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An exploratory analysis of low-carbon transitions in China's construction industry based on multi-level perspective

Abstract

Climate change caused by carbon emissions is a concern for many countries. As the world's largest carbon emitter, China's construction industry generates substantial carbon emissions. However, previous research has primarily focused on promoting low-carbon building products or calculating carbon emissions to propose low-carbon transition measures. There has been limited research on low-carbon transitions in the construction industry from an industry system perspective. This study aimed to identify the driving factors and their interrelationships for low-carbon transitions in the construction industry. A multi-level perspective (MLP) was presented as a heuristic structure to analyze driving factors. An integrated interpretative structural model (ISM) and cross-impact matrix multiplication applied to classification (MICMAC) technique was adopted to explore the interactions among factors. The results demonstrate that a six-level hierarchy of 22 drivers was constructed, and relationship degrees between the factors were discovered. The strongest drivers were low-carbon legal regulation, followed by industrial structure and organizational characteristics connected to industrial development. Improving these fundamental factors will increase the probability of successful transitions. The results also demonstrate that transitions are a collaborative process that involves multiple stakeholders. These findings can provide suggestions for low-carbon practices in the construction industry.

Keywords: Low-carbon transitions, Construction industry, Driving factors, Multi-

level perspective, ISM-MICMAC

Highlights:

- Introduced a multi-level perspective into construction industry system studies
- Identified driving factors for implementing low-carbon transitions in construction industry
- Used an integrated ISM-MICMAC method to explore the interactions among factors
- Formed a multi-stakeholder collaborative system to clarify the main responsibility

1. Introduction

Climate change is one of the most pressing global issues today, and the IPCC's Sixth Assessment Report identifies that increasing carbon emissions is a major contributor to global warming (Masson-Delmotte et al., 2021). China is the world's largest emitter of carbon dioxide, accounting for 31% of global carbon emissions in 2020 (Friedlingstein et al., 2022). China's construction industry, which contributes significantly to the country's carbon emissions, produced 1.4 billion tons of CO_2 in 2016 and accounted for 15% of the total emissions (Du et al., 2019; Zhou et al., 2018). As urbanization and living standards continue to rise in the future, the scale of buildings and demand for energy services will keep climbing, and the construction industry's carbon emissions will increase considerably (Huo et al., 2022). Therefore, achieving low-carbon transitions in the construction industry is necessary and meaningful to promote the sustainable development of the industry and society. It is crucial to identify the factors driving the transitions precisely and propose workable opinions.

China's construction industry is undergoing a rapid low-carbon transitions and there are two main research areas on low-carbon transitions in the construction industry. Some studies considered that the transitions should focus on building products that meet the sustainable development needs of society, such as low-carbon buildings (Shi et al., 2015), green buildings (Friedman & Rosen, 2022; Shurrab et al., 2019) and assembled buildings (Teng et al., 2018). Since building products are the ultimate transition vectors, many studies examined the factors influencing the low-carbon transitions of the construction industry from a product viewpoint. These factors include legislative system and technical standards (Shi et al., 2014), low-carbon building design (Dawood et al., 2013), low-carbon technology innovation (Lai et al., 2017), low-carbon market demand (Zuo et al., 2012), low-carbon awareness and consciousness (Liu et al., 2012), and the capacity of construction businesses (Zhang et al., 2017). Besides, others emphasized calculating carbon emissions in the construction industry and breaking them down using formulae to identify the factors that affect the transitions. Shi et al. (2017) indicated that most of the rise in carbon emissions in construction can be canceled out by the energy intensity effect. Lai et al. (2019) concluded that construction GDP growth affected carbon emissions. Li et al. (2020) found that boosting the quality of the construction workforce can minimize carbon emissions. Zhou et al. (2019) denoted that technological progress, energy structure modification, and economic scale can increase carbon emission efficiency. Existing literature shows that a low-carbon transitions in the construction industry depends on a mix of market, technical, regulatory, capital, and human resources factors.

