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Lean construction management: A catalyst for evaluating and enhancing prefabricated building project performance in China

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ABSTRACT

The development of prefabricated construction in China has encountered challenges that prevent it from fully realizing its potential advantages. To overcome the challenges, this research examines the implementation of lean construction management in prefabricated building projects as a strategic approach to enhance their performance. Initially, this study examines the casual links between the driving factors of lean construction management and the performance indicators in prefabricated buildings by employing a structural equation model. Moreover, a fuzzy comprehensive evaluation method is used to assess the performance of a selected prefabricated building across the four dimensions: project schedule, quality, cost and safety. Furthermore, through the analysis and research above, this paper proposes a performance enhancement path for prefabricated building projects based on the key driving factors of lean construction management. The research identifies 23 driving factors and 16 performance indicators. 13 key driving factors are identified, including (1) accurate positioning and lean evaluation of the project, (2) identification of project product market demand, (3) modular collaborative design of the project implementation plan, (4) component production plant standardization, (5) production procurement costs reduction, (6) distance and cost of component transportation reduction, (7) lean transportation program plan, (8) construction and assembly costs reduction and waste elimination, (9) modular parallel construction, (10) lean construction assembly technology and management technology, (11) internal performance incentive mechanism of the project organization, (12) lean culture cultivation and lean management training, and (13) support from senior management. In addition, this research proposes a performance enhancement path for prefabricated buildings. The findings contribute to the theoretical knowledge of lean construction management in prefabricated building projects and offer valuable guidance for its practical implementation.

1. Introduction

Prefabricated building involves the standardized design of various components of the building system, including the structure, periphery, interior decoration, and equipment. These components are manufactured in prefabricated processing plants, replacing traditional cast-in-place construction processes, and then transported to the construction assembly site, where they are assembled and

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installed, enabling prefabricated components into finalized building projects [1]. Prefabricated buildings originated in Europe at the end of the 19th century [2]. Post-World War II, the imperative for post-war reconstruction and a surge in housing needs prompted European governments to actively champion the development of prefabricated buildings. This initiative gradually extended to the United States, Japan, Singapore, and other nations [1]. The development and application of prefabricated buildings in these countries have not only resulted in a comprehensive technical specification and standard system but have also found widespread use in public projects, particularly in residential constructions. Having examined the development process of prefabricated buildings in these countries, the development process can be divided into three stages: (1) the initial formation of prefabricated building industrialization, emphasizing the establishment and enhancement of standardized industrial construction systems; (2) the developmental phase, focusing on improving the quality and cost performance of building products; and (3) the mature phase, emphasizing cost reduction, environmental impact mitigation, and the development of resource-recycling buildings.

In contrast, the exploration of prefabricated buildings in China commenced in the 1950s, but traditional cast-in-place technology dominated the construction market. China's prefabricated building sector has only started to grow rapidly in recent years due to the development of prefabricated technologies, increased awareness of green environmental practices, and government incentive policies. However, several challenges impede the development progress of prefabricated buildings in China. Firstly, the cost for creating prefabricated buildings remains high [3]. Secondly, there is a lack of a comprehensive and standardized system of technical specifications and standards [4]. Thirdly, there is a lack of the project management methods specifically tailored for the prefabricated building projects [5]. These challenges result in issues in schedule, quality, cost, and safety of prefabricated building projects in China. As a result, the development speed of prefabricated construction falls short of expectations. Therefore, there is a pressing need for addressing the challenges and promoting the widespread adoption of prefabricated buildings.

Lean construction, proposed by Professor Lauri Koskela in 1992, is a production management method aimed at minimizing waste in terms of human resources, materials, costs, time and other resources during the construction project's production process, while maximizing the value derived from the invested resources [6]. Lean construction management, as an advanced industrial management model, has become a prominent topic for investigation. The key principles of lean construction management involve minimizing variability by managing cycle times and batch sizes, aiming for a single-piece flow [7]. This approach also enhances flexibility through the selection of suitable production control methods and the creation of standardized processes. Additionally, continuous improvement is achieved by utilizing a visual production system to monitor and expand partner networks. Lean construction management principles align closely with prefabricated building projects, as both aim to minimize waste and standardize the production process [8]. Implementing lean construction management in prefabricated building projects has the potential to optimize the production processes and improve the performance, notably enhancing product quality, elevating construction technology, reducing waste, cutting costs, and mitigating construction safety risks [8]. Numerous studies have applied lean tools in the prefabricated construction sector, using tools like six sigma management, kanban, and value stream mapping [9–11]. However, these studies primarily focus on the application of lean construction technologies or tools in prefabricated buildings, without adequately addressing how lean construction can enhance their overall the performance. As a result, the potential benefits of implementing lean construction in prefabricated buildings have not been fully realized. Therefore, it is critical to understand the impacts of lean construction management on the performance of prefabricated buildings.

2. Literature review

Numerous researchers have recognized the importance of lean construction in managing the performance of prefabricated buildings. This research examines studies related to lean construction management and prefabricated construction. First, this research investigates the performance management of prefabricated buildings and the factors influencing the implementation of lean construction management, aiming to better understand its impact on the performance of prefabricated buildings. Then, this research examines previous studies on implementing lean construction management in prefabricated construction. They are detailed in the following subsections.

2.1. Research on prefabricated building performance management

Project performance management encompasses the process wherein the project organizer breaks down overall project objectives into sub-objectives, implementing specific measures to facilitate the effective input of resources required for project tasks and the expected output of project objective [12]. The multifaceted objectives of prefabricated building projects, spanning cost, quality, timeline, and safety, necessitate effective coordination and resource management across various stages such as design, production, transportation, and construction and assembly.

The performance management in prefabricated building projects have been explored in previous research, focusing on enhancing quality, improving schedule and cost performance, and mitigating safety risks. For instance, the analytic hierarchy process and fuzzy evaluation methods were employed to assess construction quality across three stages of prefabricated building projects [13]. Su et al. [14] proposed an intelligent quality management platform for prefabricated buildings, addressing quality issues by integrating technologies such as BIM, the Internet of Things, and 3D scanning. In regards to the schedule management, BIM technology was used for comprehensive progress management throughout the prefabricated building life cycle [15]. The uncertainties in the progress process were addressed by constructing a BIM-based construction schedule [16]. The key schedule risk factors affecting prefabricated construction were identified by Li et al. [17]. Using an RFID-based BIM platform, they addressed these factors to reduce risks and enhance schedule performance. Furthermore, to achieve real-time monitoring of on-site assembly progress and cost, an IoT-based BIM platform was developed, thereby improving schedule and cost performance in on-site assembly of prefabricated building projects [18].

In cost management, Li et al. [19] explored reasons for high costs in prefabricated building projects, offering improvement suggestions based on a cost comparison with traditional cast-in-place methods. Measures to reduce production costs were proposed through informatization and industrialization technology analysis [20]. Regarding safety risk factors, Navaratnam et al. [1] constructed an evaluation system, and proposed a cloud model-based safety performance evaluation method, identifying significant risk factors affecting safety in prefabricated building projects. From a safety management perspective, the main factors affecting construction safety were identified using a grey clustering safety evaluation model [21]. In line with the construction safety risk levels, measures were proposed to mitigate risks and strengthen safety management in prefabricated building projects [22].

2.2. Driving factors for lean construction management

Regarding the driving factors of lean construction management, while the direct driving factors are limited in the literature, many scholars have extensively studied constraints and obstacles based on the development status in their own regions. Addressing and removing these constraints can potentially transform them into driving forces for the implementation of lean construction management. Therefore, an examination of obstacle factors serves as inspiration for identifying the drivers of lean construction management implementation.

This paper primarily reviews the research concerning the driving factors and barriers to lean construction management. In this regard, Alarcón et al. [23] identified key problems impacting lean construction implementation, including a lack of training, insufficient time for adopting new technologies, organizational responses to challenges, and self-criticism. Finance and management-related barriers within construction organizations were identified as key obstacles to lean construction in Uganda [24]. Bashir et al. [25] identified the reluctance of construction operators to change behaviour and practices as a critical obstacle in the UK construction industry, aligning with the conclusion of a prior study wherein government-related issues and adversarial relationships among construction professionals were identified as significant barriers to lean construction in China [26]. Olamilokun [27] noted corruption in government agencies as an obstacle to lean construction in Nigeria. Moreover, 22 barriers to lean construction in Saudi Arabia were identified and they were classified into factors such as traditional practices, customer relevance, technology, performance and knowledge, and cost-related barriers [28]. In another study, Albalkhy and Sweis [29] identified and classified 29 barriers to lean construction implementation into internal environmental, labour-related, materials-related, and exogenous barriers. In terms of the lean construction implementation in China, research by Liao and Bao [30] identified obstacles such as the absence of a lean construction management mode suitable for China's construction industry, a lack of lean construction concept and culture, insufficient professional quality of practitioners, and ineffective communication among construction project participants [30]. In another study, the core role of lean management in project implementation, construction site, and logistics and transportation in lean construction implementation in China were emphasized [31]. Moreover, collaborative organization and management are identified as a crucial factor affecting lean construction management implementation in engineering projects [32].

