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Factors Influencing the Environmental Performance of Prefabricated Buildings: A Case Study of Community A in Henan Province of China

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ABSTRACT

Various problems of traditional cast-in-place buildings, such as heavy energy consumption, severe environmental pollution, and low labour productivity, have hindered the development of the construction industry. Prefabricated buildings have a direct bearing on national economic development and transformation of people's lifestyle because of their high economic, environmental, social, and safety benefits. The technological research and development level for prefabricated buildings and system policies in China are still in the initial stage, and the environmental performance and influencing factors of prefabricated buildings limit their large-scale implementation. The literature in developed countries regarding the environmental performance and influencing factors of prefabricated buildings was first reviewed in this study. Community A in Zhengzhou City, Henan Province was used as the case study. AHP (Analytic Hierarchy Process) was applied to measure the factors influencing the environmental performance of prefabricated buildings, and policy suggestions were proposed to improve their environmental performance. Results indicate that developed countries tend to construct prefabricated buildings in large areas because of their remarkable economic, environmental, social, and safety benefits. Measurement results of Community A in Zhengzhou City, Henan Province show that the main environmental pollution factor of prefabricated buildings is waste discharge, accounting for 40%, followed by noise pollution, energy consumption, and dust pollution. The environmental performance of prefabricated buildings can be improved by promoting their development, reducing their environmental pollution, establishing a standard prefabricated concrete system, enhancing the environmental standards for buildings, expanding the application scope of prefabricated concrete, encouraging environmental technology innovation of buildings, cultivating prefabricated building bases, and strengthening environmental governance of construction sites. The findings will serve as reference in determining the main factors influencing the environmental performance of prefabricated buildings, establishing an evaluation system for the environmental benefits of prefabricated buildings, promoting their improvement and optimized development, and enriching and perfecting an evaluation research system for their comprehensive benefits.

INTRODUCTION

As a pillar industry in China, building construction has experienced remarkable development and improved production with rapid urbanization. Buildings should satisfy basic requirements, such as construction quality and use functions, and should minimize resource and energy consumption, improve labour productivity, and protect the environment during construction and use. The emergence of prefabricated buildings has provided a new direction in the development of the construction industry. The components and members of prefabricated buildings are prefabricated in a plant based on design standards and transported to the construction site for assembly, thereby accelerating the construction speed, reducing the construction period, and has remarkable advantages in terms of improved labour productivity, energy consumption reduction, and environment protection.

Henan Province in China has a large population with rapidly developing construction industry. As shown in Fig. 1, the gross output value of construction in Henan Province has increased from RMB 359.649 billion in 2009 to RMB 1,136.052 billion in 2018 with an average annual growth rate of 23.98%. The development of prefabricated buildings in Henan Province is still in the initial stage, and their prefabrication degree remains at a low level. Incomplete technical specifications, low modulus coordination degree between product materials, absence of standard modulus system that can be implemented at the national level, and the uncertainty in the comprehensive benefits of prefabricated buildings hinder their development progress. The development of prefabricated buildings should be accelerated and the innovation of building construction and high-efficiency coordination between production departments should be promoted on the

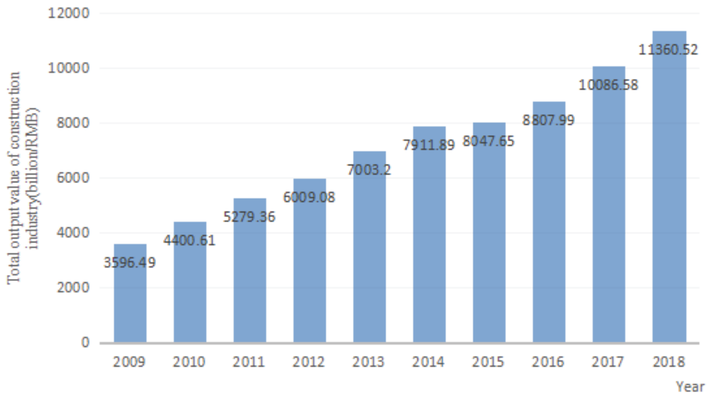

Fig. 1: Gross output values of the construction industry in Henan Province during 2009-2018.
(Data derived from Henan Statistical Yearbook)

basis of the modernization requirements and development tendency of the current construction industry. An evaluation research system should be developed to identify the comprehensive benefits of prefabricated buildings for satisfying the fundamental realities existing in the development of China's construction industry. The evaluation research system should cover the entire life cycle of prefabricated buildings and analyse and evaluate their comprehensive benefits during construction, operation, use, recycling, and demolition to support the development of the construction industry.