In spite of an increasing amount of prior literature that examined low-carbon development in the construction industry, most studies have focused on developing low-carbon building products and calculating carbon emissions in the construction industry. The construction industry, as a material production industry, produces low-carbon building products with specific functional characteristics that are connected to the interrelated economic sectors of the construction industry chain. Therefore, the low-carbon transitions of the construction industry are not constrained to the energy conservation and emission reduction of a certain type of product, but rather the low-carbonization of the whole construction system. There has been limited research on low-carbon transitions in construction industry from an industry system perspective and lack of mature theoretical support to effectively guide the construction industry's transition practices.

Sustainable transition theory, developed from socio-technical systems theory, contends that fields like energy, transportation, housing, and food can be viewed as socio-technical systems. These systems comprise various participants (including users, enterprises, and policymakers), networks of individuals and organizations, institutions (such as norms and regulations), and tangible products and knowledge. The strength of sustainable transition theory lies in examining the co-evolution of socio-technical elements from a systemic perspective, intending to achieve sustainable innovation throughout the entire system (Keller et al., 2022). The multi-level perspective (MLP), a primary theoretical structure in sustainable transition research (Wang et al., 2022), has been extensively used in transition research on energy systems, power systems, industrial systems, and other topics. This study focuses primarily on introducing a multi-level perspective as a heuristic structure to analyze the low-carbon transitions in the construction industry for two reasons: (1) MLP is based on the co-evolution of technology and society, involving multiple dimensions (technology, industry, market, policy, infrastructure, and cultural values, focusing on the dynamic changes in the system); (2) MLP is a participant-based approach that takes into account the various stakeholder interactions between groups.

Therefore, this study aimed to address how to effectively promote low-carbon transition practices in the construction industry. The objectives of this study were as follows: (1) introducing MLP into low-carbon transitions in the construction industry based on the current low-carbon development status; (2) identifying factors driving the low-carbon transitions in the construction industry through systematic literature study and expert survey; (3) investigating the interrelationships and priorities between factors using the integrated ISM-MICMAC approach; (4) forming a multi-stakeholder collaborative system to clarify the main responsibility. The findings from this study will provide direction for the establishment of low-carbon transition plans and strategies in the construction industry. The remainder of the study is organized as follows: Section 2 covers the research methodology of MLP and integrated ISM-MICMAC approach. Section 3 identifies the drivers for the low-carbon transitions in the construction industry by combining the literature review and MLP. Section 4 provides the hierarchy structure of factors and the degree of the relationship between factors according to the implementation of the ISM and MICMAC analysis, respectively. Section 5 summarizes the results and discussion. Section 6 contains conclusions, implications, and limitations.

2. Research Methodology

2.1. Contents and principles of the MLP

MLP in socio-technical transition theory provides essential analytical concepts to encourage sustainable development in resource constraints, environmental degradation, and global warming. (Geels, 2010; 2002) explained that transitions are nonlinear processes generated by the interaction of multiple developments at three levels: socio-technical landscape, socio-technical regime, and innovation niche. The socio-technical landscape means the external environment, including political, economic, social, and cultural aspects, which will influence the development of socio-technical regimes and niches (Lachman, 2013). The socio-technical regime dominates the socio-technical system. It is a highly interconnected and stable structure that consists of consumer preferences, products, technology, organizations, rules, standards, and knowledge (Geels, 2012). Once a regime has been established, it will be path-dependent or technologically and institutionally locked. It is impossible to make a short-term change and the existing regime will remain dominant. The innovation niche is an incubator of new technologies and the seed of institutional change that is not restrained to mainstream rules, including innovative technologies, innovative items, innovative management, technology demonstration projects, existing niche markets, and others (Martínez Arranz, 2017).

Fig. 1 provides an idealized illustration of the dynamic interaction between the three levels as socio-technical transitions occur. Innovations generally occur in niches outside of regimes and develop with learning in all dimensions, expression of expectations or vision, and social networking. A highly stable regime can considerably hinder innovation; only innovation that creates a competitive advantage can reduce the constraints of regime and lead to transitions. The socio-technical landscape changes slowly, but when it does, it places pressure on the existing socio-technical regime and creates an opportunity for the niche. When the niche can compete with the socio-technical system, the existing regime will be changed under the pressure of landscape and the disruption of niche, then producing a new regime. However, it does not mean that the transitions are simple causal processes or will necessarily succeed. A new regime will emerge when the innovative development has undergone enough tests to mature and the existing regime may have gradually adapted to external pressures.

