Key factors affecting carbon emissions during the construction phase of prefabricated buildings

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Abstract. To explore the key factors influencing carbon emissions during the construction stage of prefabricated buildings in China, this paper initially identified the influencing factors through literature review and semi-structured interviews with industry experts in the Chinese construction sector. Subsequently, exploratory factor analysis (EFA) and relative importance index (RII) analysis were conducted based on the questionnaire data from 150 construction professionals. Five major categories of key influencing factors were identified: construction organization management and resource utilization efficiency, quality of project coordination and personnel execution ability, integration of prefabricated technology and digitalization level, green construction processes and standardization of techniques, and temporary energy consumption during construction and project schedule planning and control capabilities. The analysis results indicated that the category of "quality of project coordination and personnel execution ability" had the most significant impact. In response to the identified key factors, this study suggests a comprehensive approach including the establishment of a BIM-based collaborative management platform, the development of specialized training systems, and the promotion of process standardization, with the aim of reducing carbon emissions during the construction stage. This research provides valuable insights for promoting low-carbon development in China's construction industry.

1 Introduction

With the acceleration of global industrialization, climate warming and environmental pollution induced by carbon emissions have grown increasingly severe1. Currently, countries worldwide have fully recognized such hazards and are actively adopting measures to address climate challenges2. As a major global carbon emitter, China had President Xi Jinping state at the 75th UN Climate Change Conference in 2020 that China will strive to achieve carbon peaking before 2030 and make every effort to reach carbon neutrality before 20603.

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In China, the construction industry is a pillar of domestic economic development and a primary contributor to energy consumption and carbon emissions4; its carbon emissions accounted for 48.3% of China's energy-related carbon emissions in 2022. Affected by factors like the inherent development rules of the sector and the pace of technological iteration, carbon emissions from China's construction industry are projected to keep rising in the short term5. Thus, promoting carbon reduction in the construction industry is imperative for China to fulfill its dual carbon goals.

Existing studies have shown that prefabricated buildings are a critical approach to carbon abatement in the construction industry6. Within a building's whole life cycle (WLC), the construction phase is characterized by complex processes, multiple carbon emission sources, high-intensity and concentrated emissions, making it pivotal in the total life-cycle carbon emissions of a building7. Therefore, it is essential to sort out and analyze the key factors influencing carbon emissions during the construction phase of prefabricated buildings. The research results will provide valuable references for advancing carbon reduction in China's construction industry.

2 Literature Review

Prefabricated buildings, characterized by standardized design, factory-based production, and rapid on-site assembly, are widely regarded as an important approach to reducing carbon emissions in the construction industry6. To promote carbon reduction in the construction sector, the Chinese central government and local authorities have successively issued policies and documents to support the vigorous development of prefabricated buildings8. At present, a large number of scholars have devoted themselves to research on carbon emissions and sustainable development of prefabricated buildings. Teng et al. conducted a quantitative analysis of factors affecting the life-cycle cost of prefabricated buildings and confirmed that prefabricated construction performs remarkably well in reducing carbon emissions9. Cao et al. compared cast-in-place construction with prefabricated construction, and the results showed that the prefabricated approach reduced resource consumption by 35.82%, demonstrating significant advantages in energy conservation and emission reduction10.
However, the emission reduction potential of prefabricated buildings has not yet been fully realized. Within the full life cycle of buildings, the construction stage—due to the intensive use of machinery and equipment, component transportation, and on-site energy consumption—has become a relatively critical phase in the entire prefabricated building process. Research on carbon reduction at the construction stage is therefore conducive to energy conservation and emission reduction in the construction industry. Liu Yongguo et al., based on life-cycle theory for prefabricated buildings, developed a carbon emission model and explored key influencing factors from the perspective of energy-saving and emission-reduction pathways during the construction stage, proposing corresponding countermeasures in terms of material production, transportation processes, and on-site lifting operations11. Li Huishan and Zhao Ruirui constructed a green performance evaluation index system for prefabricated buildings across four stages—design, production and transportation, construction, and operation and maintenance—from a life-cycle perspective. Through case studies, they found that production and transportation as well as construction are the dominant stages for controlling carbon emissions in prefabricated buildings over the entire life cycle12.

In summary, most existing studies tend to analyze carbon emissions of prefabricated buildings from a full life-cycle perspective, while systematic analyses of the key factors influencing carbon emissions during the construction stage remain relatively limited. Therefore, it is still necessary for this study to systematically identify and analyze the key factors affecting carbon emissions at this stage, which can contribute to promoting low-carbon development in China's construction industry.

