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Research in the Field of Prefabricated Building Management: A Case Study

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Abstract:

Due to its low energy consumption, short construction period, low labor cost, and great construction efficiency, prefabricated buildings have garnered extensive interest from scholars worldwide as a novel production method. Nevertheless, research on prefabricated houses is not yet thoroughly analyzed. This study summarized the existing state and research hotspots of prefabricated building research by thorough study and summarization of research on prefabricated buildings. According to the findings, there are five key areas of study within the prefabrication field: the sustainability of prefab structures, their meaning and current state of development, the development environment, project lifecycle management, and organizational management. Finally, offer some recommendations for future theoretical and practical work on prefabricated structures based on where the industry is at the moment in terms of development.

Keywords: *prefabricated buildings, research review, full life cycle management, sustainable architecture.*

Introduction

The term "prefabricated building" can mean many different things depending on context. The terms "industrialized building" and "modular building" are also used. To begin with, prefabrication is a relatively new concept in the construction industry. It entails off-site fabrication of some building components, with on-site assembly serving to complete the structure (Li, et al., 2020; Navaratnam, et al., 2022; Shah, et al., 2022; Gutiérrez, et al., 2024). In the field of prefabricated building management, the integration of AI, cloud computing, digital twin, and robotics is bringing revolutionary changes. AI technologies can analyze and optimize various data in prefabricated building management, improving decision-making efficiency (Nawaz, et al., 2022). Cloud computing provides a powerful platform for data storage and sharing, facilitating real-time collaboration (Jabeen, et al., 2022). Digital twin technology creates a virtual replica of the prefabricated building, enabling comprehensive monitoring and simulation (Shoukat, et al., 2023; Niaz, et al., 2022). Meanwhile, robotics can assist in the construction and maintenance of prefabricated buildings, improving work efficiency and quality (Shoukat, et al., 2024; Almansoub, et al., 2023). These cutting-edge technologies are driving the development and innovation of prefabricated building management, bringing more intelligent and efficient solutions.

The level of integration and development across the entire building industry chain is exemplified by prefabricated construction, on the other hand (Pelli, & Lähtinen, 2020). The conventional wisdom holds that prefabricated buildings have several advantages over conventional structures, including higher engineering quality, shorter construction times, less labor, and lower energy usage (Rocha, et al., 2022; Sojobi, & Liew, 2022). Prefabricated structures have caught the interest of government agencies, construction companies, and academics as a sustainable construction approach, especially in light of the growing number of environmental and resource constraints encountered by modern society (Chen, Okudan, & Riley, 2010; Xu, Zayed, & Niu, 2020; Boafo, Kim, & Kim, 2016; Li, Shen, & Xue, 2014).

Recently, both domestic and international researchers have organized and consolidated the study accomplishments in the field of prefabricated buildings from various viewpoints. Li et al. (2014) conducted a comprehensive review on the management of prefabricated buildings. They analyzed the primary research countries and regions in this field and identified the key areas of research in prefabricated building management. These areas include the industry's future prospects, the practical applications of prefabricated buildings, performance evaluation, technology application environment, and strategies for design product transportation and assembly. Yashiro et al., (2014) extensively studied the implied meaning of industrial architecture and put forward a conceptual framework for researching industrial architecture. This framework covers various aspects such as the requirements for developing new technology, production techniques, product systems, managing the lifecycle of products, organizational management, the maturity of the supply chain, and the factors that drive or limit industrial architecture. Mostafa et al. (2016) evaluated prefabricated building literature from lean construction and agile manufacturing viewpoints and advocated simulation technology's use in prefabricated buildings. From an economic, social, and environmental perspective, Zabihi et al. (2013) summed up the meaning of prefabrication. Several limitations remain in the above research. First, the literature evaluation above includes only 100 publications from a few journals and analyzes a tiny amount of data. Second, the summary of prefabricated building research is incomplete, and there is a dearth of systematic study on prefabricated buildings throughout their life cycle. Finally, the proposed research framework is primarily country- and region-specific and not general.