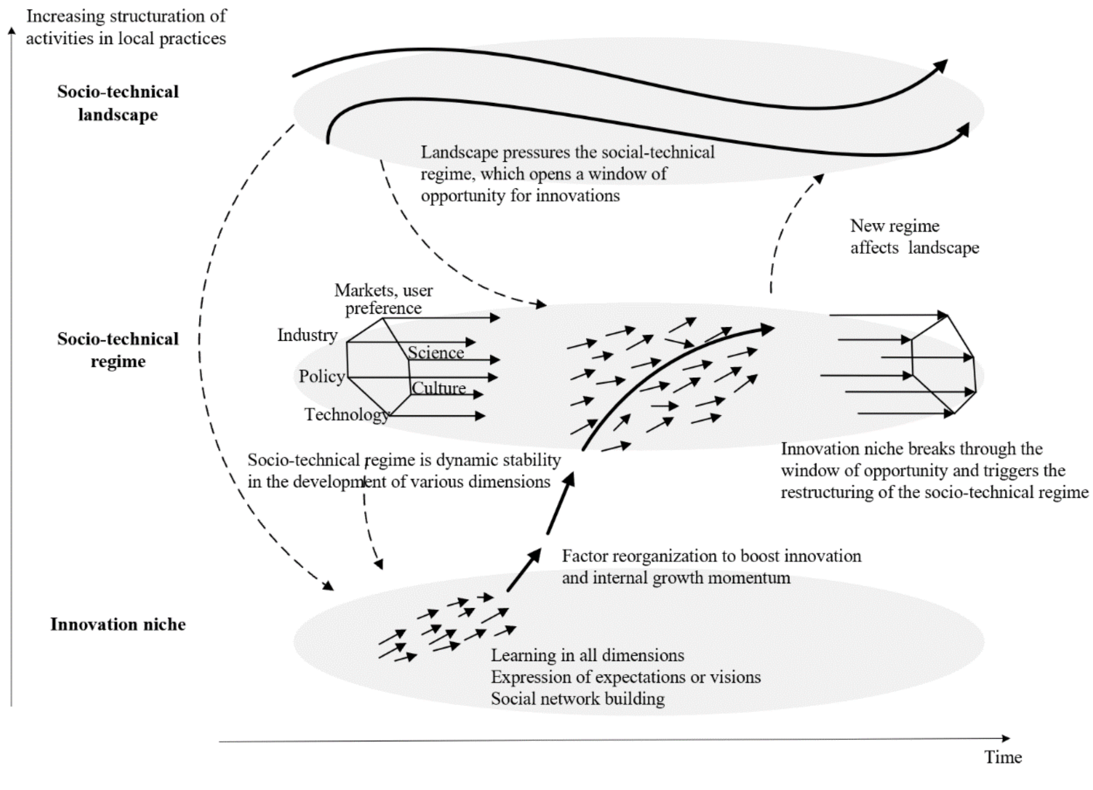

Fig. 1. Multi-level perspective on transitions (Geels, 2002)

2.2. Integrated ISM-MICMAC method

2.2.1. ISM hierarchy analysis

The Interpretative Structural Modeling Method (ISM) is first proposed by Professor Warfield. It can convert fuzzy perspectives into accessible models with solid contextual structural relationships (Warfield, 1974), and has been widely applied in sustainability-related research (Kumar & Barua, 2022; Yu et al., 2018). This study adopted this method to analyze the system structure of the low-carbon transitions factors. Following are specific steps：

Step 1: Identifying the set of system factors S. Assuming that there are n ($n \geq 2$) factors in the system, which can be described as formula (1):

$$S=\{S_1,S_2,S_3,\ldots,S_n\} \quad (1)$$

Step 2: Constructing a self-interaction matrix (SSIM). The contextual correlations between the factors are determined by interviewing a group of construction industry experts. The four symbols listed below show the interaction between two factors:

V: S_i influences S_j, but S_j does not influence S_i;

A: S_i does not influence S_j, but S_j influences S_i;

X: S_i and S_j influence each other;

O: S_i and S_j are not related.