3 Research design

This study adopts an exploratory sequential mixed-methods approach, as shown in Figure 1. Firstly, through a systematic literature review, authoritative literature and reports in the fields of prefabricated building construction carbon emissions and low-carbon construction were screened to preliminarily identify and summarize potential factors influencing carbon emissions during the construction phase of prefabricated buildings, ensuring the initial indicators' relevance to the research topic. Subsequently, semi-structured interviews were conducted, inviting 16 experts with extensive experience to perform a dual verification of the 'necessity and relevance' of the initial factors, eliminating redundant factors and combining duplicated ones, ultimately determining 25 key influencing factors to ensure the content validity of the study.

Based on the interview results, a questionnaire was designed using the Wenjuanxing platform, employing a 5-point Likert scale, where 1 to 5 represent 'very unimportant' to 'very important', respectively. The study collected valid data from 150 professionals (including project managers, technical managers, engineering technicians, and frontline construction workers) from different companies and regions within China's construction industry. Descriptive statistical analysis of the data was performed using SPSS software, followed by exploratory factor analysis (EFA) to identify the latent dimensional structure of influencing factors. In combination with the Relative Importance Index (RII), the influence intensity of each factor and category on carbon emissions was quantified. The two methods collaboratively support the systematic identification and prioritization of key factors.

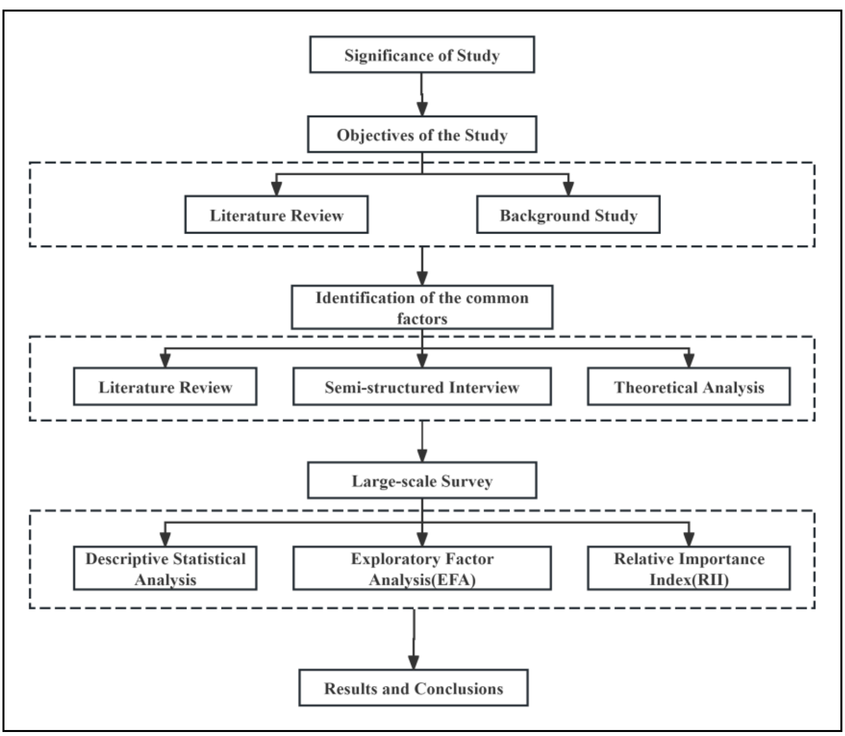

Fig. 1. Research methodology framework.

4 Results and discussion

This study identifies key influencing factors through the combined analysis of EFA and RII methods: EFA focuses on 'structural identification,' summarizing 25 specific factors into 5 logically consistent categories, addressing issues of scattered single factors and unclear dimensions; RII focuses on 'weight ranking,' quantifying the impact intensity of each factor and category, clarifying the priority of emission reduction. The combination of the two methods ensures both the systematic nature of influencing factors and the practicality of application. The specific analysis results are presented below.

4.1 General information

Table 1 summarizes the basic characteristics of the 150 valid samples.

Table 1. Demographic Profile of the Sample Data.