2.3. Application of lean construction management in prefabricated buildings

There are multiple studies employing lean construction principles in prefabricated building projects. For example, lean construction principles were often incorporated with information integration technologies such as building information modelling for the visual management of prefabricated modules [33], the optimization of prefabricated construction schedule [34] and the decision-making of building design elements and materials [35]. Moreover, a couple of studies focused on the sustainability of prefabricated buildings based on lean construction principles. For instance, Nahmens and Ikuma [36] utilized the lean construction, particularly the lean tool kaizen, as a strategy to reduce material waste, key safety hazards, and production hours of sustainable homebuilding. In another study, the practices for industrialized renovation of the building envelop were examined and a lean and prefabricated construction method was proposed as a strategy to reduce the energy and carbon emissions for prefabricated construction [37]. Furthermore, the benefits of using lean construction to enhance the performance of prefabricated buildings have been demonstrated in previous work. For example, a lean and agile construction system that promotes health, safety and productivity has been developed for prefabricated construction [38]. In a similar study, lean principles were used to redesign the production plant and improve the safety in the production process of prefabricated components [39]. Using lean management methods, in particular values stream mapping, just in time, continuous flow and total productive maintenance methods, allows to improve the performance of production and installation processes of pre-fabricated steel frames in building projects [40]. Additionally, the flexibility and customer satisfaction in building components production could be improved through the engagement of customers and implementation of lean principles in the production process [41,42].

2.4. Review summary

Above research reveals that significant research efforts has been made to enhance project quality, improve project schedule and cost performance, and mitigate safety risks through various approaches and advanced techniques including the implementation of lean principles and tools. Moreover, while some scholars have delved into the influencing factors of lean construction management implementation, the studies primarily focus on the obstacle factors that limited the implementation of lean construction management. Multiple obstacles in China were identified such as government-related issues, collaborative organization and management issues, and the absence of a lean construction management mode suitable for China's construction industry. There is a shortage of literature on the driving factors of lean construction management implementation s, particularly concerning the influence of lean construction management driving factors on the performance of prefabricated building projects.

Furthermore, lean construction has been implemented in prefabricated building projects for visual presentation and management, optimization of perfected construction, and informed decision-making. Previous studies have also demonstrated that lean construction could contribute to enhancing the performance of prefabricated building. However, limited research has investigated the mechanism by which how lean construction management enhances the prefabricated building performance. A notable gap exists in research exploring the correlation between driving factors of lean construction management and the performance management of prefabricated building projects. As a result, the methods for enhancing the performance of prefabricated building projects remain unclear, posing significant obstacles to their wider adoption and development. Consequently, it is imperative to explore the mechanisms through which lean construction can improve the performance of prefabricated buildings.

In line with this background, this paper aims to address above issues. The novelty of this study lies in clarifying the influence of lean construction management on prefabricated building project performance by identifying driving factors for using lean construction management and performance indicators of prefabricated buildings, and investigating their relationships in prefabricated building projects. The driving mechanism of implementing lean construction in prefabricated buildings is applied to a prefabricated case. Building upon this analysis, this research proposes a pathway for enhancing the performance of prefabricated building projects grounded in the driving factors of lean construction management. The outcomes of this research can effectively address the current challenges faced by prefabricated buildings, contributing to valuable insights into the application of lean construction management in prefabricated buildings and fostering the advancement of prefabricated buildings within the construction industry.

3. Methods

To achieve the research aim, the research design is illustrated in Fig. 1:

The initial step involved identifying driving factors for lean construction management and performance indicators of prefabricated buildings through literature review and expert interviews. Then, theoretical hypotheses on the impact of these driving factors on performance indicators were formulated, and a Structural Equation Model (SEM) was constructed using data gathered from a questionnaire survey. Subsequently, a performance evaluation was conducted a representative prefabricated building project case using Fuzzy comprehensive evaluation method. Based on the findings of the lean construction management driving mechanism in prefabricated buildings, a path for enhancing the performance of prefabricated building projects is proposed from the perspective of driving factors.

3.1. Identifying driving factors and performance indicators

The implementation of prefabricated building projects involves decision-making design, production and procurement, transportation management, and construction and assembly. Accordingly, this study identifies the driving factors of lean construction management in prefabricated buildings across five dimensions: lean decision-making design, lean production and procurement, lean transportation management, lean construction and assembly, and lean project organization and management. Initially, literature

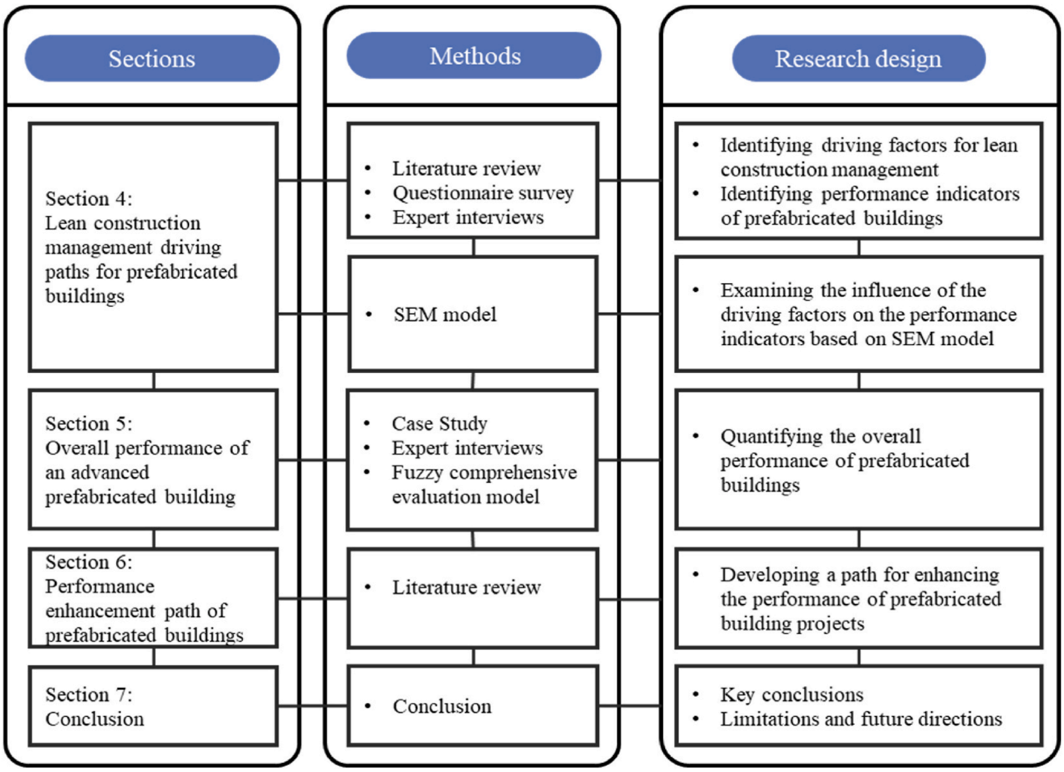

Fig. 1. Research design of this study.

related to obstacles and constraints in the implementation of lean construction management in prefabricated buildings was examined from databases such as CNKI being the largest scholarly publication search engines in China, Web of Science, and Scopus as they cover critically influential abstract and citation databases in construction field [43]. Then, a full search of lean - and prefabricated construction-related papers published in these databases from 2013 to December 2023 was conducted. The key words and phrases used in literature search were: (prefabricated OR offsite OR modular OR industrialized OR precast) AND (lean principle OR lean practice OR lean management OR lean manufacturing OR value stream mapping) AND (construction OR housing OR building OR component). The literature retrieval results are limited to journal articles. There are 280, 168 and 104 journal articles initially obtained from Scopus, Web of Science and CNKI respectively. Subsequently, by comparing the articles between the three databases and removing the duplicated articles, 221 research articles were selected for further analysis. Having examined the identified articles, initial factors associated with the driving factors of lean construction management implementation in prefabricated buildings were identified. Subsequently, through expert interviews with leaders, technicians, and scholars from real estate development enterprises, construction units, and universities, the initially identified factors were refined and supplemented. Online questionnaires were predominantly used for interviews. The study concludes by presenting a comprehensive list of driving factors for implementing lean construction management in prefabricated building projects.

This study categorizes the performance of prefabricated buildings into four dimensions: schedule performance, quality performance, cost performance, and safety performance. Using the literature research method, performance indicators for prefabricated building projects were identified. The research literature on the schedule, quality, cost, and safety performance of prefabricated building projects was retrieved from the same databases used for collecting information on the driving factors in the implementation of lean construction management. A comprehensive review and analysis of the literature led to the classification and detailed summarization of second-level performance indicators under each of the four primary indicators. This process yielded a set of performance indicators for prefabricated building projects, including their specific components.

3.2. Examining the influence of the driving factors on the performance indicators based on SEM

The SEM method is a linear equation method based the covariance matrix. It is employed to explore the causal relationships among latent and observed variables in complex phenomena. Unlike traditional modelling methods focused on single variables, SEM adeptly handles multiple latent variables by integrating linear regression, path analysis, and factor analysis [44]. This method has been widely utilized in the field of prefabricated building and lean construction [45,46]. Consequently, this paper utilizes the SEM to explore the causal links between driving factors of lean construction management implementation and the performance of prefabricated building projects.

To gather actual data for SEM model operation and simulation, a questionnaire survey method was employed. The questionnaire, designed using the Likert 5-point scale method, was distributed to professionals, experts, and scholars in the construction field for responses. The questionnaire comprises two parts: the first part gathers basic information about the respondents, including the nature of the respondent's unit, years of experience in prefabricated building or lean construction projects, education level, position, and understanding of prefabricated building or lean construction ideas. The second part involves the scale of the driving factors and project performance questionnaire for implementing lean construction management in prefabricated buildings in China. This includes the evaluation scale for driving factors and the performance evaluation scale for prefabricated buildings, presented in the form of a 5-point Likert scale. While SEM models can perform well with 50–100 samples, a conservative approach suggests collecting at least 200 samples [47]. Another study found that out of 84 SEM applications in construction, 26 models had less than100 samples, 39 models had 100 to 200 samples, and 19 models had over 200 samples [48].

3.3. Quantifying the overall performance of prefabricated buildings

Subsequently, the overall performance of prefabricated buildings was evaluated using the fuzzy comprehensive evaluation method, a technique grounded in fuzzy mathematical theory for quantitative and systematic evaluation of subjects affected by multiple challenging-to-quantify factors [49]. The fundamental principle involves dissecting the subject into various aspects and employing fuzzy mathematical theory to comprehensively evaluate primary and higher-level indicators [45]. The method involves the following steps.

