modular design. According to interviewees, it is not possible to decompose the non-modular design entirely into modules. In most cases, these components end up with in-situ cast on site. Such practices also present significant challenges for the manufacturers as it is difficult to achieve standardization of module design and manufacturing. This risk is also associated with the defects of the components system, missing catalogue of building parts and components. Interviewees suggested that the government plays a crucial role in leading the industry towards the standardized modular design and system. In addition, the professional body and industry association can facilitate this process via industry-wide training programs. Similarly, efforts are required to improve the performance of factory management. As all modules are manufactured and tested in the factory environment, the performance of managing resources (e.g., human resources, machinery, storage, etc.) has a significant impact on the quality of prefabricated components. Poor management of a factory will lead to significant wastes of time, cost, and space. Another two areas to be concentrated on are located in the operation stage. The first risk is related to adaptability of prefabricated building during the operation stage. This is arguably because of the connection system adopted in China.

In China, the common practice to connect prefabricated components is through in-situ cast concrete. This makes it very difficult to adapt prefabricated buildings, e.g., removing existing modules or adding new modules. The second risk is related to the evidence for the benefits associated with prefabricated buildings. At the moment, the vast majority of existing studies rely on the subject comments made by industry professionals or simulation results. Some interviewees revealed that some prefabricated building projects suffer from cost overruns and delays, predominately due to the lack of necessary human resources and poor management of logistics. A database of actual cases with lessons learnt and benefits will help the industry to gain confidence and further promote the prefabrication sector.

6. Conclusion

Our findings reveal that the prefabricated building industry in China, like in many growing markets, faces many challenges throughout a project's lifecycle. From the early planning stages to when the building is in use, there are both risks and opportunities that shape this developing industry. The top concerns we identified were high overall costs, changes in supportive policies, and lack of unique designs. These issues show that the challenges in this industry are complex and varied. Our research highlights how important it is for different parts of the supply chain to work well together to address these challenges. We found that while many risks are seen as important, they're not always managed well, especially in the later stages of projects. This suggests that we need better strategies for integrating the supply chain. We also found that there are problems with the strength and quality of prefabricated components, as well as issues with lifting and installing them. This shows that designers, manufacturers, and construction teams need to work together more closely. It supports the idea that upstream and downstream companies should be more tightly connected, possibly by using advanced technologies and standard processes. Our study also shows that government policies and industry standards play a big role in shaping industry. Supportive policies have helped the industry grow, and there's a need for standard designs and component lists. This suggests that government bodies and industry groups have an important part to play in creating an environment that helps the supply chain work together better. Looking ahead, we see several key areas that are critical for improving prefabricated building supply chains:

Standardization: The industry needs wide-ranging standards and modular design principles to help different stages of the supply chain work together smoothly.

Technology Use: Using technologies like Building Information Modeling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI) across the supply chain can improve coordination, reduce mistakes, and help with decision-making.

Skills Development: There's a shortage of skilled workers, especially in specialized areas of prefabrication. Addressing this is crucial for improving how the supply chain performs.

Policy Support: Continuing to improve supportive policies and regulations can help create a more stable and predictable environment for the industry to grow and innovate.

Lifecycle Approach: Looking at the whole lifecycle of a project when planning and executing can help predict and reduce risks at all stages of prefabricated building projects.

As the construction industry continues to change in response to global challenges like growing cities, climate change, and resource scarcity, improving prefabricated building supply chains will become increasingly important. Future research should focus on developing practical ways to use the insights from this study, possibly through case studies and pilot projects that show the real-world impact of better supply chain integration in prefabricated construction. The success of the prefabricated building industry will depend on its ability to create strong, flexible, and well-integrated supply chains that can adapt to changing market conditions and new technologies. By encouraging collaboration between researchers, industry professionals, and policymakers, we can work towards a future where prefabricated construction reaches its full potential as a key part of sustainable and efficient urban development.

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