Characteristics	Category	Percentage
Position	Project managener	20%
	Technical manager	33.33%
	Engineering technican	26.67%
	Construction worker	11.33%
	Other	8.67%
Educational level	Doctoral degree	5.33%
	Master's degree	36%
	Bachelor degree	44%
	Other	14.67%
Years worked in the construction industry	0-5	41.33%
	6-15	47.33%
	16 or above	11.33%
Number of prefabricated building projects participated in	No experience	14%
	Participated in a small number (1-3)	42.67%
	Participated in several (4-10)	38%
	Participated in a relatively large number (>10)	5.33%

4.2 Exploratory factor analysis.

The primary objective of this study is to identify the key factors influencing carbon emissions during the construction phase of prefabricated buildings. To achieve this, we performed exploratory factor analysis (EFA) on the questionnaire data using SPSS software. Common factors were extracted based on principal components with initial eigenvalues greater than 1, and the factor matrix was determined using the varimax rotation method. The results of the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity are presented in Table 2. The KMO value of 0.883 (>0.6) indicates that the original variables meet the requirements for exploratory factor analysis. Furthermore, Bartlett's test of sphericity shows statistical significance (<0.001), which is below the threshold of 0.05, confirming that the selected indicators are suitable for factor analysis and that there is a significant difference between the correlation matrix of the variables and the identity matrix, allowing for the extraction of common factors.

Table 2. KMO and Bartlett Test.

Number of KMO sample tangents	0.883	
Bartlett's sphericity test	Approximate chi square	1210.100
	Degree of freedom	300
	Statistical significance	＜0.001

Using principal component analysis, common factors were extracted based on the criterion of eigenvalues greater than 1. The analysis identified a total of five common factors, with a cumulative variance contribution rate of 51.849%, which exceeds 50%. Although this value is slightly below the traditionally recommended threshold of 60%, the vast majority of factor loadings were greater than 0.5, and the communalities among factors all exceeded 0.4. This indicates that the factor structure is relatively clear, and the distribution of variable loadings across the factors aligns with theoretical expectations, demonstrating that the current model effectively reflects the underlying structure of the data.

The results (Table 3) show that the key factors affecting the construction phase of prefabricated buildings are categorized into five types: Construction Organization Management and Resource Utilization Efficiency, Engineering Coordination Quality and Personnel Execution Capability, Integration of Prefabricated Technology and Digitalization Level, Green Construction Practices and Process Standardization, and Temporary Construction Energy Consumption and Schedule Planning & Control. These comprise 25 factors in total, with 7 factors under Construction Organization Management and Resource Utilization Efficiency, 6 under Engineering Coordination Quality and Personnel Execution Capability, 5 under Integration of Prefabricated Technology and Digitalization Level, 5 under Green Construction Practices and Process Standardization, and 2 under Temporary Construction Energy Consumption and Schedule Planning & Control.

Table 3. Factor Load Matrix after Rotation.

Attributes	**Factor load factor**				
	1	2	3	4	5
Q2	0.534				
Q5	0.618				
Q7	0.538				
Q11	0.593				
Q18	0.482				
Q19	0.607				
Q22	0.658				
Q4		0.404			
Q9		0.693			
Q16		0.528			
Q17		0.626			
Q21		0.663			
Q25		0.550			
Q1			0.518		
Q6			0.670		
Q10			0.623		
Q14			0.650		
Q23			0.537		
Q3				0.685	
Q8				0.485	
Q12				0.522	
Q15				0.606	
Q24				0.489	
Q13					0.733

Q20					0.582

4.3 Relative importance indices.

This study employed the Relative Importance Index (RII) ranking method to assess the significance of each factor, thereby effectively identifying the key factors influencing carbon emissions during the construction phase of prefabricated buildings. The RII is calculated using the formula: the sum of all respondents' scores for a given factor is divided by the total number of respondents and then multiplied by the maximum score on the rating scale (where a 5-point scale is used, with 5 being the highest score).

The RII takes into account the scores of all items, enabling it to assess the relative importance of each disadvantage and thereby helping to identify the most critical issues. To calculate the overall RII percentage, the RII percentage for each study item is first calculated, followed by determining the weighted average percentage across all categorized items, as shown in Table 4.

Table 4. Relative Importance Indices.