Step 3: Generating the adjacency matrix (AM). According to the following rules, the SSIM can be converted into AM:

If the relation in SSIM is V, then the binary relation (Si, Sj) is 1, and (Sj, Si) is 0;

If the relation in SSIM is A, then the binary relation (Si, Sj) is 0, and (Sj, Si) is 1;

If the relation in SSIM is X, then the binary relation (Si, Sj) and (Sj, Si) are both 1;

If the relation in SSIM is O, then the binary relation (Si, Sj) and (Sj, Si) are both 0.

Step 4: Calculating the reachability matrix (RM). The reachability matrix explains how a factor connects with another along a particular path, such as if S_i can reach S_j through a path of length 1, and S_j can reach S_k through a path of length 1, then S_i can reach S_k through a path of length 2. The reachable matrix is calculated according to formula (2):

$$RM=(AM+IM)^{n+1}=(AM+IM)^{n}\neq(AM+IM)^{n-1}\neq\ldots(AM+IM)^{2}\neq(AM+IM) \qquad (2)$$

IM is an unit matrix, the rules of boolean algebraic operation are: 0 + 0 = 0, 0 + 1 = 1, 1 + 1 = 1, 1 × 0 = 0, 1 × 1 = 1.

Step 5: Calculating regional division table. It involves evaluating antecedent set $A(S_i)$, reachable set $R(S_i)$, and the intersection set $C(S_i)$.

Step 6: Extracting hierarchical structure. According to formula (3), the hierarchy determines whether the reachable and intersection sets are consistent:

$$\text{Level N}=\{S_i \mid R(S_i) = C(S_i)\} \qquad (3)$$

Step 7: Forming hierarchical structure model.

2.2.2. MICMAC driver analysis

The cross-influence matrix multiplication method (MICMAC), a matrix multiplication system, was made by Duperrin and Godet in 1975 (Duperrin & Godet, 1975). The role and function of factors depend on their driving and dependence power.

Driving power means the impact of S_i on others; dependence power means the impact of others on S_i (Dubey et al., 2017). Different sets of factors are represented by the four quadrants of the coordinate system, with the horizontal coordinate indicates dependence power, and the vertical coordinate represents the driving power.

Autonomous factors (quadrant I), which have weak driving power and dependence power;

Dependent factors (quadrant II), which have weak driving power but strong dependence power;

Linkage factors (quadrant III), which have strong driving power and dependence power;

Independent factors (quadrant IV), which have strong driving forces but weak dependence power.

2.3. Research framework

In conclusion, this study develops a framework for analysing the factors influencing the low-carbon transitions of the construction industry under the guidance of MLP by using the ISM-MICMAC approach. The MLP is utilized to discover factors driving the low-carbon transitions. The ISM is used to hierarchize identified factors and investigate their interrelationships in detail. The MICMAC distinguishes the functions of factors under driving and dependence power. The combination of theory and technique is intended to investigate potential structural linkages in the low-carbon transitions of the construction industry, as shown in Fig. 2.