(1) Establish an evaluation index set and the corresponding evaluation index based on the hierarchical structure of the evaluation
(2) Determine the set of comments (V), representing actual results of comments made by evaluators on the subject. Quantify comments by assigning values to elements in the comment set, reflecting different levels of comments.
(3) Establish a single-factor fuzzy evaluation matrix: quantify and evaluate each factor or index individually, and then determine the membership degree of each factor or index to elements in the comment set, resulting in the fuzzy evaluation matrix Ri:

$$\mathrm{Ri} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{j1} & r_{j2} & \ldots & r_{jm} \end{bmatrix} \quad (1)$$

where m in the matrix is the number of elements of the comment set, and j is the number of second-level evaluation indicators corresponding to the first-level evaluation index i.

(4) Determine the indicator weight matrix (W), indicating the importance of each second-level evaluation index corresponding to the first-level index. The weights for the performance indicators of prefabricated buildings were determined using the mean square deviation method and standardized path coefficients. The variance of the first-level performance index for the prefabricated building project is derived from the SEM model. Subsequently, the mean square deviation of the first-level performance index is calculated by taking the arithmetic square root of the variance. This mean square deviation is then normalized to obtain the weight of the first-level performance index. The standardized path coefficient is utilized to determine the weight of the second-level evaluation index.
(5) Analysis of comprehensive evaluation results: Multiply the weight matrix of second-level evaluation indices by the corresponding one-factor fuzzy evaluation matrix Ri to obtain the single-factor fuzzy comprehensive evaluation result matrix Bi. Multiply the weight matrix W of first-level indices by the one-factor fuzzy comprehensive evaluation result matrices Bi to derive the final fuzzy comprehensive evaluation result matrix A, which is shown in Equation (2).

$$\mathrm{A} = \mathrm{W} * \mathrm{B} = [\mathrm{w}_1 , \mathrm{w}_2 , \cdots , \mathrm{w}_\mathrm{i}] * \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_i \end{bmatrix} \tag{2}$$

Finally, the obtained fuzzy comprehensive evaluation result matrix A is multiplied by the transpose matrix VT of the predetermined comment set V to obtain the ultimate fuzzy comprehensive evaluation value F, as shown in Equation (3):

$$\left(\mathrm{F} = \mathrm{A} * \mathrm{V}^\mathrm{T}\right) \tag{3}$$

4. Lean construction management driving paths for prefabricated buildings

In this section, we identify the driving factors and performance indicators essential for implementing lean construction management in prefabricated building projects. Subsequently, we establish the SEM theoretical framework for the driving mechanism of lean construction management in prefabricated building projects. The SEM model undergoes testing and refinement through data collected via questionnaire surveys, leading to the development of the final structural equation model for the driving mechanism of lean construction management in prefabricated building projects.

4.1. *Identified driving factors for lean construction management*

Initially, 18 driving factors for the implementation of lean construction management in prefabricated buildings were identified through literature review, as shown in Table 1. Then, to enhance this list, expert interviews were conducted with 5 selected individuals from real estate development enterprises, construction units, universities, and other construction industry leaders, technicians, experts, and scholars. All participants have actively engaged in prefabricated building projects or conducted research in the field of prefabricated buildings and lean construction. The interview records are displayed in the form in Appendix A. An additional five driving factors were identified through the interview: modular collaborative design of project implementation plan, reduction of

Table 1
Driving factors for lean construction management in prefabricated buildings.

Classification of indicators			Specific metrics	
No.	Primary drivers	Source	No.	Secondary drivers
D1	Lean decision-making design	(S. [54–57])	D1R1	Accurate positioning and lean evaluation of the project
			D1R2	Identification of project product market demand
			D1R3	Lean and standardized design of components and moulds
			D1R4	Modular collaborative design of the project implementation plan
D2	Lean production procurement	[8,55,58,59]	D2R1	Component production plant standardization and punctual pulling
			D2R2	Lean procurement on time and on demand
			D2R3	Lean and perfect supply chain management
			D2R4	Reduce production procurement costs
D3	Lean transportation management	[59–61]	D3R1	Reduce the distance and cost of component transportation
			D3R2	Specialization of component transport vehicles
			D3R3	Real-time and efficient transportation of components
			D3R4	Lean transportation program plan
D4	Lean construction and assembly	[8,55,59]	D4R1	Reduce construction and assembly costs and eliminate waste
			D4R2	Punctual pull and modular parallel construction
			D4R3	Mechanization and standardization of construction and assembly
			D4R4	Prefabricated integrated hardcover construction
			D4R5	Lean construction assembly technology and management technology
D5	Lean project organization management	[28,29,62]	D5R1	The internal performance incentive mechanism of the project organization
			D5R2	The project organizes lean culture and lean training
			D5R3	Support from senior management of the project organization
			D5R4	Organize information communication and sharing of projects
			D5R5	The quality and participation of the project organizers
			D5R6	Project organization goals driven by benefits

production and procurement costs, lean transportation program planning, lean construction assembly technology and management technology, and project organization goal benefit drive. The cumulative outcome consists of 23 driving factors, organized across five levels: lean decision-making design, lean production procurement, lean transportation management, lean construction and assembly, and lean project organization and management (refer to Table 1).

4.2. Identified performance indicators of prefabricated building projects

A total of 16 performance indicators have been identified across four performance dimensions for prefabricated building projects. Each indicator is categorized into primary and secondary performance metrics. The detailed list is presented in Table 2.

4.3. SEM model of lean construction management for prefabricated building projects

4.3.1. Theoretical hypotheses on the impact of driving factors on performance indicators

The structural model aims to elucidate the internal causal relationships among latent variables. In this context, we explore the relationships between the driving factors of lean construction management implementation and the performance of prefabricated building projects. Constructing a robust structural model necessitates reasonable assumptions grounded in relevant theories and practices. Considering the current state of prefabricated buildings, we make the following assumptions about the impact of driving factors on performance indicators.

- H1: Lean decision-making design has a significant positive impact on the progress and performance of prefabricated building projects;
- H2: Lean decision-making design has a significant positive impact on the quality performance of prefabricated building projects;
- H3: Lean decision-making design has a significant positive impact on the cost performance of prefabricated building projects;
- H4: Lean decision-making design has a significant positive impact on the safety performance of prefabricated building projects;
- H5: Lean production procurement has a significant positive impact on the progress and performance of prefabricated building projects;
- H6: Lean production procurement has a significant positive impact on the quality performance of prefabricated building projects;
- H7: Lean production procurement has a significant positive impact on the cost performance of prefabricated building projects;
- H8: Lean production procurement has a significant positive impact on the safety performance of prefabricated building projects;
- H9: Lean transportation management has a significant positive impact on the progress and performance of prefabricated building projects;
- H10: Lean transportation management has a significant positive impact on the quality performance of prefabricated building projects;
- H11: Lean transportation management has a significant positive impact on the cost performance of prefabricated building projects;
- H12: Lean transportation management has a significant positive impact on the safety performance of prefabricated building projects;
- H13: Lean construction and assembly have a significant positive impact on the progress and performance of prefabricated building projects;
- H14: Lean construction and assembly have a significant positive impact on the quality performance of prefabricated building projects;
- H15: Lean construction and assembly have a significant positive impact on the cost performance of prefabricated building projects;

Table 2
List of performance indicators for prefabricated building projects.

Classification of indicators			Specific metrics	
No.	Primary performance indicators	Source	No.	Secondary performance indicators
P1	Progress performance	[17,63]	P1R1	The level of risk management and control of the project schedule and the efficiency of plan completion
			P1R2	Efficiency of the implementation schedule of the whole cycle process of prefabricated components
			P1R3	Timeliness and sharing of information and data
			P1R4	Schedule, efficiency, and timeliness of resource allocation
P2	Quality performance	[64,65]	P2R1	The degree of standardization of the project design and implementation plan
			P2R2	The quality management level of the whole cycle process of prefabricated components
			P2R3	Proficiency in the application of construction technology and professional equipment
			P2R4	The acceptance rate and standardization of the construction quality of the project
P3	Cost performance	[48,66,67]	P3R1	The utilization rate of materials, equipment and funds required for the project
			P3R2	The cost control effect of the whole cycle implementation process of the prefabricated components of the project
			P3R3	The level of investment cost control of project organization and operation management
			P3R4	Ability to control project cost budgeting and settlement
P4	Safety performance	(J. [67, 68])	P4R1	The level of safety management and control at the project site
			P4R2	Safety inspection and maintenance of project machinery and equipment
			P4R3	Safety training and safety awareness of project site personnel
			P4R4	The degree of standardization of the safety specifications and management system of the project site

- H16: Lean construction and assembly have a significant positive impact on the safety performance of prefabricated building projects;
- H17: Lean project organization and management has a significant positive impact on the progress and performance of prefabricated building projects;
- H18: Lean project organization and management has a significant positive impact on the quality performance of prefabricated building projects;
- H19: Lean project organization and management has a significant positive impact on the cost performance of prefabricated building projects;
- H20: Lean project organization and management has a significant positive impact on the safety performance of prefabricated building projects;

4.3.2. Questionnaire survey data

A total of 468 questionnaires were initially collected from the distributed surveys in this study. After excluding questionnaires with identical responses and significantly distorted information, a total of 430 valid questionnaires remained. Respondents from universities, construction units, design units, prefabricated component production suppliers, engineering consulting units, and construction units account for 21.86 %, 18.84 %, 16.74 %, 15.35 %, 10.23 %, and 10 %, respectively. This distribution ensures a comprehensive coverage of key stakeholders in the construction industry, enhancing the reliability of the questionnaire results.