PAST STUDIES

Foreign prefabricated buildings have originated from Western Europe. Prefabricated buildings can overcome the limitations of current buildings, such as slow construction and long construction period, and they have been implemented in developed countries, such as America and Japan, in the 1960s. Construction technologies and related theoretical studies on prefabricated buildings are the most mature in western countries among other foreign studies. Most of these studies have focused on the production system of prefabricated construction accessories, energy conservation, and emission reduction, and studies on their comprehensive benefits have mainly concentrated on single aspects, such as economic and environmental benefits. Tam et al. analysed and investigated the reduction of construction wastes from four prefabricated buildings compared with traditional cast-in-place buildings, and their results showed that prefabricated buildings have satisfactory environmental benefits in energy conservation and emission reduction, where the quantity of construction wastes and concrete use and template consumption are reduced by approximately 55% and 80% compared with those of traditional cast-in-place buildings (Tam et al. 2005). Altes conducted a statistical analysis on the factors influencing the development of prefabricated buildings and indicated that the prefabrication degree worldwide is low because of unstable industrial chain and the lack of long-term strategic cooperative relationship of enterprises between industrial (Altes 2005). Jaillon et al. believed that a standardized design of prefabricated buildings could effectively improve the production efficiency of product components and achieve remarkable environmental advantages, such as energy conservation and emission and environmental pollution reduction (Jaillon et al. 2009). Begum et al. compared the prefabrication mode with the traditional cast-in-place mode of buildings and stated that the prefabrication mode could reduce the use of building materials and improve the environmental performance of buildings in terms of reduced construction period, energy source conservation, and environment protection (Begum et al. 2010). Mohamad et al. mainly studied the ability of industrial prefabrication to solve the shortage of houses, discussed the results using a SWOT (Strength Weakness Opportunity Threat) method, and concluded that prefabricated buildings could effectively reduce environmental pollution and realize large-scale house provision (Mohamad et al. 2012). Bari et al. selected four low-rise buildings using IBS and conventional construction methods as a case study. Their results showed that prefabricated buildings could help reduce waste pollution from the environmental perspective and provide their positive economic benefits and environmental performance (Bari et al. 2012). Silva et al. analysed the module transformation scheme for exterior walls of existing prefabricated buildings, including 3D model construction and cost effectiveness analysis. Their results showed that prefabricated buildings could notably realize energy conservation and greenhouse gas emission reduction (Silva et al. 2013). Agren et al. presented the five phases of prefabricated buildings from appearance to mature development and analysed their environmental performance under different phases (Agren et al. 2014). Yashiro explained the concept of prefabricated buildings and related theories, proposed a whole-life-cycle management method for prefabricated buildings, and indicated that the organizational form of prefabricated building construction is crucial in the environmental performance of prefabricated buildings (Yashiro 2014). Hong et al. explored the life-cycle energy utilization of prefabricated members and their influence on overall energy utilization by using actual building projects as the study objects. Their results showed that prefabricated buildings could reduce wastes and conserve energy sources, and minimize whole-life-cycle energy consumption by approximately 4%-14% (Hong et al. 2016). Chang et al. (2018) believed that the Chinese government should actively promote building prefabrication, analysed the advantages and disadvantages of building prefabrication in China in terms of productivity, resources, and environmental sustainability, and constructed a strategic concept of obtaining green benefits through prefabricated buildings (Chang et al. 2018). Li et al. conducted qualitative and quantitative analyses of the indoor thermal environment of prefabricated houses by taking Zhengzhou City in central China as an example. Their results indicated that prefabricated buildings have important advantages in terms of energy source conservation (Li et al. 2019). Navaratnam et al. reviewed the existing literature related to the structural behaviour, advantages, limitations, and challenges of prefabricated building systems by taking Australia as an example and believed that prefabricated buildings have good application prospects (Navaratnam et al. 2019). Lindblad analysed the environmental pollution caused by prefabricated concrete components during transportation (Lindblad 2019). Wang et al. utilized a performance analysis method to investigate the critical risk factors related to prefabricated buildings in China, and the results indicated that the risks of prefabricated buildings are caused by incomplete decomposition system, low plant management level, imperfect quality assurance system, and to-be-improved environmental benefits (Wang et al. 2019). Existing studies have indicated that prefabricated buildings are a kind of architectural model with high cost and scientific and technological level. Prefabricated buildings have remarkable economic, environmental, social, and safety benefits. Most studies on prefabricated buildings have analysed and evaluated their quality and cost. Some scholars have investigated the environmental benefits of prefabricated buildings, and few studies have comprehensively evaluated the angles of society and safety. Some case studies have ignored the factors influencing the environmental performance of prefabricated buildings and the specific solutions. Therefore, the environmental performance of prefabricated buildings was analysed and evaluated in this study. Community A in Zhengzhou City, Henan Province was used as the study object. Analytic hierarchy process (AHP) was used to assign weight values for various indicators of prefabricated buildings, followed by an analysis of factors influencing environmental performance of prefabricated buildings. The results of this study will serve as reference for standardizing the market of prefabricated buildings.