As a consequence, this study is conducted using a sample of relevant literature obtained from the SCI (Sciences Citation Index) and EI (Engineering Index) databases spanning from 2003 to 2023. Initially, the fundamental state of prefabricated building research is organized, encompassing the quantity of published papers, types of journals, regions of study, institutions involved in research, and researchers conducting research. Additionally, a methodical structure for examining prefabricated structures is suggested based on five aspects: the meaning and current state of prefabricated construction projects, the surrounding conditions for development, comprehensive management during the entire lifespan, organizational management, and sustainability. Ultimately, the objective of this work is to offer a point of reference for the theoretical investigation of prefabricated buildings worldwide.

Research Methods and Data Sources

A search was conducted in the SCI core database and EI database using specific search terms such as "Prefabricated construction," "Prefabricated building," "Offsite construction," "Offsite building," "Modular construction," "Modular building," "Industrialized building," "Industrialized housing," "Modern method of construction," "IBS," and "Modulation". A total of 580 articles were found, and after screening, 330 articles were considered valid. Industrialized Western countries initiated a repositioning of the construction industry, which led to the emergence of new development potential for prefabricated buildings. Hence, the timeframe for acquiring material in this study ranges from 2003 to the initial half of 2023.

The quantity of papers pertaining to prefabricated building is progressively rising, as evidenced by Figure 1, indicating a gradual increase in scholarly interest in this topic. Applying the quadratic average method to analyze the data on the number of articles, it is evident that there will be intermittent periods of decline in the number of articles pertaining to prefabricated buildings. These periods exhibit a distinct periodic pattern, specifically observed from 2003 to 2006, 2007 to 20011, and 2014 to 2016.

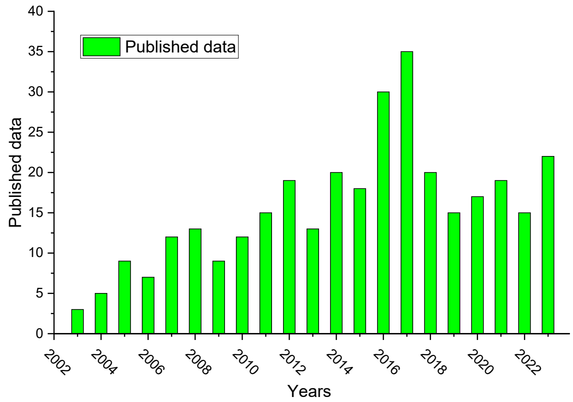

Figure 1. Number of Articles Related to Prefabricated Buildings Published from 2003 to the First Half of 2023

The 330 chosen articles in this compilation encompass a collective of 47 academic publications, encompassing several disciplines including civil engineering, construction management, real estate management, design planning, and building environment. Based on the articles included in the SCI database, Automation in Construction has the highest number of articles focused on prefabricated buildings, followed by Construction Management and Economics and Journal of Construction Engineering and Management. These three publications have a significant standing in the field of construction management and can be considered as authoritative journals in this domain, exerting substantial international influence. The Journal of Architectural Engineering and Construction Innovation publishes the highest number of articles in EI journals.

Analysis of Research Topics

Tomonari Yashiro, a Japanese scholar, put forward an analytical framework for industrial architecture. He examined the progress and changes in Japanese industrial architecture by considering factors such as the necessary conditions for innovative methods, manufacturing and product technology, building functionality, organizational management, supply chain maturity, and driving and limiting factors (Yashiro, 2014).