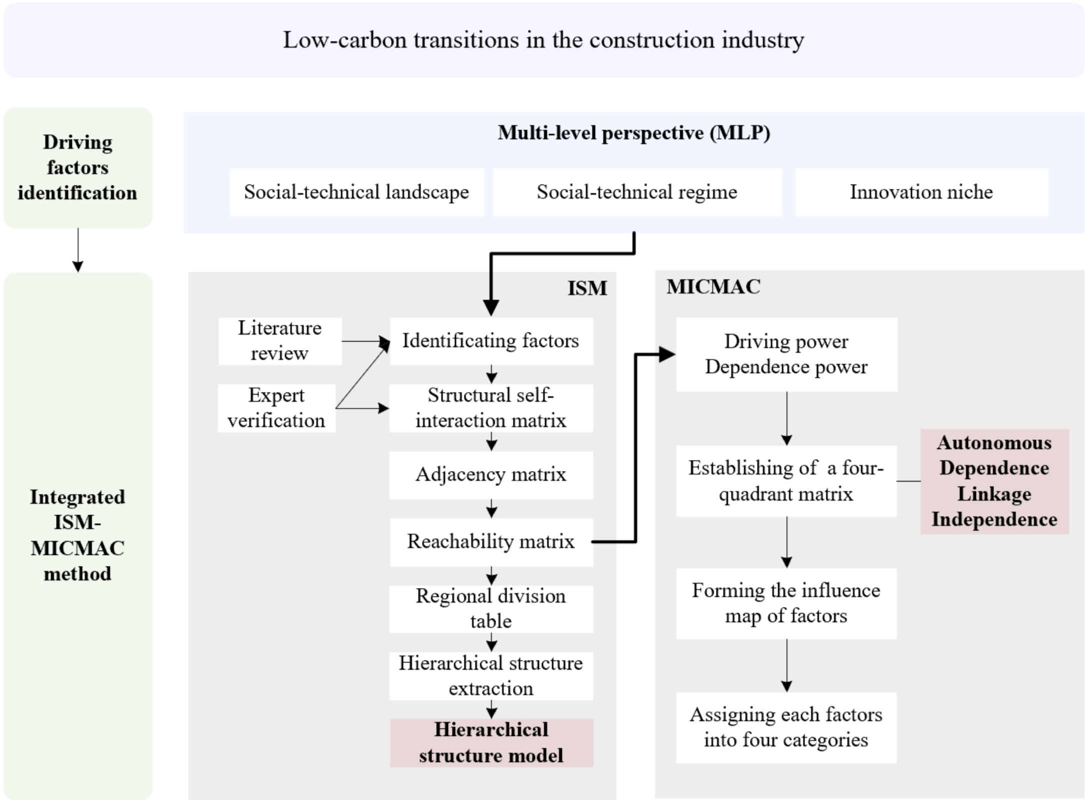

Fig. 2. Research framework for low-carbon transitions in construction industry

3. Driving factors for the low-carbon transitions of the construction industry

3.1. MLP for low-carbon transitions in the construction industry

The current development of the construction industry is impacted by the limitations of conventional technology, the fragmented thinking of the industry chain, and the interests of construction workers (Chang et al., 2016a). As a result, the industry's economic growth, energy consumption structure, and technical development track have been dominated by high-carbon mode, resulting in a carbon-locked state. Over the past 40 years, the construction industry has experienced two stages of development: one driven by factors and the other by investments. In the future, innovation will be the driving force behind the transitions. Technological innovation has been considered the essential part of multi-dimensional drivers, but it cannot make the low-carbon transitions on its own; it must be incorporated into a complex social structure. Therefore, the low-carbon transitions of the construction industry need to evolve synergistically from organization, technology, market, policy, finance, management, etc.

According to the MLP, the low-carbon transitions in the construction industry are dynamic process that comprises socio-technical landscape, socio-technical regime, and innovation niche. The landscape layer provides an opening for innovation and places pressure on existing institutions during social processes such as global warming, the energy crisis, economic growth, and urbanization. The socio-technical system is the main focus of the MLP and the most decisive aspect of the transitions. Based on a literature review and related theoretical studies, the socio-technical regime can be divided into seven aspects: industrial structure, industrial organization, policy, technology, market, finances, and workforce. Industrial structure transitions refer to advancing the industrial structure and output structure of the construction industry; industrial organizational transitions mean creating intense competition and collaboration among companies; policy transitions imply establishing a series of policy standards with regulatory, punishment, and incentives; technology transitions indicate promoting the development of low-carbon tech; market transitions denote cultivating a low-carbon market environment for the construction industry; financial transitions reflect financial institutions are providing low-carbon investment and financing for construction firms; workforce transitions emphasize low-carbon consumption awareness and introducing high-quality workers. The innovation niche will provide a haven for innovations such as new technology, management, and demonstration projects that develop from mutual learning and collaboration between innovation agents (e.g., construction companies, governments, research institutions, intermediaries, financial institutions, and end users).