MODEL PROFILE AND INDEX CONSTRUCTION

AHP

AHP, which is proposed by an American operational research expert T. L. Saaty, is an analytical method combining qualitative analysis and quantitative research. AHP has systematic and hierarchical characteristics with high practicability and effectiveness for complex decision problems by modelling and quantifying the decision-making process of a decision maker of a complex system.

Construction of a hierarchical structure model: Problems are analysed with a priori knowledge and data, and the factors influencing them and their mutual relations are established. The factors are decomposed into several layers based on their property, and the factors at the same layer are subjected to the factors in a previous layer or a layer that impacts them. The factors can dominate the factors in the previous layer or be influenced by them. The top layer is the target layer, that is the general objective that must be reached by AHP. The bottom layer contains measures or schemes used to solve the problem. The middle layer is the criterion layer that includes intermediate processes, such as adopted rules to realize a preset goal.

Construction of paired comparison matrix: A comparison matrix is constructed through paired comparison and 1-9

Table 1: Comparison matrix.

	B1	*B2*	…	…	*Bn*
B1	b11	b12	…	…	b1n
B2	b21	b22	…	…	b2n
…	…	…	…	…	…
…	…	…	…	…	…
Bn	bn1	bn2	…	…	bnn

scale until the bottom layer is reached on the basis of related data, expert opinions, and analyser experience by starting from the middle layer of the hierarchical structure model to determine the relative importance of factors at the same layer that are subject to each factor at the previous layer. The paired comparison matrix is shown in Table 1.

As shown in Table 1, the corresponding relation between the b_{ij} value in the matrix and the relative importance of the compared factor is presented as follows: B_i is as important as B_j because $b_{ij} = 1$ and $b_{ji} = 1$; B_i is slightly more important than B_j because b_{ij}=3 and $b_{ji} = 1/3$; B_j is more important than B_j because $b_{ij} = 5$ and $b_{ji} = 1/5$; B_j is more important than B_j because $b_{ij} = 7$ and $b_{ji} = 1/7$; B_j is more important than B_j because B_j and $b_{ji} = 1/9$.

Weight calculation and consistency test: The maximum characteristic root and its eigenvector are calculated using the comparison matrix of factors. Consistency index (*C.I.*), random consistency (*R.I.*), and consistency ratio (*C.R.*) are used to perform the consistency test. $C.I. = \frac{\lambda \max - n}{n-1}$, where *C.I.* denotes the deviation degree of the comparison matrix through crash consistency. *R.I.* is a given constant that changes with the order number of the comparison matrix. $C.R. = \frac{C.I.}{R.I.}$. The comparison matrix has acceptable consistency, and the eigenvector (normalized) is the weight value when $C.R. < 0.10$. Otherwise, the judgment matrix should be adjusted and corrected to satisfy the consistency requirement.