The framework proposed has limited applicability in assessing research subjects related to prefabricated buildings. It primarily focuses on the production and construction stages of prefabricated buildings and does not comprehensively analyze the complete life cycle of such buildings. Furthermore, the framework is founded upon the advancement of preconstructed structures in Japan and does not encompass extensive study subjects. This article classifies and summarizes 19 research topics using literature title analysis, keyword extraction, and an overview of the article content. These topics include conceptual connotation (Shackley, & Green, 2007), development status (Crosthwaite, 2000), adoption behavior drivers and constraints (Lee, 2004), market customer analysis (Bock, 2007), construction method decision-making (Ofori, & Kien, 2004), standardized and modular design (Chandra, & Kamrani, 2003), technical system (Viotti, 2002), product system and production process (Evans, Partidário, & Lambert, 2007), construction layout and schedule scheduling (Moghadam, Alwisy, & Al-Hussein, 2012), project management (safety, quality, cost, schedule, risk) (Luo, et al., 2015; Eriksson, et al., 2014; Mao, et al., 2015), construction waste and recycling management (Bari, et al., 2012; Lu, & Yuan, 2010), supply chain management (Čuš-Babič, et al., 2014), advanced technology application (Shoukat et al., 2022), productivity and performance evaluation (Jonsson, & Rudberg, 2014), building energy consumption (Abbood, et al., 2015), sustainability (Wandahl, & Ussing, 2013), organizational change, business models, and collaborative innovation. The research topics mentioned above are categorized into five dimensions based on systems theory and the theory of the entire life cycle of buildings. These dimensions include conceptual connotation and development status, development environment, project lifecycle management, sustainable management, and organizational management. This article presents a methodical framework for researching and analyzing prefabricated buildings, which is detailed in Table 1.

Table 1 List of Research Topics for Prefabricated Buildings

Research dimensions	Research topic	Number of articles	Percentage
Concept connotation and development status	Conceptual connotation	13	3.94
	Development status	25	7.58
Development environment	Adopting Behavioral Drivers and Constraints	33	10.00
Project lifecycle management	Market customer analysis	12	3.64
	Construction method decision-making	9	2.73
	Standardized and modular design	20	6.06
	Technical system	18	5.45
	Product system and production process	43	13.03
	Construction layout and schedule scheduling	21	6.36
	Safety, quality, cost, schedule, and risk management	16	4.85
	Construction waste and recycling management	6	1.82
	supply chain management	7	2.12
	Advanced technology application	27	8.18
	Productivity and performance evaluation	15	4.55
sustainable management	Building energy consumption	20	6.06
	Sustainability	23	6.97
Organizational management	Organizational change	11	3.33
	business model	7	2.12
	Collaborative innovation	4	1.21

Source: Yashiro, T. (2014)

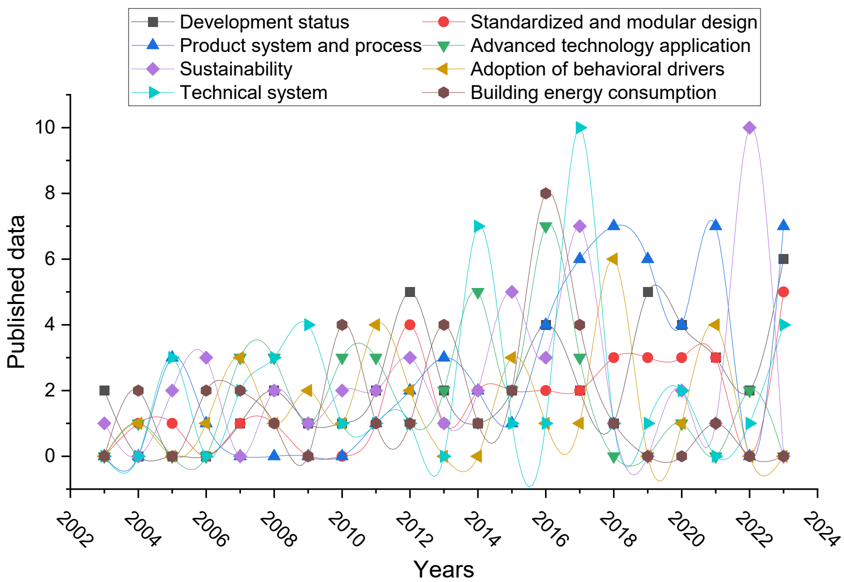

Figure 2 Trends in Research Themes of Prefabricated Buildings

The findings suggest that both domestic and international scholars have primarily focused their research on the product system and production process of prefabricated buildings, which accounts for 13.03% of the total number of articles. Following this, there has been significant research on the factors that drive and constrain the adoption behavior of prefabricated buildings, as well as the application of advanced technology. Figure 2 illustrates that the prevailing focus of research lies in the product system and production process of prefabricated structures, with an emphasis on advanced technological application, standardized modular design, and sustainability.