Type	Items	Factor Loading	RII%	Overall RII%	Ran king s
Construction Organization Management and Resource Utilization Efficiency	Total consumption of main building materials (e.g., cement, steel)	0.534	78.93%	78.84%	16
	Amount of construction waste generated and its recycling rate	0.618	77.87%		22
	Load utilization rate of transport vehicles	0.538	77.33%		24
	Coordinated operation efficiency of on-site machinery and equipment	0.593	79.07%		14
	Optimization and executability of construction organization design	0.482	80.13%		8
	Scheduling and coordination efficiency at the construction site	0.607	80.40%		6
	Depth and effectiveness of specialized technical briefings for prefabricated building construction	0.658	78.13%		20
Engineering Coordination Quality and Personnel Execution Capability	.Material loss rate of construction materials on-site	0.404	79.20%	80.33%	12
	Complexity of transportation plans for special or oversized components	0.693	78.27%		19
	Smoothness of transitions between key processes	0.528	79.60%		10
	Professional skills and training level of on-site construction personnel	0.626	81.33%		3
	Frequency of changes and rework during the construction process	0.663	81.07%		4
	Collaboration and information-sharing efficiency among all project stakeholders	0.550	82.53%		1
Integration of Prefabricated Technology and Digitalization Level	Prefabrication ratio	0.518	79.07%	78.96%	14
	Average transportation distance of prefabricated components from factory to construction site	0.670	78.67%		17
	Energy efficiency rating and selection compatibility of main hoisting machinery	0.623	81.47%		2
	Additional lighting and temperature control energy consumption required for night construction	0.650	78.13%		20
	Degree of on-site management using digital tools	0.537	77.47%		23
Green	Adoption rate of low-	0.685	80.27%	79.71%	7

Construction Practices and Process Standardization	carbon/environmentally friendly building materials				
	Rationality of transportation route planning	0.485	79.20%		12
	Regular maintenance and upkeep status of machinery and equipment	0.522	78.67%		17
	Workmanship methods and operational standardization for on-site installation of prefabricated components	0.606	81.07%		4
	Level of safety production and civilized construction management on-site	0.489	79.33%		11
Temporary Construction Energy Consumption and Schedule Planning	Energy consumption intensity of temporary facilities at the construction site (e.g., office areas,living areas)	0.733	77.07%	78.47%	25
	Compactness and rationality of the overall construction schedule (total duration in days)	0.582	79.87%		9

4.4 Discussion

In the ranking of specific factors by importance, the top-ranked factor, "coordination and information-sharing efficiency among project stakeholders" (RII = 82.53%), clearly indicates that prefabricated construction involves multi-disciplinary and multi-stage collaboration. Information asymmetry and communication delays can easily lead to process conflicts, equipment idling, and rework, thereby directly increasing energy consumption and carbon emissions. It is therefore recommended to promote the application of BIM-based collaborative management platforms to enable real-time sharing of design, production, and construction data and synchronized decision-making, thereby reducing repetitive work and resource waste at the source13.

The second- and third-ranked factors are "energy efficiency of lifting equipment" (RII = 81.47%) and "workers' skill level" (RII = 81.33%), respectively, reflecting that equipment technology and human capital together constitute key pillars for emission reduction. A dedicated evaluation system for the selection of prefabrication-specific equipment should be established, prioritizing the use of high-efficiency electric or hybrid machinery14. In addition, a training and certification system for prefabricated construction skills should be developed to enhance frontline workers' ability to meet precision and process requirements.

Furthermore, the high impact of "frequency of construction changes and rework" (RII = 81.07%) and "standardization of installation processes" (RII = 81.07%) highlights the importance of achieving a high first-time pass rate in construction for emission reduction. This can be achieved by adopting standardized construction techniques and methods, implementing upfront design reviews, reducing on-site adjustments and secondary operations, and promoting modular installation to improve construction accuracy and quality control9. In addition, it is noteworthy that "quality of process integration and personnel execution capability" exhibits the highest impact among the five major categories of factors (80.33%), further confirming the systemic role of process coordination and personnel management in carbon reduction15. In contrast, factors such as energy consumption of temporary facilities and vehicle load utilization rank relatively lower at present, possibly due to insufficient monitoring and control mechanisms. However, with the advancement of more refined carbon accounting practices, their emission reduction potential remains worthy of further attention.

5 Conclusion

Carbon reduction in China's construction industry still faces numerous challenges. Identifying and analyzing the key factors during the construction phase of prefabricated buildings will help promote the low-carbon development of the industry. The research results indicate that project coordination quality and personnel execution capability are the most significant categories of influencing factors, which are primarily constrained by information synergy, personnel skills, process changes, and sequence bridging.

To address these constraints, the primary solutions include: constructing a BIM-based collaborative management platform, establishing a skill certification and training system for prefabricated construction personnel, implementing refined management mechanisms for process changes and rework, and promoting the standardization of key sequences and dynamic scheduling optimization. These solutions provide actionable levers for unleashing the low-carbon potential of prefabricated buildings. In the future, it is necessary to further strengthen government guidance, industry collaboration, and technological R&D to drive prefabricated construction toward low-carbon, efficient, and refined development. This study provides a reference for decision-making and practice regarding carbon reduction in the construction phase of prefabricated buildings in China.

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