Moreover, the questionnaire data underwent a rigorous examination, encompassing reliability and validity tests:

Reliability test: Cronbach's alpha coefficient (α), a standard measure for assessing internal reliability, was employed to evaluate the questionnaire data. The calculated results are provided in Appendix B-1. It is observed from the calculated results that the overall Cronbach's Alpha coefficient among latent variables is 0.947, which exceeds the threshold of 0.7, indicating a high level of internal consistency. Additionally, each latent variable's Cronbach's Alpha coefficient surpasses 0.7 individually. These outcomes affirm that the scale exhibits a high level of internal consistency and reliability in measuring the latent variables. Consequently, the sample data in this study are considered reliable.

Validity test: Validity consists of content and structural validity. Content validity was ensured by expert judgments and statistical analysis. According to experts, the questionnaire covers all aspects of the research questions, indicating good content validity. Statistical analysis using SPSS 25.0 software assessed principal component contributions and total variance contributions. The results are presented in Appendix B-2. Typically, the cumulative contribution rate of the principal components extracted when conducting factor analysis using SPSS software on collected sample data should not be less than 60 % [50]. From the results in Appendix B-2, it can be observed that a total of 8 common factors were extracted, and these 8 common factors collectively explained 66.03 % of the variance in all variables of the sample data. This exceeds the acceptable criterion of 60 %, demonstrating that the content validity test of the survey questionnaire sample data has passed successfully.

For structural validity, exploratory factor analysis was conducted to evaluate the independence of each index. Before factor analysis, the data underwent Bartlett's sphericity test and the Kaiser-Meyer-Olkin (KMO) test. A KMO value above 0.7 and a Bartlett's sphericity test Sig value less than 0.05 are considered suitable for factor analysis. The results of the Bartlett's sphericity test and the KMO test are summarized in Appendix B-3. As shown in this table, the KMO value for the sample data is 0.941, exceeding the threshold of 0.7. Simultaneously, the significance probability (Sig) value for Bartlett's Sphericity Test is 0.000, which is less than 0.05. These results indicate that the sample data is highly suitable for factor analysis. Subsequently, SPSS 25.0 software was employed to conduct structural validity. The rotated component matrix was computed, and the corresponding coefficients were sorted based on their magnitudes. The results are presented in Appendix B-4. Typically, for structural validity in the social science research field, if the factor loading value is greater than 0.4, the structural validity of the questionnaire is considered acceptable [51]. As observed in Appendix B-4, the factor loading values in the rotated component matrix range from 0.402 to 0.816, all exceeding the standard test value of 0.4. This indicates that the data meets the criteria for structural validity testing. Therefore, both the reliability and validity tests of the questionnaire data have passed, meeting the requirements for further analysis.

4.3.3. SEM model

Upon using the questionnaire data, an initial SEM model was developed. However, three paths, namely "D1→P4, D2→P4, and D3→P4", exhibited insignificance between the driving factors and performance indicators. In other words, the impact paths of lean decision-making design (D1), lean production and procurement (D2), and lean transportation management (D3) on the safety performance (P4) in prefabricated building projects were deemed unqualified. To improve the fit indices, these three paths were removed.

Table 3
Results of the modified fit test of the SEM model.

Model	RMSEA	GFI	NFI	CFI	PNFI	CMIN/DF
Default model	**0.025**	**0.908**	**0.906**	**0.978**	**0.826**	**1.276**
Saturated model	/	1.000	1.000	1.000	0.000	/
Independence model	0.163	0.195	0.000	0.000	0.000	12.435

Note: RMSEA <0.05, excellent; <0.08, good.
GFI: >0.9, Passed.
CFI: >0.9, Passed.
PNFI>0.5, Passed.
CMIN/DF < 3.00, Passed.

Subsequently, individual re-evaluation of the paths, SEM model suitability tests, and significance tests for all paths were conducted. As recommended by McDonald and Ho [52] who surveyed articles using SEM from 1995 to 1997, there are four key rules of the selection of model fit evaluation indices: (1) The selection principles of evaluation indices cannot be rigorously validated by existing empirical evidence; (2) The relative merits of different evaluation indices remain inconclusive; (3) The selection of model fit evaluation indices should be grounded in relevant theoretical foundations and the specific models; and (4) The assessment of model fit is highly susceptible to errors arising from model boundary conditions. Although an abundance of indices has been developed as measures of the goodness of fit, this research selected 6 commonly used indicators based on the rules and the specifics of this case, including the comparative fit index (CFI), the root mean square error of approximation (RMSEA), the goodness-of-fit index (GFI), and the normed fit index (NFI), the Parsimony-Adjusted Normed Fit Index (PNFI), and the Chi-Square/Degrees of Freedom Ratio (CMIN/DF). The evaluation yielded satisfactory results, as outlined in Table 3.

According to Table 3, the RMSEA is below 0.05, while GFI, NFI, and CFI all exceed 0.9. Moreover, PNFI surpasses 0.5, and CMIN/DF is less than 3. These values meet the standard criteria for fit evaluation. The modified SEM model, post the removal of the three unwarranted paths, successfully passed the suitability test and the significance test for all paths. Thus, it is established as the final SEM model. Moreover, the standardized path diagram for the SEM model was obtained by utilizing the standardized path coefficient estimation module in AMOS 22.0 software. The standardized path coefficients on the path lines represent the strength of the influence relationships between the paths, as depicted in Fig. 2.

After developing the SEM model, a systematic verification of the 20 research hypotheses was conducted. The results are presented in Table 4, illustrating the outcomes of hypothesis testing within the SEM model for the influence of lean construction management on

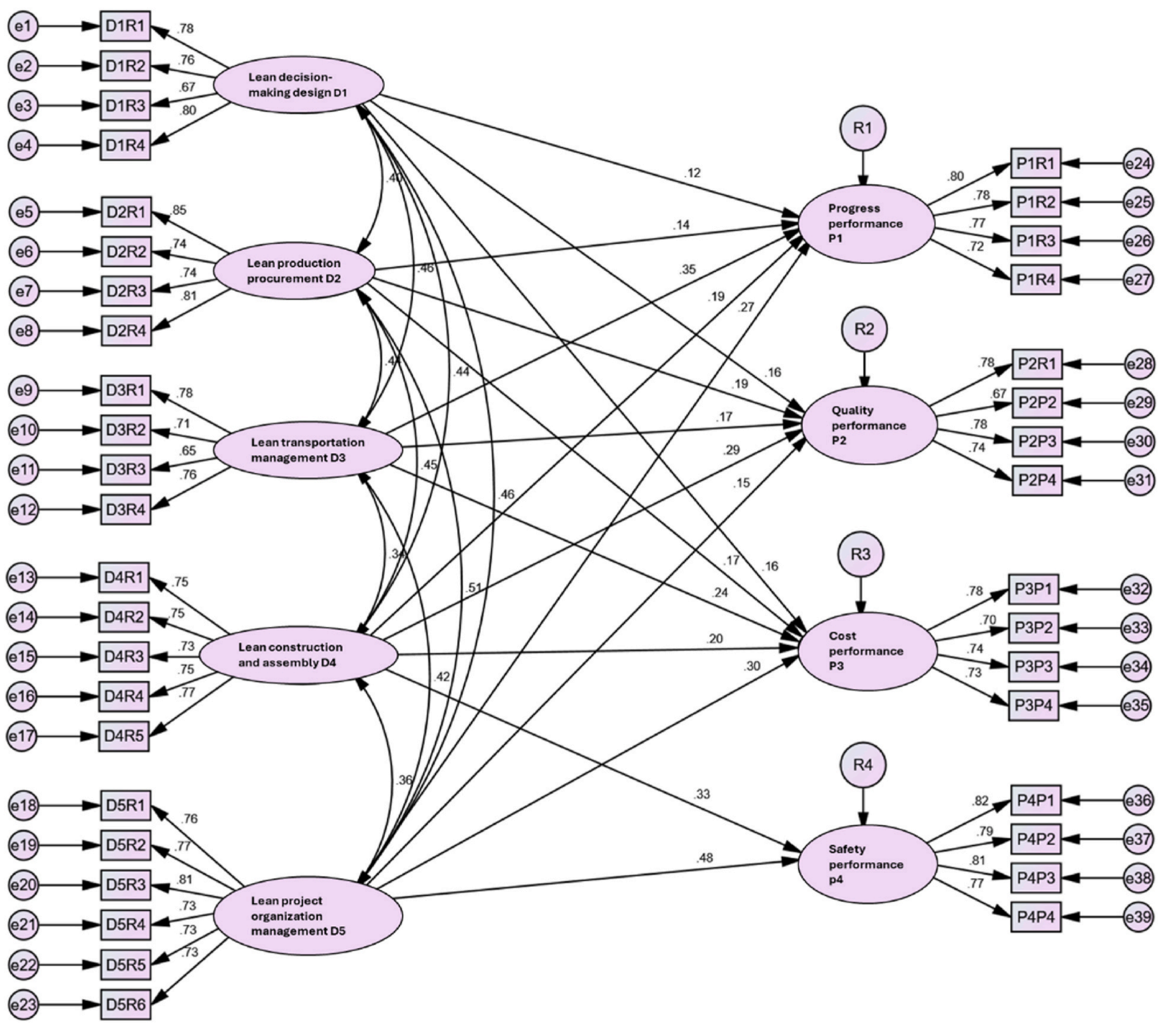

Fig. 2. Standardized path diagram of the SEM model.