The Connotation and Characteristics

The nomenclature of prefabricated structures differs across many countries and regions, encompassing terminology such as Prefabricated Construction Building, Off-site Construction, Modular Construction Building, Industrialized Construction Building, and Modern Methods of Construction. The UK, Sweden, and Australia frequently employ the terms "Off site Construction" and "Modern Methods of Construction", while the US typically uses "Modular Construction Building". In contrast, Japan, China, and South Korea commonly refer to "Prefabricated Construction Building" and "Industrialized Construction Building". Malaysia is familiar with the utilization of "Industrialized Construction Building" or "IB". The concept of prefabricated buildings also differs, as shown in Table 2.

Table 2 Prefabricated Buildings' Concepts and Ideas

Years	Authors	Concepts/ideas
2014	Pons et al.	This study seeks to assess the sustainability of prefabricated structures by examining the economic, environmental, and social consequences of the prefabrication processes employed in their construction.
2016	Generalova et al.	The article examines the transient techniques of employing modular components in building. An analysis is conducted on the global expertise in constructing modular buildings.
2018	Minunno et al.	This work applies a circular-economy framework to the prefabricated building sector in order to examine the environmental benefits of prefabrication in terms of reducing waste, promoting reuse, enabling adaptation, and facilitating recycling of its components.
2020	Nam et al.	Module construction, an industrialized construction method, relies on production planning for project length, quality, and sustainability. Each project has different limits (production area, delivery due date), but modular construction production planning has not changed.
2021	Zairul et al.	This article aims to examine the existing literature on prefabricated construction using a circular economy (CE) methodology and forecast the future directions of prefabricated construction within the framework of circular economy.
2022	Liu et al.	This study utilized the TBL theory to establish the scope of the comprehensive benefits of the prefabricated building system model (CBPBSM). As a result, the model was categorized into three subsystems: economic, environmental, and social. The technique of system dynamics (SD) was employed to determine and measure the connections between important variables in the subsystems.

It can be seen that prefabricated buildings have the following characteristics:

(1) Standardization of architectural design: Through standardized design, the complexity of modular buildings can be reduced, achieving large-scale production and economic benefits. Standardized design enables large-scale customization of prefabricated products.

(2) Product modularization: Each component must be independent and have defined interfaces for modularization. Modular houses consist of modular parts assembled using standardized interfaces and modern connecting technologies.

Japan, where prefabricated buildings were created early, has a complete industrial construction industry chain with a professional component production and sales market. Thus, after the house's service life, its components can be recycled and reused, maximizing life cycle advantages (Salama, Moselhi, & Al-Hussein, 2021).

(3) Production automation: Production automation refers to the use of mechanized production methods for the production of prefabricated components and parts, achieving maximum production efficiency through optimized production lines and resource scheduling. Meanwhile, concepts such as lean manufacturing and flexible production can also be introduced into the construction industry.

(4) Assembly mechanization: After the prefabricated components and parts are transported to the construction site, they are assembled into a new building through mechanical equipment lifting and certain connection techniques. Some scholars have studied the lifting scheme of prefabricated buildings and the optimization of on-site layout. At present, mechanization is the main characteristic of industrialized construction, and its higher stage is automation and intelligence.

(5) Refined management: Prefabricated buildings are not just about moving some of the on-site construction work to the factory, but also redesigning the entire production process of the building. From design to component production and on-site assembly, coordination and cooperation from multiple stakeholders are required. Unlike traditional architecture, each stage of prefabricated building is no longer independent of division of labor, but requires collaborative cooperation, emphasizing standardized design, standardized processes, and standardized organizational management.