3.2. Driving factors of low-carbon transitions in construction industry based on MLP

MLP is a helpful tool for identifying critical factors in the construction industry's low-carbon transitions. This study conducted a bibliometric search using the keywords "green building," "construction industry," "low-carbon development," and "sustainability" in Scopus, Google Scholar, and Web of Science databases. The drivers were extracted from three aspects based on the MLP: the landscape, the socio-technical system, and the innovation niche. A group of 15 building specialists was formed to exchange knowledge by distributing questionnaires to determine the final variables, as shown in Table 1. They have rich experience with the development of green buildings, low-carbon buildings and sustainable building. Table 2 shows the 22 drivers identified.

Table 1 Experts Information Form.

Experts	Working organization	Role in the organization	Working years
1	Government Sector	Director	13
2	Government Sector	Department head	15
3	Government Sector	Department head	11
4	Construction Enterprise	General manager	12
5	Construction Enterprise	Department Manager	10
6	Construction Enterprise	General manager	18
7	Construction Enterprise	Engineer	14
8	Construction Enterprise	Department Manager	12
9	Construction Industry	Member	10
10	Construction Industry	Member	12

11	Construction Industry	Member	10
12	Scientific Research Units	Professor	17
13	Scientific Research Units	Associate Professor	10
14	Scientific Research Units	Associate Professor	14
15	Scientific Research Units	Professor	16

Table 2 Driving factors on low-carbon transitions.

S_i	Drivers			Explanation	Source of data
S_1	**Landscape**	energy structure		Energy structure in China has long been dominated by high carbon fossil energy sources. Optimizing the energy consumption structure by developing and using clean energy will significantly reduce carbon emissions.	(Hong et al., 2017; Jiang et al., 2022; Wu et al., 2019; Zhou et al., 2019)
S_2		urbanization		Urbanization can boost economic growth and production factor concentration to hasten low-carbon technology development and encourage population clustering to improve the energy use efficiency.	(Ahmad et al., 2019; Wang & Zhao, 2018; Zhang et al., 2021)
S_3		economic growth		Economic growth may lead to industrial agglomeration and an increase in energy efficiency and productivity.	(Lai et al., 2019; Wen et al., 2020)
S_4	**Socio-technical regime**	Structure	ownership structure	Non-SOEs have higher technical and energy efficiency levels than SOEs, and are more conducive to emission reduction.	(Long et al., 2016; Wang et al., 2019a)
S_5			opening degree	Increased openness promotes the introduction of innovative technology managerial skills, which is positively associated with carbon productivity.	(Liao & Li, 2022; Long et al., 2016; Wang et al., 2019a)
S_6		Organization	market concentrate	The unreasonable structure of the construction market has produced competition focused on price wars,	(Liu et al., 2013a; Liu et al., 2013b; Wang & Li, 2021)

			which will result in insufficient investment in innovative activities.	
S_7		supply chain integration	Carbon emissions are generated at every stage of the construction project supply chain, and by integrating the construction supply chain, green economic growth and sustainability can be encouraged.	(Hossain et al., 2020; Kosanoglu & Kus, 2021; Zeng et al., 2018)
S_8		industry cluster	High-density agglomeration promotes low-carbon innovation because it generates strong links between various businesses, specialized cooperative division of labor, and substantial information exchange.	(Lu et al., 2020; Xu et al., 2022)
S_9	Technology	low-carbon building technology	The development of green building technologies can realize the transitions of green buildings from concepts to actual buildings.	(Darko & Chan, 2018; Gao et al., 2020; Song et al., 2020; Wang et al., 2019b)
S_{10}		Industrialization and informatization	Industrialization and information technology can improve the energy efficiency of construction process by coordinating all stages in a project.	(Dong et al., 2019; Kamali & Hewage, 2016; Teng et al., 2017; Xie et al., 2022)
S_{11}	Policy	low-carbon legal regulation	Government policies and regulations can reduce the negative economic externalities connected to low-carbon buildings that cause market failures.	(Gan et al., 2015; Gao et al., 2020; Li et al., 2014)
S_{12}		incentive policy	Market-driven demand can be stimulated by offering various incentives to construction industry stakeholders, such as project approval, and finance for developers.	(Gao et al., 2020; Olubunmi et al., 2016; Yin et al., 2018)
S_{13}	Market	Low-carbon product demand	The low-carbon building market can promote the growth of	(Liao & Li, 2022; Wang et al., 2019b)