Table 4
Hypothesis testing within the SEM model.

hypothetical paths	Performance indicators	correlation	Driving factors	Normalized parameter estimates	S.E.	C.R.	P
H1	P1	←	D1	0.122	0.051	2.292	0.022
H2	P2	←	D1	0.157	0.058	2.634	0.008
H3	P3	←	D1	0.160	0.052	2.915	0.004
H4	P4	←	D1	/	/	/	/
H5	P1	←	D2	0.145	0.044	2.723	0.006
H6	P2	←	D2	0.188	0.05	3.15	0.002
H7	P3	←	D2	0.173	0.046	3.153	0.002
H8	P4	←	D2	/	/	/	/
H9	P1	←	D3	0.346	0.052	6.303	
H10	P2	←	D3	0.169	0.056	2.897	0.004
H11	P3	←	D3	0.239	0.051	4.401	
H12	P4	←	D3	/	/	/	/
H13	P1	←	D4	0.192	0.056	3.848	
H14	P2	←	D4	0.293	0.065	5.141	
H15	P3	←	D4	0.196	0.057	3.827	
H16	P4	←	D4	0.332	0.059	6.476	
H17	P1	←	D5	0.271	0.049	5.13	
H18	P2	←	D5	0.153	0.054	2.66	0.008
H19	P3	←	D5	0.304	0.051	5.552	
H20	P4	←	D5	0.484	0.052	9.029	

Note.
1S.E.: Approximate standard error.
2C.R.: Critical ratio, which is the ratio of the parameter estimate to the estimated standard error. When the absolute value of C.R. is greater than 1.96, the parameter estimate reaches the 0.05 significance level.
3P: Significance probability value. If P-value is less than 0.001, the output in the P-value column will be displayed as "***." Conversely, if the P-value is greater than 0.001, the numerical result will be directly output.

the performance of prefabricated buildings.

As shown in Table 4, except for the three deleted paths (H4, H8 and H12) which are unqualified, the S.E., C.R., and P values corresponding to the remaining 17 hypotheses all adhere to the standards (i.e., S.E. < 0.95, C.R. > 1.96, and P < 0.05). Therefore, testing results of the 20 hypotheses are presented as follows.

4.3.4. Analysis the degree of influence of driving factors on performance indicators

In accordance with Table 5, to investigate the extent to which each driving factor influences performance indicators, Fig. 3 has been generated.

The findings from Fig. 3 reveal the varying degrees of impact that different driving factors have on performance indicators in prefabricated building projects. Regarding the progress performance of perfricated building projects (P1), Lean Transportation

Table 5
Hypothesis testing results.

No.	Hypothesis	Testing results
H1	Lean decision-making design has a significant positive impact on the progress performance of prefabricated building projects	validated
H2	Lean decision-making design has a significant positive impact on the quality performance of prefabricated building projects	validated
H3	Lean decision-making design has a significant positive impact on the cost performance of prefabricated building projects	validated
H4	Lean decision-making design has a significant positive impact on the safety performance of prefabricated building projects	not validated
H5	Lean production procurement has a significant positive impact on the progress performance of prefabricated building projects	validated
H6	Lean production procurement has a significant positive impact on the quality performance of prefabricated building projects	validated
H7	Lean production procurement has a significant positive impact on the cost performance of prefabricated building projects	validated
H8	Lean production procurement has a significant positive impact on the safety performance of prefabricated building projects	not validated
H9	Lean transportation management has a significant positive impact on the progress performance of prefabricated building projects	validated
H10	Lean transportation management has a significant positive impact on the quality performance of prefabricated building projects	validated
H11	Lean transportation management has a significant positive impact on the cost performance of prefabricated building projects	validated
H12	Lean transportation management has a significant positive impact on the safety performance of prefabricated building projects	not validated
H13	Lean construction and assembly have a significant positive impact on the progress performance of prefabricated building projects	validated
H14	Lean construction assembly has a significant positive impact on the quality performance of prefabricated building projects	validated
H15	Lean construction assembly has a significant positive impact on the cost performance of prefabricated building projects	validated
H16	Lean construction and assembly have a significant positive impact on the safety performance of prefabricated building projects	validated
H17	Lean project organization and management has a significant positive impact on the progress performance of prefabricated building projects	validated
H18	Lean project organization and management has a significant positive impact on the quality performance of prefabricated building projects	validated
H19	Lean project organization and management have a significant positive impact on the cost performance of prefabricated building projects	validated
H20	Lean project organization and management have a significant positive impact on the safety performance of prefabricated building projects	validated

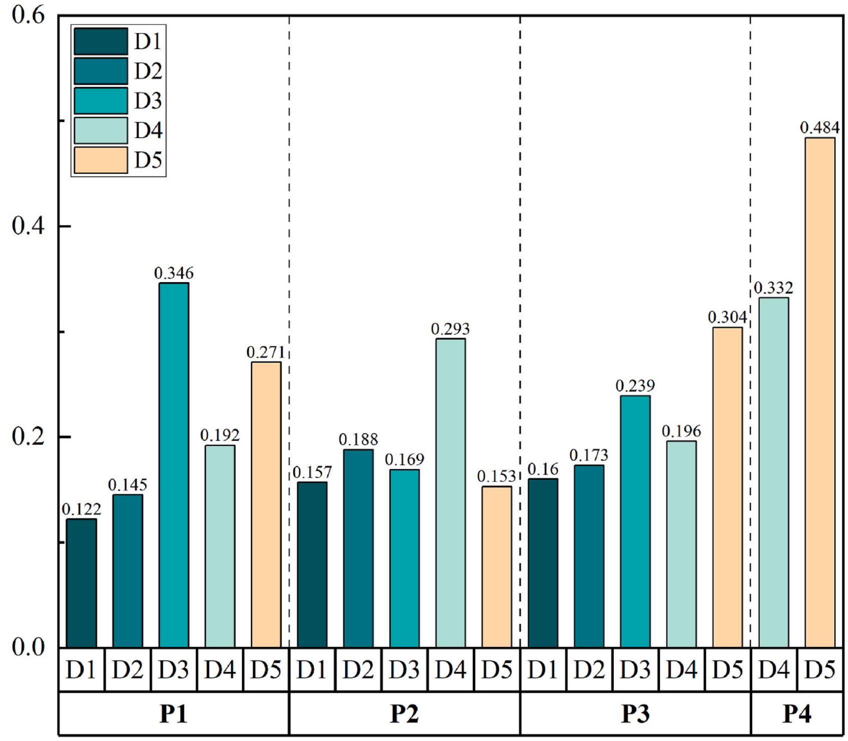

Fig. 3. Histogram of performance indicators influenced by each driving factor.

Management (D3) has the greatest positive impact, while Lean decision-making design (D1) has the least influence. In terms of quality performance (P2), Lean Construction and Assembly (D4) is the factor with the greatest influence on enhancing the quality performance of prefabricated building projects. Despite the least influence produced by Lean project organization management (D5), its degree of influence on quality performance is slightly lower than that of the other three driving factors, namely Lean decision-making design (D1), Lean production procurement (D2), Lean transportation management (D3). Regarding cost performance (P3), the greatest driving factor is Lean Project Organization and Management (D5), while the driving factor with the least positive impact is Lean decision-making design (D1). When it comes to safety performance (P4), three driving factors, namely Lean decision-making design (D1), Lean production procurement (D2), Lean transportation management (D3) exhibit insignificance in enhancing safety performance of prefabricated buildings. Moreover, Lean Project Organization and Management (D5) has greater impact than that of Lean Construction and Assembly (D4).

4.3.5. Key driving factors

Identification of key driving factors is primarily based on the magnitude of the normalized path coefficient. Normalized path coefficients can exert varying degrees of influence on results across different research fields, and a universally accepted standard

Table 6
Key driving factors of lean construction management in prefabricated buildings.

Key driving factors for the implementation of lean construction management in prefabricated buildings		Normalized path coefficients
Lean decision-making design (D1)	Accurate positioning and lean evaluation of the project (D1R1)	0.780
	Identification of project product market demand (D1R2)	0.756
	Modular collaborative design of the project implementation plan (D1R4)	0.795
Lean Production Procurement (D2)	Component production plant standardization and punctual pulling (D2R1)	0.846
	Reduce production procurement costs (D2R4)	0.809
Lean Transportation Management (D3)	Reduce the distance and cost of component transportation (D3R1)	0.775
	Lean transportation program plan (D3R4)	0.759
Lean construction assembly (D4)	Reduce construction and assembly costs and eliminate waste (D4R1)	0.751
	Punctual pull and modular parallel construction (D4R2)	0.752
	Lean construction assembly technology and management technology (D4R5)	0.774
Lean Project Organization and Management (D5)	The internal performance incentive mechanism of the project organization (D5R1)	0.763
	The project organizes lean culture and lean training (D5R2)	0.773
	Support from senior management of the project organization (D5R3)	0.808

definition for coefficients and their influence is lacking. Nevertheless, Cohen [53] offered a reference standard based on his research experience. He proposed classifying normalized path coefficients into three grades: large (0.3–1.0), medium (0.2–0.3), and small (0–0.2). Cohen also emphasized that researchers should make specific adjustments according to the actual research context. Therefore, based on the standardized path coefficients from observed variables to each latent variable obtained from the SEM model, the driving factors in the measurement model are grouped into different levels: first-level drivers (0.75–1.0), second-level drivers (0.7–0.75), and third-level drivers (0–0.7). The results are presented in Table 5. Factors classified as first-level driver are identified as key driving factors, resulting in a total of 13 key driving factors, as shown in Table 6.

5. Overall performance of an advanced prefabricated building

In this section, the performance of a selected prefabricated building is evaluated by employing the fuzzy comprehensive evaluation method. The chosen case for evaluation is Yujing Happy Home project located in Pingshan District, Shenzhen, Guangdong Province, China. The selection criteria were based on the project's leading overall prefabrication and assembly rates among the completed prefabricated construction projects in Shenzhen, as well as its designation as a nationally recognized exemplary prefabricated building project. This renders it particularly representative for the purposes of understanding the performance of an advanced prefabricated building in this study.