Development Environment

The development environment encompasses the socio-economic conditions that facilitate the advancement of prefabricated construction techniques. This includes studying the factors that drive or limit the adoption of prefabricated construction methods, analyzing national policies, and researching the market dynamics surrounding prefabricated construction. Currently, numerous countries are conducting substantial study on the factors that drive and limit the adoption of prefabricated construction systems.

Several studies have identified and measured the factors that drive and restrict the development of prefabricated buildings. Pan et al. (2007)] found that time, cost, quality, and productivity are the primary criteria that encourage British developers to use prefabricated construction technologies. According to Lu et al. (2008), the main elements that influence the use of modular construction are the time it takes to complete the construction, the overall progress of the project, and the weather conditions at the construction site. Blismas et al. (2009) conducted an analysis of the development environment of prefabricated buildings in Australia, focusing on the economic, social, and environmental aspects. The study identified greater productivity, reduced labor force, and improved lifecycle performance as the primary factors pushing the adoption of prefabricated buildings in the construction industry. The findings of Zhai et al. (2014) suggest that environmental concerns are the main catalyst for the advancement of prefabricated structures in China. These concerns include the reduction of construction waste, the decrease in building energy usage, and the promotion of green technologies. Additionally, the utilization of prefabricated buildings can effectively decrease the duration of on-site construction and enhance the overall quality of the building.

Full Life Cycle Management

The comprehensive management of construction projects across their entire life cycle is intended to enhance the project's value. It entails overseeing the entire process, including project decision-making, implementation, and subsequent use, to accomplish the five objectives of comprehensive life cycle management: societal satisfaction, safety, economic efficiency, timeliness, and quality.

This article is structured according to the theory of project lifecycle management. It covers various research topics including market customer analysis, construction method decision-making, standardized and modular design, technical system, product system and production process control, construction layout and schedule scheduling, safety, quality, cost, schedule, risk management, supply chain management, advanced technology application, and construction waste and recycling management. These topics are illustrated in Figure 3. The research on product systems and production processes is highly comprehensive, with a particular emphasis on the application of innovative technology in prefabricated buildings.