Synthetic weights and ranking: The weight vectors in all layers are calculated, and the weights of factors are synthesized and ranked. The weight value of each evaluation index relative to the overall objective is expressed as $w_j = l_j \prod_{j=1}^{k} a_{ij}$, and $i = 1, 2, ..., n$, where l_j is the weight value obtained by evaluation index v_i in hierarchical single sorting at the bottom layer, k is the number of ancestors used to evaluate index v_i in the target tree, a_{ij} is the weight value of ancestor j of index v_i in hierarchical single sorting, and $a_{i1} = 1$ is the root node.

Index Construction

Resource consumption: Material and resource consumption during building construction mainly include water, rebar, and template consumption. The material expenses in building construction account for approximately 70% of the total construction and installation costs. The generation of prefabricated buildings has provided a new idea to reduce the resource consumption in the construction industry.

Energy consumption: The total energy consumption during building construction, operation, and use refers to the total energy quantity consumed in the usage of buildings, including daily use of heating, air conditioning, and illuminating lamps. Related energy-saving designs can be combined with the standardized design of prefabricated buildings to reduce energy consumption.

Waste discharge: The total waste discharge generated during building construction, recycling, and demolition specifically includes solid building wastes, waste gases, and wastewater.

Dust pollution: Dust pollution is generated during building construction. The dust pollution in the current construction industry of China must be solved to improve air quality and protect and enhance the atmospheric environment.

Noise pollution: Harmful noise pollution is generated by large-scale mechanical equipment during building construction. During the entire building construction, the noise pollution generated by the construction of a major structure has a great impact on the surrounding environment. Therefore, the noises generated by concrete pump truck, vibrating equipment, electric generator, and electric saw, which are used in the major structure construction, are all higher than the limiting noise value in the environment.

EMPIRICAL ANALYSIS

A survey questionnaire method was adopted based on the evaluation model of environmental performance of prefabricated buildings to analyse the index weights. The questionnaires were mainly provided to the relevant technical personnel of prefabricated buildings in Community A in Zhengzhou City, Henan Province and technology R & D personnel and constructors of enterprises constructing prefabricated buildings. A total of 1,032 questionnaires were distributed. Invalid questionnaires and those with incomplete information were excluded from the study. The valid questionnaires (876) obtained an effective rate of 84.9%, indicating the validity of the survey. The judgment matrix of index systems at all levels is shown in Table 2.

1. Calculation of importance ranking

$$\overline{W_{B_i}} = \sum_{1}^{n} \frac{b_{ij}}{\sum_{1}^{n} b_{ij}} (i, j = 1, 2, ..., n)$$, where

$(\overline{W_{B_1}}, \overline{W_{B_2}}, \overline{W_{B_3}}, \overline{W_{B_4}}, \overline{W_{B_5}}) = (0.55, 0.81, 1.96, 0.82, 0.86)$.

Vector $\overline{W_A} = (\overline{W_{B_1}}, \overline{W_{B_2}}, \overline{W_{B_3}}, \overline{W_{B_4}}, \overline{W_{B_5}})$ is normalized to obtain eigenvector W_A = (0.11, 0.16, 0.40, 0.16, 0.17), which yields:

Table 2: Judgment matrix of environmental benefits.

Target layer A	*Resource consumption B1*	*Energy consumption B2*	*Waste discharge B3*	*Dust pollution B4*	*Noise pollution B5*
Resource consumption B1	1	1/2	1/3	1/2	1
Energy consumption B2	2	1	1/2	1	1/2
Waste discharge B3	3	2	1	3	3
Dust pollution B4	2	1	1/3	1	1
Noise pollution B5	1	2	1/3	1	1

$$BW_A = \begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{2} & 1 \\ 2 & 1 & \frac{1}{2} & 1 & \frac{1}{2} \\ 3 & 2 & 1 & 3 & 3 \\ 2 & 1 & \frac{1}{3} & 1 & 1 \\ 1 & 2 & \frac{1}{3} & 1 & 1 \end{pmatrix} \bullet \begin{pmatrix} 0.11 \\ 0.16 \\ 0.40 \\ 0.16 \\ 0.17 \end{pmatrix} = \begin{pmatrix} 0.576 \\ 0.828 \\ 2.053 \\ 0.849 \\ 0.899 \end{pmatrix}$$

The maximum characteristic root of the matrix is $\lambda_{\max} = \sum_{1}^{n} \frac{(BW_A)_i}{nW_i}$.