5.1. Project overview

The Yujing Happy Home Project, a social housing in Shenzhen, carries a project budget estimated at 316.5 million yuan. The project is a showcase project for the Ministry of Housing and Urban Rural Development of the People's republic of China and its details are collected from the website of Shenzhen Huayang International Engineering Design Co., Ltd. and China Construction Science & Technology Group CO., LTD. This building has a total floor area of 64,000 square meters, with 48,000 square meters implementing prefabricated construction. The prefabrication rate is 48 %, and the assembly rate is 70 %. The prefabricated components include prefabricated shear walls, external wall panels, interior walls, laminated beams, laminated floor slabs, balcony panels, staircases, and mixed interior partition panels.

5.2. Single-factor evaluation matrix for prefabricated building performance

The paper categorizes the performance levels of prefabricated building projects into five grades, ranging from low to high, denoted as: V=(V1, V2, V3, V4, V5) = (not high, not too high, average, relatively high, very high). The corresponding numerical values and their ranges of each grade are shown in Table 7.

To ensure the accuracy of the evaluation in this study, 10 experts in the field of prefabricated buildings were invited to conduct a single-factor evaluation of prefabricated building project performance. The evaluation results are presented in Table 8.

Based on Table 8, the following single-factor evaluation matrix of prefabricated building project performance is established.

(1) The single-factor evaluation matrix of progress performance P1

$$R1 = \begin{bmatrix} 0 & 0.1 & 0.3 & 0.4 & 0.2 \\ 0 & 0 & 0.2 & 0.5 & 0.3 \\ 0.1 & 0.2 & 0.1 & 0.3 & 0.3 \\ 0 & 0.1 & 0.2 & 0.4 & 0.3 \end{bmatrix}$$

(2) The single-factor evaluation matrix of quality performance P2

$$R2 = \begin{bmatrix} 0.1 & 0.1 & 0.2 & 0.3 & 0.3 \\ 0 & 0.1 & 0.2 & 0.3 & 0.4 \\ 0.1 & 0.1 & 0.3 & 0.2 & 0.3 \\ 0 & 0.2 & 0.2 & 0.2 & 0.4 \end{bmatrix}$$

(3) The single-factor evaluation matrix of cost performance P3

$$R3 = \begin{bmatrix} 0.1 & 0.2 & 0.3 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.3 & 0.1 & 0.2 \\ 0.1 & 0.3 & 0.2 & 0.2 & 0.2 \\ 0.2 & 0.1 & 0.4 & 0.2 & 0.1 \end{bmatrix}$$

Table 7
Numerical range of the fuzzy comprehensive evaluation of prefabricated building performance.

Comment Collection V	Not high	Not too high	Average	Relatively high	Very high
numeric value	1	2	3	4	5

With the representation of the comment set, it is evident from Table 7 that the comment set V = (1,2,3,4,5), and the transpose matrix V^T of the comment set V = $(1,2,3,4,5)^T$.

Table 8
Experts' scoring results of the prefabricated building performance.

Level 1 performance indicators	Secondary performance indicators		count for each performance level				
			Not high	Not too high	Average	Relatively high	Very high
Progress performance P1	P1R1	The level of risk management and control of the project schedule and the efficiency of plan completion	0	1	3	4	2
	P1R2	Efficiency of the implementation schedule of the whole cycle process of prefabricated components	0	0	2	5	3
	P1R3	Timeliness and sharing of information and data	1	2	1	3	3
	P1R4	Schedule, efficiency, and timeliness of resource allocation	0	1	2	4	3
Quality performance P2	P2R1	The degree of standardization of the project design and implementation plan	1	1	2	3	3
	P2R2	The quality management level of the whole cycle process of prefabricated components	0	1	2	3	4
	P2R3	Proficiency in the application of construction technology and professional equipment	1	1	3	2	3
	P2R4	The acceptance rate and standardization of the construction quality of the project	0	2	2	2	4
Cost performance P3	P3R1	The utilization rate of materials, equipment and funds required for the project	1	2	3	2	2
	P3R2	The cost control effect of the whole cycle implementation process of the prefabricated components of the project	2	2	3	1	2
	P3R3	The level of investment cost control of project organization and operation management	1	3	2	2	2
	P3R4	Ability to control project cost budgeting and settlement	2	1	4	2	1
Safety performance P4	P4R1	The level of safety management and control at the project site	0	0	2	4	4
	P4R2	Safety inspection and maintenance of project machinery and equipment	0	0	1	4	5
	P4R3	Safety training and safety awareness of project site personnel	1	1	1	4	3
	P4R4	The degree of standardization of the safety specifications and management system of the project site	0	1	2	3	4

Table 9
Variance of the first-level performance indicators and the estimated standardized parameter of the second-level performance indicators.

Level 1 performance indicators	variance	Secondary performance indicators		Estimated standardized parameters
Progress performance P1	0.602	P1R1	The level of risk management and control of the project schedule and the efficiency of plan completion	0.793
		P1R2	Efficiency of the implementation schedule of the whole cycle process of prefabricated components	0.774
		P1R3	Timeliness and sharing of information and data	0.779
		P1R4	Schedule, efficiency, and timeliness of resource allocation	0.710
Quality performance P2	0.611	P2R1	The degree of standardization of the project design and implementation plan	0.774
		P2R2	The quality management level of the whole cycle process of prefabricated components	0.672
		P2R3	Proficiency in the application of construction technology and professional equipment	0.783
		P2R4	The acceptance rate and standardization of the construction quality of the project	0.737
Cost performance P3	0.605	P3R1	The utilization rate of materials, equipment and funds required for the project	0.782
		P3R2	The cost control effect of the whole cycle implementation process of the prefabricated components of the project	0.695
		P3R3	The level of investment cost control of project organization and operation management	0.742
		P3R4	Ability to control project cost budgeting and settlement	0.734
Safety performance P4	0.643	P4R1	The level of safety management and control at the project site	0.825
		P4R2	Safety inspection and maintenance of project machinery and equipment	0.787
		P4R3	Safety training and safety awareness of project site personnel	0.798
		P4R4	The degree of standardization of the safety specifications and management system of the project site	0.775

(4) The single-factor evaluation matrix of safety performance P4

$$R4 = \begin{bmatrix} 0 & 0 & 0.2 & 0.4 & 0.4 \\ 0 & 0 & 0.1 & 0.4 & 0.5 \\ 0.1 & 0.1 & 0.1 & 0.4 & 0.3 \\ 0 & 0.1 & 0.2 & 0.3 & 0.4 \end{bmatrix}$$

5.3. *Weights of the performance evaluation index of the prefabricated building*

Following the methods outlined in Section 3.3 for determining the weights of the performance evaluation index for prefabricated buildings, the variance of the first-level performance indicators and the estimated standardized parameters of the second-level performance indicators could be obtained, as shown in Table 9.

As can be seen from Table 9, the variances of P1, P2, P3 and P4 are 0.602, 0.611, 0.605 and 0.643, respectively. Their mean square deviations are calculated as 0.247, 0.249, 0.248 and 0.256. In other words, the weights assigned to the four first-level performance indicators - progress performance (P1), quality performance (P2), cost performance (P3), and safety performance (P4) - are 0.247, 0.249, 0.248 and 0.256, respectively.

By normalizing the estimated standardized parameter for the second-level indicators in Table 9, the weights for the second-level indicators can be determined:

For P1: 0.260 (P1R1), 0.253 (P1R2), 0.255 (P1R3), 0.232 (P1R4);

For P2: 0.261(P2R1), 0.227(P2R2), 0.264 (P2R3), 0.248(P2R4);

For P3: 0.265 (P3R1), 0.235 (P3R2), 0.251(P3R3), 0.249 (P3R4);

For P4: 0.259 (P4R1), 0.247 (P4R2), 0.251 (P4R3), 0.243 (P4R4).

Therefore, the weight matrix can be expressed as follows:

$$W = [0.247 \quad 0.249 \quad 0.248 \quad 0.256]$$

$$W_1 = [0.260 \quad 0.253 \quad 0.255 \quad 0.232]$$

$$W_2 = [0.261 \quad 0.227 \quad 0.264 \quad 0.248]$$

$$W_3 = [0.265 \quad 0.235 \quad 0.251 \quad 0.249]$$

$$W_4 = [0.259 \quad 0.247 \quad 0.251 \quad 0.243]$$

W and Wi represent the weights of the first-level and the second-level performance evaluation indices, respectively.

5.4. *Comprehensive evaluation results of the prefabricated building performance*

Following the fuzzy comprehensive evaluation method in section 3.3, based on the single-factor evaluation matrix and corresponding weights of the performance indicators of the prefabricated building, the fuzzy comprehensive evaluation results are presented as follows:

For progress performance (P1):

$$B_1 = W_1 * R_1 = [0.026 \quad 0.100 \quad 0.201 \quad 0.400 \quad 0.274]$$

For quality performance (P2):

$$B_2 = W_2 * R_2 = [0.053 \quad 0.125 \quad 0.226 \quad 0.249 \quad 0.348]$$

For cost performance (P3):

$$B_3 = W_3 * R_3 = [0.148 \quad 0.200 \quad 0.300 \quad 0.177 \quad 0.175]$$

For safety performance (P4):

$$B_4 = W_4 * R_4 = [0.025 \quad 0.049 \quad 0.150 \quad 0.376 \quad 0.400]$$

Then, the fuzzy comprehensive evaluation result matrix of the performance of the prefabricated building can be calculated as follows:

$$A = W * B = [0.063 \quad 0.118 \quad 0.219 \quad 0.301 \quad 0.300]$$

Finally, the score of the fuzzy comprehensive evaluation result of the performance of the prefabricated building project can be calculated as:

$$F = A * V^T = 3.66$$

Where, evaluation score value of the progress performance (P1):

$F_1 = B_1 * V^T = 3.80$

Evaluation score of the quality performance (P2):

$F_2 = B_2 * V^T = 3.72$

Evaluation score of the cost performance (P3):

$F_3 = B_3 * V^T = 3.03$

Evaluation score of the safety performance (P4):

$F_4 = B_4 * V^T = 4.08$

5.5. Analysis of evaluation results

The overall evaluation score for the prefabricated building performance is 3.66, with the following breakdown: progress performance (P1) scored 3.80, quality performance (P2) scored 3.72, cost performance (P3) scored 3.03, and safety performance (P4) scored 4.08. These evaluation results are presented in the radar chart depicted in Fig. 4.