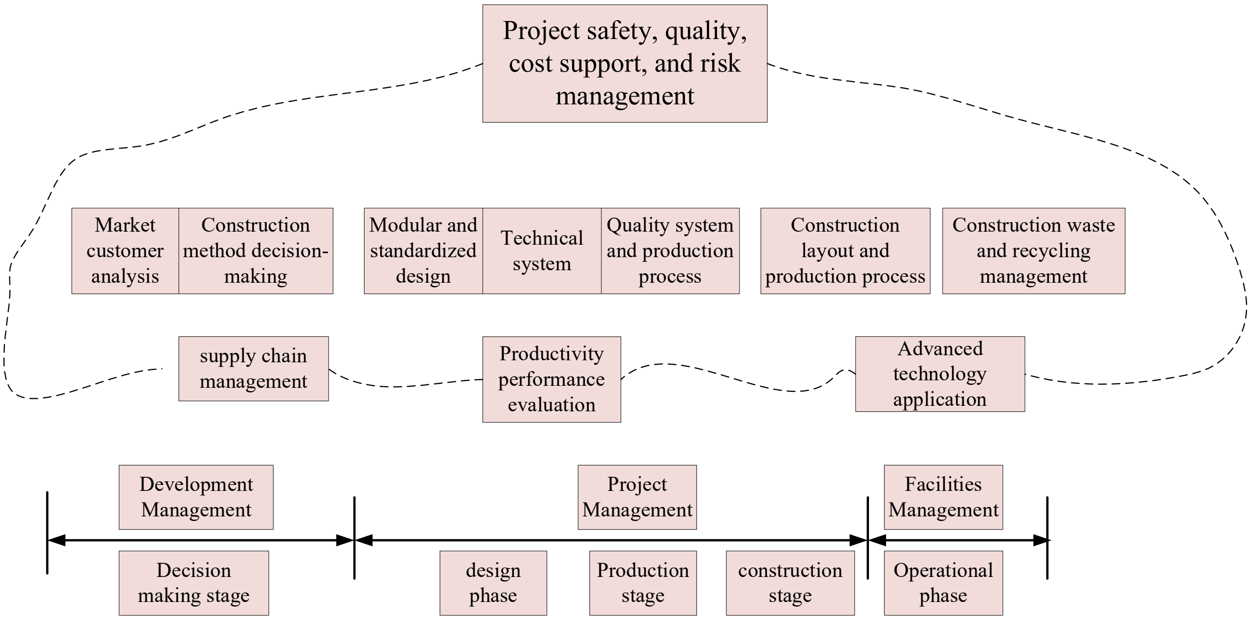

Figure 3 Full Life Cycle Management of Prefabricated Buildings

The research primarily focuses on the categorization of product systems, development of product platforms, implementation of production planning systems, adoption of lean production practices, and optimization of production processes. Jonsson et al. (2014) developed a prefabricated building product matrix for classifying product systems. This matrix takes into account three dimensions: standardization level, assembly level, and production scale. It considers both market demand and production system design in a thorough manner. Jansson et al. (2015) suggested four approaches for constructing prefabricated component product platforms: design planning, collaborative design, design optimization, and requirement iteration. Ko et al. (2011) devised a method for organizing the manufacture of prefabricated components using genetic algorithms. The objective was to optimize resource utilization and minimize waste. Jeong et al. (2011) developed a methodology for optimizing product portfolios with the aim of reducing delivery cycles, minimizing inventory, and cutting costs. Lean construction has been extensively implemented in the manufacturing of prefabricated items. Lu et al. (2011) created a lean agile production system for prefabricated residential products that aligns with market demand and production processes, effectively balancing market demand and production capacity. Nahmens et al. (2011) suggested that establishing strong supplier relationships is crucial for achieving lean production in prefabricated buildings. Anvari et al. (2016) developed an optimization model using a multi-objective genetic algorithm to improve the production process, transportation, and installation of prefabricated buildings. Their goal was to address the resource scheduling problem that occurs throughout the entire process.

With the development of building informatization, the application of new technologies has become a hot topic. Similarly, there is also a significant amount of research in the field of prefabricated buildings. This study indicates that the advanced technologies applied in the production process of prefabricated buildings mainly involve Building Information Modeling (BIM) (Adeel, et al., 2023), Internet of Things, 3D printing, Radio Frequency Identification (RFID), Geographic Information System (GIS), sensor technology, and virtual technology. From the perspective of research content, these technologies are mainly applied to prefabricated building design, product design, production process simulation, product transportation process tracking, on-site assembly simulation, quality inspection and other processes.

Organizational Management

The primary focus of research on organizational change revolves around two key areas: organizational readiness and customer relationship management. Musa et al. (2016) developed a framework model to study the readiness of organizations in the industrial construction system. The model consists of six dimensions: technology, process, factory, personnel, management, and cost. The aim of the study was to evaluate the readiness of different stakeholders in the prefabricated construction method and to support the development of industrial construction in Malaysia. In the context of industrial construction methods, Bildsten (2014) conducted a study on the interaction between customers and suppliers in the field of prefabricated buildings. As a result, a novel procurement combination model was proposed. The study demonstrated the need to enhance the productivity of prefabricated items by implementing customized services and standardizing designs. Additionally, it emphasized the importance of developing long-term and effective collaborations to enhance the value of the products. Jeong et al. (2009) introduced a paradigm for customer relationship management specifically designed for manufacturers and retailers.

The research on collaborative innovation primarily focuses on examining collaboration mechanisms among stakeholders in prefabricated construction and the dissemination of innovative technology in this field. In their study, Xue et al. (2018) examined the relationship between inter-organizational cooperation and innovation in industrial construction processes.

Sustainable Construction

The research on energy consumption of prefabricated buildings focuses on the following three aspects:

(1) Environmental impact assessment of prefabricated buildings with different structural systems based on the Life Cycle Analysis (LCA) framework. Bonamentea et al. (2014) analyzed the carbon footprint and energy consumption of prefabricated buildings using simulation methods based on the LCA framework. Aye et al. (2012) compared and analyzed the greenhouse gas emissions and energy consumption of steel structure buildings and concrete structure buildings throughout their entire life cycle.