2. Consistency test

$C.I. = 0.049$ is obtained using $C.I. = \frac{\lambda_{\max} - n}{n-1}$ of the matrix. Random consistency ratio is $C.R. = \frac{C.I.}{R.I.}$, where $R.I. = 1.24$ under a five-order matrix, and $C.R. = 0.044 <$ 0.10, indicating that the judgment matrix has satisfactory consistency. The weights of five influencing factors are listed in Table 3.

As shown in Table 3, the main environmental pollution factor of prefabricated buildings is waste discharge, accounting for 40%. The main problem existing in the current prefabricated buildings is the connection between the prefabricated portion and cast-in-place structure node because of the lack of fundamental studies on prefabricated buildings in China. In the broad application of prefabricated concrete shear wall structures, the effective occlusal force of sleeve grouting connection remains unclear in practical engineering construction. The longitudinal bars on the wall body are mainly connected through sleeve grouting, and the connection of concrete-reinforced sandwich panels is influenced by many external factors, such as stress bearing, endurance, and expansion under heating and contraction under cold conditions. Thus, a complete construction scheme has not been formed for node connection. Therefore, a large quantity of waste discharge is generated in the construction of prefabricated buildings.

The secondary factor influencing environmental pollution of prefabricated buildings is noise pollution. The prefabricated concrete structures used in housing construction should be completed in a plant without requiring additional workers, and these prefabricated concrete structures should be spliced. Therefore, noise pollution is mainly generated in the construction site. Night-time construction is absolutely forbidden in the building field, and noisy construction is not allowed at midday break in residential areas. The punishment imposed on building enterprises violating the rules in noise pollution during building construction process is heavy, forcing them to optimize their designs and construction schemes and immediately complete the noisy construction in their plants.

In the aspects of energy consumption and dust pollution, the transportation of prefabricated parts is expensive. A large quantity of manpower, transportation, and moving workload are needed from raw materials to the completion of major structure. Prefabricated parts in the construction site are directly transported to the workbench for on-site assembly, and cooperation with cast-in-place after parts are produced on the plant production line in the plant is maintained to reach the construction intensity. Therefore, the energy consumption generated in the transportation and loading and unloading processes is the main factor causing environmental pollution of prefabricated buildings. Meanwhile, beams, plates, and columns of building structures in the construction site is directly manufactured in the plant production line and transported to the construction site, thereby generating dust pollution.

Table 3: Weights of environmental pollution factors of prefabricated buildings.

Index	***Resource consumption***	***Energy consumption***	***Waste discharge***	***Dust pollution***	***Noise pollution***
Weight	0.11	0.16	0.40	0.16	0.17

POLICY SUGGESTIONS

Promoting the Development of Prefabricated Buildings and Reducing Their Environmental Pollution

The proportion occupied by prefabricated concrete buildings in the industrial production technology should be enhanced, and technical and economic policies conforming to the construction features of prefabricated concrete buildings should be provided. National policies should be partial to links, such as approval and initiation of projects, planning, and construction, the supporting force of financial funds should be enlarged, and the research and application of crucial technologies should be supported. Local governments should reinforce their policy support and implement supporting policies, including area calculation, area reward, financial fund reward, forward sale of houses, and scientific research. Following the development trend of prefabricated buildings, governments at all levels in China should guide government investment projects, newly built public rental and settlement houses for shantytown transportation to implement prefabricated buildings. Under the support of governmental preferential policies, additional enterprises will be attracted to join the development team of prefabricated buildings.