Fig. 4 indicates that the performance indicators of the prefabricated building project rank from low to high as follows: cost performance (P3), quality performance (P2), schedule performance (P1), and safety performance (P4). To enhance the overall performance of the prefabricated building project, the focus should be on improving cost performance initially. This involves reducing the overall project cost, continuously enhancing efficiency, and eliminating waste—a principle aligned with lean construction management ideology. Subsequently, attention should be directed towards improving quality performance (P2), schedule performance (P1), and safety performance (P4).

Moreover, the results suggest that there is room for improvement in the performance of prefabricated buildings in China. According to Section 4, the implementation of lean construction management can significantly enhance performance across these four areas during the execution of prefabricated buildings. Consequently, based on the driving factors identified for the implementation of lean construction management, a proposed pathway for enhancing the performance of prefabricated building projects is presented in the following section.

6. Performance enhancement path of prefabricated buildings

Building upon the identified key driving factors in Section 4, and the evaluated performance of the prefabricated building, this section promotes a specific path to enhance the performance of the prefabricated building.

6.1. Strengthening lean decision-making design

In the early stage of prefabricated building decision-making design, it is crucial to strengthen accurate project positioning and conduct lean evaluations. This involves considering factors such as national and regional policies, the regional status of prefabricated building development, the level of construction technology development, the implementation and application of lean construction management, and the expected project implementation goals. Moreover, extensive surveys should be conducted to understand user needs related to prefabricated building projects. This allows for the identification of project market demand directions for development and improvement. Considering the supply chain's upstream and downstream is essential to share information, formulate effective

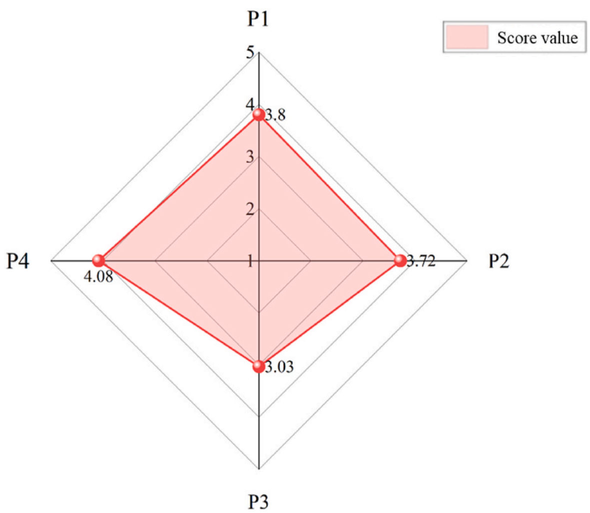

Fig. 4. The performance evaluation results of the prefabricated building.

production management plans, and achieve the goal of enhancing project quality and maximizing market demand satisfaction. Additionally, it is imperative to enhance the coordination of all parties involved in design, production and procurement, transportation, construction, and assembly stages. Utilizing the modular concept and BIM model software can be helpful.

6.2. Strengthening lean production procurement

Standardizing prefabricated components and utilizing factory production are critical. The prefabricated components and their corresponding moulds needed for production should adhere to a standardized modulus, streamlining the production process.: Moreover, it is essential to implement a demand-driven approach to manage production and procurement by promptly sharing the demands for prefabricated building components with suppliers. This demand-oriented strategy facilitates material order-pull production and just-in-time supply procurement, mitigating inventory costs resulting from potential excess. This approach enhances the cost-performance level of production and procurement. Furthermore, a market-oriented production and procurement management mechanism should be developed to enhance flexibility and timely responsiveness to market changes This ensures the timeliness of production and procurement, meets product quality standards, and reduces production and procurement costs.

6.3. Strengthening lean transportation management

The distance between the production site of prefabricated components and the construction site significantly affects the transportation costs. Presently, many prefabricated component production bases are concentrated in the eastern coastal areas of China, resulting in a longer transportation distance to reach the vast domestic market. To address this issue, it is imperative to consider factors such as transportation routes and distances based on the planned prefabricated building projects in various regions and strategically layout the production industries. Moreover, a comprehensive transportation plan should be developed in accordance with the assembly site's lifting plans the selection of transportation vehicles and routes, and guidelines for component stacking and shelving. This plan should be continually refined to enhance transportation efficiency.

6.4. Strengthening lean construction and assembly

The construction and assembly costs associated with prefabricated building projects remain high due to various inefficiencies and wastes Therefore, it is imperative to identify and address these sources of waste. In this regard, incorporating lean construction management principles into leveraging techniques such as operation cost management, standardized processes, and flow construction methods, continuous optimization and improvement of cost management practices can be achieved. Moreover, based on the characteristics of prefabricated building projects, it is critical to adopt a modular approach by dividing the project into independent module units. Prefabricated factories complete the production of different module units, and they are transported to the construction assembly site for assembly. The modular approach significantly shortens the construction period, enhances construction schedule efficiency, reduces costs, and mitigates potential safety risks during construction and assembly.

Furthermore, it is crucial to integrate lean principles and advanced technologies into the installation of prefabricated components. For example, employing technologies such as remote video monitoring systems, large-scale equipment condition monitoring, and Internet of Things (IoT) facilitates real-time dynamic monitoring of construction and assembly sites. This includes monitoring the status of construction sites and the operational status of mechanical equipment, providing real-time progress insights.

6.5. Strengthening lean project organization and management

To encourage project personnel to actively embrace lean management in prefabricated building projects, economic incentives can be established, such as increasing various welfare subsidies, salaries and bonuses. Furthermore, those with excellent and outstanding performance in lean construction management can be rewarded with job promotions or honorary titles. This recognition enhances the sense of achievement among project personnel, serving as effective internal motivation and guidance. Promoting the adoption of lean construction management in prefabricated building projects involves cultivating a lean management culture within the project organization. This can be achieved through promotion, education, advocacy, and pilot projects prefabricated building projects.

It is also imperative to provide project personnel with lean construction management training. A training plan can be developed, which covers core skills, management methods, key work progress nodes, and the implementation of lean construction management. This approach aims to improve the overall skills and quality of project organizers, facilitating the successful implementation of lean construction management in prefabricated building projects.

The successful implementation of lean construction management in prefabricated building projects relies on strong support from senior leaders at the organizational level. Senior managers within the project organization should actively engage in learning and using the principles of lean construction management in their work. In addition, senior managers should create dedicated institutions within the organization to conduct training and promote awareness of lean construction management ideologies, methods, techniques, and the associated advantages in the context of prefabricated building projects. Moreover, providing essential support for project personnel, including manpower, capital, materials, and adherence to management rules and regulations, is essential for advancing the implementation of lean construction management in prefabricated building projects.

7. Conclusion

This research has explored the implementation of lean construction management in prefabricated buildings. By employing SEM model, this study examined the casual links between the driving factors of lean construction management and the performance indicators in prefabricated buildings. Moreover, a fuzzy comprehensive evaluation method was used to assess the performance of a selected excellent prefabricated building across the four dimensions: project schedule, quality, cost and safety. Furthermore, through the analysis and research above, this paper proposes a performance enhancement path for prefabricated building projects based on the key driving factors of lean construction management. Key conclusions include.

(1) This paper identified 23 driving factors and 16 performance indicators, categorized into five dimensions: lean decision-making design, lean production and procurement, lean transportation management, lean construction and assembly, and lean project organization and management.
(2) From the SEM model, 13 key driving factors were obtained, namely: Accurate positioning and lean evaluation of the project (D1R1), Identification of project product market demand (D1R2), Modular collaborative design of the project implementation plan (D1R4), Component production plant standardization and punctual pulling (D2R1), Reduce production procurement costs (D2R4), Reduce the distance and cost of component transportation (D3R1), Lean transportation program plan (D3R4), Reduce construction and assembly costs and eliminate waste (D4R1), Punctual pull and modular parallel construction (D4R2), Lean construction assembly technology and management technology (D4R5), The internal performance incentive mechanism of the project organization (D5R1), The project organizes lean culture and lean training (D5R2) and Support from senior management of the project organization (D5R3).
(3) It was concluded that the prefabricated building performance needs for improvement, with cost performance ranking lowest, followed by quality, schedule, and safety performances.
(4) This paper proposes a performance enhancement path for prefabricated buildings in terms of the five driving factors of lean construction management: (1) In terms of lean decision-making design path, we should enhance accurate positioning and lean evaluation, reinforce identification of project product market demand, and strengthen modular collaborative design in project implementation plans; (2) In terms of lean production procurement path, we need to implement standardized factory component production management, establish a demand-driven production and procurement management mechanism and strengthen management of external strategic resources in production and procurement; (3) In terms of lean transportation management path, we need to enhance production industry chain layout for reduced transportation distance and develop and refine lean transportation plans; (4) At the level of lean construction and assembly path, we will continue to minimize construction and assembly costs and eliminate waste and implement just-in-time production and modular parallel construction; and (5) At the level of lean project organization and management path, we need to improve the internal performance incentive mechanism, foster a lean management culture and conduct lean construction management training, and leverage senior management's leadership and exemplary role.