(2) Calculation and evaluation of energy efficiency of prefabricated components. Hong et al. (2016) used input-output models to calculate and compare the energy consumption of major prefabricated components throughout their entire life cycle. Jeong et al. (2017) established a multi-objective evaluation framework for production efficiency, cost, and carbon dioxide emissions, and used simulation and equilibrium analysis methods to comprehensively evaluate prefabricated and cast-in-place columns.

(3) Application practice of prefabricated technology in energy-saving renovation. Silva et al. (2013) proposed an optimized energy-saving renovation plan for prefabricated exterior walls

using simulation methods. Larsen et al. (2011) a method for energy-saving renovation of traditional buildings based on 3D laser scanning and BIM application of prefabricated components has been proposed.

For sustainability research, it mainly focuses on the following three aspects:

(1) Analysis of sustainable influencing factors for prefabricated buildings. The research results of Shari et al. (2014) show that the market economy of Malaysian architects is the main factor in the decision-making of prefabricated construction projects. Furthermore, Yunus et al. (2014) analyzed the potential key sustainability drivers and constraints of prefabricated building applications.

(2) Sustainability performance evaluation. Chen et al. (2010) established a sustainability indicator system for decision-making on construction methods. Kamali et al. (2017) conducted a comparative evaluation of prefabricated buildings and traditional buildings using a sustainability performance evaluation model.

(3) The impact of lean thinking on the sustainable performance of prefabricated buildings. Kim et al. (2010) applied lean and agile thinking to the prefabricated building supply chain system and evaluated its environmental benefits.

Future of Prefabricated Buildings

Based on the analysis of research hotspots and the induction of research topics, the following suggestions are proposed for future research on prefabricated buildings worldwide:

(1) Focusing on the full life cycle management of prefabricated buildings, systematically studying the production process of prefabricated buildings from the aspects of technical system, product system, production process, etc. At present, industrial construction is still in its early stage of development, and there is relatively little research on component design, product platform development, and standardization and customization. As a technological innovation, the prefabricated construction method should prioritize technology.

(2) Strengthen the application research of advanced technology in prefabricated buildings. At present, research on the application of advanced technologies is relatively weak and cannot be effectively applied to engineering practice. Therefore, we should draw on the ideas of lean construction and agile manufacturing, and strengthen the application research of advanced technologies in the design of prefabricated building products, production of prefabricated components, transportation, on-site assembly, and quality acceptance.

(3) In terms of organizational research, the focus should be on studying the role positioning and decision-making process of stakeholders in the development of prefabricated buildings, and strengthening the cooperation, innovation, and collaborative development between the supply chains of prefabricated buildings. To promote the market-oriented development of prefabricated buildings, it is necessary to form a business model that is suitable for the national development situation.

(4) Pay attention to research on environmental performance and sustainability evaluation of prefabricated buildings. Global environmental issues are becoming increasingly prominent, and more and more countries and regions are exploring the energy consumption and environmental impact of prefabricated buildings. All countries should also keep up with the world and actively carry out research on the sustainability of prefabricated buildings.

Conclusion

This article provides a comprehensive analysis of representative literature sources collected from SCI and EI databases. The aim is to gain a macro-level understanding of the research sources, research regions, and research groups involved in the field of prefabricated buildings. A framework for the research theme of prefabricated building is suggested, based on the five dimensions of connotation and development state, development environment, whole life cycle management, organizational management, and sustainable management. The research findings suggest that the focus of study in this sector includes the product system and production process of prefabricated buildings, the utilization of sophisticated technology, sustainability, and the factors that drive or hinder the adoption of prefabricated buildings. Based on the current research state of prefabricated structures, this study proposes proposals for future research in the areas of technology system research and development, new technology application, and organizational innovation management. Future study will focus on predicting trends in prefabricated buildings and exploring the relationship between research subjects. This study will have a significant influence on the theoretical research and practical implementation of prefabricated structures worldwide.

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