Build A Standard System for Prefabricated Buildings and Promote Their Environmental Standard

The building goals should be understood and the solving of actual system problems of prefabricated buildings should be used as the criterion to build a standard system for prefabricated concrete buildings. A supporting system should be built, and the integrated industrialization of prefabricated buildings, including the entire set of systematic and diversified standard systems for prefabricated concrete buildings from design, R & D, and member production to on-site installation, should be realized. The standard system, node design, and standard schematic handbook of prefabricated concrete structures must be compiled and completed in designing a standard system. Appropriate prefabricated concrete buildings should be selected based on different conditions to meet the concrete requirements of some special areas, such as high seismic intensity, collapsible loess, and some western underdeveloped areas. Special prefabricated structure systems and construction technologies should be investigated for special areas. Should focus on investigating the construction precision, separation system, high-efficiency node, and technology implementation of prefabricated concrete buildings.

Expand the Application Scope of Prefabricated Concrete Buildings and Encourage Environmental Technology Innovation of Buildings

The government should encourage the use of prefabricated concrete buildings. We should actively implement prefabricated concrete buildings in public buildings, such as medical, cultural, sports, and commercial buildings. The government should invest on constructing prefabricated concrete buildings. The construction of prefabricated concrete buildings should be considered a key project plan in urban construction. The management reform should be accelerated, and the original cast-in-place construction mode should be transformed into the mechanical hoisting mode. Building members should be spliced in the plant assembly to reduce the wet construction workload. The training of constructors should be orderly implemented. Workers should be transformed from laborers to technology-based employees. The certification work of corresponding industrial workers should be strengthened to realize production efficiency improvement under the precondition of guaranteed construction quality, thereby reducing the cost and labour intensity.

Cultivate Prefabricated Building-Based Enterprises and Strengthen Environmental Governance on Construction Sites

Although supported by national policies, prefabricated concrete buildings should be encouraged to set as typical examples. We should enlarge the input of advanced construction technologies and production equipment and improve the production quality of related components of prefabricated concrete buildings through R & D of new products and new materials in this field. The construction technology and construction facilities should be correspondingly improved. Plants for the prefabrication of small members can be constructed in the construction sites, thereby realizing the member production in the production line of the construction site, followed by assembly after the intensity is reached. This process can remarkably reduce transportation cost and accelerate the transformation of construction workers, thereby cooperating with flow construction and improving construction speed. The prefabricated parts in the construction site are directly transported to the workbench for on-site assembly, and cooperation with cast-in-place after parts produced in the plant production line are maintained to reach the construction intensity, thereby reducing the transportation and loading and unloading costs to a great extent. Beams, plates, and columns of building structures in the construction site are directly manufactured in the plant production line and transported in the construction site, thereby reducing construction speed and cost. Meanwhile, corresponding standards, such as manufacturing standards of prefabricated parts, should be completed.

CONCLUSION

The rapid economic development in China cannot be separated from the support of building infrastructures, and limited urban resources should be utilized to provide a large social value. However, unreasonable occupation and utilization of land resources, destruction of ground vegetation, flowing dust caused by earth excavations, and heavy construction noise have led to severe environmental pollution. Prefabricated buildings can realize continuous construction, effectively reduce cost and energy, protect the environment, and reach the goal of green construction through design diversification, function modernization, manufacturing standardization, and construction assembly. In this study, Community A in Zhengzhou City, Henan Province was used as the study area, and AHP was utilized to measure the factor weights influencing the environmental performance of prefabricated buildings. Policy suggestions were proposed to improve their environmental performance. The study results indicate prefabricated buildings have remarkable economic, environmental, social, and safety benefits. The primary factor of prefabricated buildings causing environmental pollution is waste discharge, accounting for 40%, followed by noise pollution, energy consumption, and dust pollution based on the measurement results of Community A in Zhengzhou City. Policy suggestions to improve the environmental performance of prefabricated buildings are proposed as follows: promote the development of prefabricated buildings and reduce their environmental pollution, build a standard system for prefabricated buildings and enhance their environmental standard, expand the application scope of prefabricated concrete and encourage the environmental technology innovation of buildings, cultivate prefabricated building-based enterprises, and strengthen the environmental governance in construction sites. Continuous in-depth study should be conducted on the aspects of whole-life-cycle environmental performance evaluation of prefabricated buildings, comparative analysis of environmental benefits between prefabricated and traditional cast-in-place buildings, and environmental performance and benefit testing of prefabricated buildings.

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