Despite the valuable insights provided, certain limitations in this study necessitate consideration for future research. Firstly, the absence of direct literature on influencing factors for implementing lean construction management in prefabricated buildings prompted the reliance on literature discussing obstacles in lean construction management plans. To enhance accuracy, future research should focus on directly relevant literature, thereby refining the identification of driving factors. In addition, project management performance includes project quality, schedule, cos, safety, stakeholder management, risk etc. This study primarily focuses on the performance factors of cost, quality, schedule and safety. Future work could be implemented to incorporate other performance factors. Moreover, the intricacies of the SEM model network introduce complexity, warranting further exploration of mediating effects within the driving mechanisms. Investigating how these factors influence the performance indicators of prefabricated building projects through mediating effects is crucial for a more nuanced understanding. Furthermore, the study's reliance on a single case, while representative of state-of-the-art prefabricated buildings, calls for a more extensive analysis. Including cases with varying performance levels, including those considered poor or average, would offer a comprehensive view and contribute to the development paths of diverse prefabricated building projects. Despite the highlighted limitations, it's noteworthy that the development path proposed based on the best-performing prefabricated building remains applicable to projects at other performance levels. This adaptability underscores the robustness of the proposed strategies and suggests their potential efficacy across a spectrum of prefabricated building projects.

CRediT authorship contribution statement

Clyde Zhengdao Li: Supervision, Conceptualization. **Vivian WY. Tam:** Writing – review & editing. **Mingcong Hu:** Writing – original draft. **Yijun Zhou:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Appendix A: Supplementary interview record form of driving factors.

Basic information about the interviewer	Name	Organization Interview date
Basic information about the experts	Name	Organization Occupation Year of work experience
Apart from the driving factors listed below, what additional factors do you believe contribute to the implementation of lean construction management in prefabricated building projects?		
No.	Categories	Driving factors
1	Lean decision-making design	Accurate positioning and lean evaluation of the project
2		Identification of project product market demand
3		Lean and standardized design of components and moulds
4		
5	Lean production procurement	Component production plant standardization and punctual pulling
6		Lean procurement on time and on demand
7		Lean and perfect supply chain management
8		
9	Lean transportation management	Reduce the distance and cost of component transportation
10		Specialization of component transport vehicles
11		Real-time and efficient transportation of components
12		
13	Lean construction and assembly	Reduce construction and assembly costs and eliminate waste
14		Punctual pull and modular parallel construction
15		Mechanization and standardization of construction and assembly
16		Prefabricated integrated hardcover construction
17		
18	Lean project organization management	The internal performance incentive mechanism of the project organization
19		The project organizes lean culture and lean training
20		Support from senior management of the project organization
21		Organize information communication and sharing of projects
22		The quality and participation of the project organizers
23		

Appendix B

Table B1
Cronbach's Alpha Coefficient

Potential variables	Cronbach's Alpha	No. of specific metrics
Lean decision-making design D1	0.837	4
Lean production procurement D2	0.862	4
Lean transportation management D3	0.809	4
Lean construction and assembly D4	0.865	5
Lean project organization management D5	0.888	6
Progress performance P1	0.848	4
Quality performance P2	0.829	4
Cost performance P3	0.827	4
Safety performance P4	0.873	4
Total	0.947	39

Table B2
Principal Component Eigenvalues and Variance

Total Variance Explained									
Component	Initial Eigenvalues			Sum of Squared Loadings			Rotated Sum of Squared Loadings		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
1	13.001	33.336	33.336	13.001	33.336	33.336	4.716	12.092	12.092
2	2.524	6.471	39.807	2.524	6.471	39.807	3.842	9.852	21.944
3	2.246	5.759	45.565	2.246	5.759	45.565	3.442	8.827	30.770

(*continued on next page*)

Table B2 (*continued*)

Total Variance Explained									
Component	Initial Eigenvalues			Sum of Squared Loadings			Rotated Sum of Squared Loadings		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
4	1.833	4.700	50.266	1.833	4.700	50.266	3.199	8.204	38.974
5	1.774	4.549	54.814	1.774	4.549	54.814	3.033	7.777	46.751
6	1.660	4.257	59.071	1.660	4.257	59.071	2.861	7.335	54.086
7	1.518	3.892	62.963	1.518	3.892	62.963	2.565	6.577	60.663
8	1.196	3.067	66.030	1.196	3.067	66.030	2.093	5.367	66.030
9	0.785	2.012	68.043						
10	0.669	1.715	69.758						
11	0.644	1.652	71.409						
12	0.624	1.600	73.010						
13	0.591	1.514	74.524						
14	0.569	1.460	75.984						
15	0.560	1.435	77.418						
16	0.548	1.406	78.825						
17	0.515	1.322	80.146						
18	0.498	1.276	81.422						
19	0.485	1.243	82.665						
20	0.479	1.229	83.894						
21	0.437	1.122	85.016						
22	0.434	1.112	86.128						
23	0.407	1.045	87.173						
24	0.402	1.031	88.204						
25	0.388	0.996	89.199						
26	0.367	0.940	90.139						
27	0.362	0.929	91.068						
28	0.354	0.908	91.976						
29	0.341	0.874	92.850						
30	0.327	0.839	93.689						
31	0.323	0.827	94.516						
32	0.314	0.804	95.321						
33	0.304	0.780	96.101						
34	0.289	0.742	96.842						
35	0.268	0.687	97.529						
36	0.264	0.677	98.206						
37	0.255	0.655	98.860						
38	0.232	0.594	99.454						
39	0.213	0.546	100.000						

Table B3
KMO and Bartlett's Sphericity Test Results

KMO Sampling Adequacy Measure		0.941
Bartlett's Test of Sphericity	Approximate Chi-Square	8917.057
	Degrees of Freedom	741
	Significance (Sig)	0.000

Table B4
Rotated Component Matrix

Component								
Variable	1	2	3	4	5	6	7	8
D5R5	**0.767**	0.081	0.090	0.032	0.078	0.170	0.017	0.070
D5R3	**0.745**	0.126	0.157	0.159	0.095	0.170	0.133	0.106
D5R1	**0.732**	0.012	0.028	0.200	0.135	0.187	0.089	0.122
D5R2	**0.714**	0.103	0.132	0.042	0.104	0.161	0.177	0.236
D5R4	**0.708**	0.072	0.030	0.141	0.125	0.142	0.155	0.117
D5R6	**0.706**	0.006	0.075	0.130	0.058	0.188	0.165	0.175
P3R2	**0.417**	0.331	0.363	0.251	0.305	−0.092	−0.055	−0.269
D4R5	0.104	**0.785**	0.096	0.065	0.052	0.110	0.141	0.097
D4R1	0.062	**0.755**	0.027	0.126	0.063	0.176	0.109	0.112
D4R3	0.057	**0.752**	0.130	0.048	0.118	0.146	0.097	0.091
D4R4	0.082	**0.716**	−0.043	0.173	0.163	0.133	0.163	0.141
D4R2	0.076	**0.715**	0.103	0.113	0.123	0.110	0.216	0.111
D3R1	0.145	0.097	**0.752**	0.028	0.096	0.125	0.112	0.161
D3R4	0.008	0.048	**0.744**	0.124	0.127	0.104	0.127	0.180
D3R2	0.111	0.045	**0.698**	0.187	0.071	0.066	0.145	0.171
D3R3	0.065	−0.002	**0.668**	0.008	0.097	0.130	0.207	0.194

(continued on next page)

Table B4 (*continued*)

Component								
Variable	1	2	3	4	5	6	7	8
P3R4	0.386	0.339	**0.440**	0.221	0.201	−0.074	0.125	−0.200
P3R3	0.398	0.260	**0.426**	0.278	0.269	0.017	0.011	−0.159
P3R1	0.386	0.332	**0.402**	0.362	0.220	0.004	0.037	−0.133
D2R1	0.137	0.113	0.138	**0.816**	0.049	0.122	0.147	0.145
D2R4	0.129	0.081	0.098	**0.782**	0.200	0.120	0.179	0.109
D2R3	0.200	0.177	0.108	**0.721**	0.140	0.133	0.110	0.067
D2R2	0.190	0.153	0.121	**0.705**	−0.024	0.142	0.173	0.194
D1R4	0.091	0.107	0.171	0.095	**0.784**	0.157	0.102	0.132
D1R1	0.200	0.112	0.159	0.066	**0.771**	0.101	0.102	0.061
D1R2	0.062	0.122	0.088	0.111	**0.769**	0.115	0.158	0.166
D1R3	0.182	0.142	0.075	0.073	**0.686**	0.075	0.158	0.077
P4R1	0.200	0.188	0.110	0.145	0.111	**0.788**	0.110	0.059
P4R4	0.187	0.167	0.086	0.086	0.103	**0.771**	0.121	0.118
P4R3	0.311	0.161	0.121	0.149	0.095	**0.734**	0.078	0.095
P4R2	0.226	0.177	0.112	0.137	0.173	**0.728**	0.174	0.023
P2R1	0.180	0.216	0.146	0.112	0.168	0.041	**0.746**	0.086
P2R4	0.131	0.117	0.181	0.239	0.121	0.129	**0.723**	0.053
P2R3	0.134	0.227	0.182	0.118	0.167	0.173	**0.708**	0.049
P2R2	0.189	0.225	0.145	0.158	0.122	0.154	**0.639**	−0.075
P1R1	0.314	0.242	0.272	0.185	0.194	0.067	0.063	**0.621**
P1R4	0.251	0.204	0.256	0.161	0.193	0.079	0.042	**0.615**
P1R3	0.223	0.249	0.262	0.220	0.190	0.180	−0.009	**0.587**
P1R2	0.248	0.181	0.378	0.218	0.148	0.105	0.063	**0.580**

Extraction Method: Principal Component Analysis
Rotation Method: Varimax with Kaiser Normalization
Rotation converged after 8 iterations

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