				supplementary industries and encourage market participation in consumption.	
S_{14}			Business model	Innovative business models can meet sustainability goals in service models and construction models, which have a positive relationship with the ability to innovate green.	(Bocken et al., 2014; Eline et al., 2018; Zhang et al., 2020)
S_{15}		Finance	Carbon finance	Implementing carbon finance can provide financial guarantees for construction companies to carry out low-carbon projects. Also, it can restrain the economic development path.	(Fu et al., 2020; Liu et al., 2018; Luo et al., 2021; Qi et al., 2021)
S_{16}			Capitalization Level	The innovation-driven low-carbon transitions are characterized by large investments and long payback periods. Adequate funding from construction companies can encourage green technology innovation.	(Li et al., 2022; Liu et al., 2014; Song et al., 2020; Wang et al., 2021b)
S_{17}		Workforce	Low-carbon awareness	The low-carbon transitions depend on how stakeholders awareness low-carbon goods and technology, and it is challenging to promote the shift without altering stakeholder attitudes and actions.	(Gan et al., 2015; Poortinga et al., 2012)
S_{18}			Human capital level	Skilled and qualified workers can improve work proficiency for energy saving and emission reduction and promote innovative research and development of new technologies, products, and materials.	(Chang et al., 2016c; Li et al., 2020; Yang et al., 2018)
S_{19}	**Innovation niche**	Innovation strategy		A clear corporate vision and strategy can guide industry and business innovation and promote low-carbon	(Chang et al., 2016b; Jain et al., 2020; Yang et al., 2018)

		building technologies and product outputs.	
S_{20}	Innovation input	The rate of low-carbon technological innovation is directly influenced by the availability of finance and workforce. Moreover, the ability to create knowledge and learn can be improved with personnel investment.	(Li et al., 2022; Wang et al., 2021b; Wen et al., 2020)
S_{21}	Innovative cooperation network	Collaboration networks can synergize and integrate different social labor divisions regarding functions and resources, which can make it easier to combine production elements and knowledge flows in low-carbon innovation activities.	(Eline et al., 2018; Fu et al., 2020; Li et al., 2022)
S_{22}	Innovative learning capabilities	Innovation agents can progress from learning the fundamentals of low-carbon information to learning the more advanced concepts of developing low-carbon information norms and values that will ultimately develop low-carbon innovation.	(Jain et al., 2020; Xia et al., 2020)

4. Application of proposed framework

The interaction between the primary forces influencing the low-carbon transitions was clarified using the ISM. The 15 experts who evaluated whether "Si directly affects Sj" were given the identified drivers, as shown in Table 1. Since each expert had a different opinion considering the relationship between the factors, we adopted the "minority follows majority" principle to deal with the issue (Yang & Lin, 2020). The relationship between the factors could be established if at least eight experts agreed. After several discussions, the contextual relations were represented in a structured self-interaction matrix (SSIM), as shown in Table 3.

Table 3 Structural self-interaction matrix.

SSIM	S_{22}	S_{21}	S_{20}	S_{19}	S_{18}	S_{17}	S_{16}	S_{15}	S_{14}	S_{13}	S_{12}	S_{11}	S_{10}	S_{9}	S_{8}	S_{7}	S_{6}	S_{5}	S_{4}	S_{3}	S_{2}	S_{1}
S_{1}	O	O	O	O	O	O	O	O	O	O	O	O	O	X	O	O	O	O	O	A	O	
S_{2}	O	O	O	O	O	O	O	O	O	V	O	O	O	O	O	O	O	O	O	A		
S_{3}	O	O	O	O	V	O	O	X	O	O	V	A	O	O	O	O	O	O	O			
S_{4}	O	O	O	V	O	O	O	O	O	O	O	O	O	O	O	O	O	V				
S_{5}	O	O	O	O	O	O	V	O	O	O	O	O	O	V	O	O	V					
S_{6}	O	O	V	V	O	O	O	O	O	O	O	O	O	O	X	O						
S_{7}	O	O	O	O	O	O	O	O	O	O	O	O	A	X	A							
S_{8}	O	V	O	O	O	O	O	O	O	O	O	O	O	O								
S_{9}	O	A	A	O	O	O	O	O	O	O	O	O	A									
S_{10}	A	O	A	O	O	O	O	O	O	O	O	O										
S_{11}	O	O	O	O	O	O	O	V	O	O	O											
S_{12}	O	O	V	V	O	O	O	O	O	V												
S_{13}	O	O	O	O	O	A	O	O	A													
S_{14}	A	O	O	A	O	O	O	O														
S_{15}	O	O	O	O	O	O	V															
S_{16}	O	O	V	O	O	O																
S_{17}	A	O	O	O	A																	
S_{18}	V	O	O	O																		
S_{19}	A	O	X																			
S_{20}	O	X																				
S_{21}	X																					
S_{22}																						

The SSIM matrix can be converted into an adjacency matrix (AM), as shown in Table 4.

Table 4 Adjacency matrix.

AM	S_{1}	S_{2}	S_{3}	S_{4}	S_{5}	S_{6}	S_{7}	S_{8}	S_{9}	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}
S_{1}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{2}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_{3}	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0
S_{4}	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
S_{5}	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0

S_6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0
S_7	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
S_8	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
S_9	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{10}	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{11}	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
S_{12}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0
S_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S_{14}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_{15}	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
S_{16}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
S_{17}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
S_{18}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
S_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
S_{20}	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	1	0
S_{21}	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1
S_{22}	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1	0	1	0

The reachability matrix (RM) is constructed from the AM, as shown in Table 5.

Table 5 Reachability matrix.

RM	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}	Driving power
S_1	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
S_2	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2
S_3	1	1	1	0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	17
S_4	1	0	0	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	1	1	1	16
S_5	1	0	0	0	1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	1	1	1	15
S_6	1	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	1	0	1	1	1	1	13
S_7	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
S_8	1	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	1	0	1	1	1	1	13
S_9	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
S_{10}	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	4
S_{11}	1	1	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	18
S_{12}	1	0	0	0	0	0	1	0	1	1	0	1	1	1	0	0	1	0	1	1	1	1	12
S_{13}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
S_{14}	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	2
S_{15}	1	1	1	0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	17
S_{16}	1	0	0	0	0	0	1	0	1	1	0	0	1	1	0	1	1	0	1	1	1	1	12

S_{17}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	2
S_{18}	1	0	0	0	0	0	1	0	1	1	0	0	1	1	0	0	1	1	1	1	1	1	12
S_{19}	1	0	0	0	0	0	1	0	1	1	0	0	1	1	0	0	1	0	1	1	1	1	11
S_{20}	1	0	0	0	0	0	1	0	1	1	0	0	1	1	0	0	1	0	1	1	1	1	11
S_{21}	1	0	0	0	0	0	1	0	1	1	0	0	1	1	0	0	1	0	1	1	1	1	11
S_{22}	1	0	0	0	0	0	1	0	1	1	0	0	1	1	0	0	1	0	1	1	1	1	11
Dependent power	18	4	3	1	2	4	18	4	18	15	1	4	18	15	3	6	15	4	14	14	14	14	

The hierarchy level is determined by evaluating the antecedent set, the reachable set, and the intersection set, as shown in Table 6.

Table 6 Hierarchy level.

Factor	Reachability set	Antecedent set	Intersection set	Level
S_1	1,7,9	1,3,4,5,6,7,8,9,10,11,12,15,16,18,19,20,21,22	1,9,7	I
S_2	2,13	2,3,11,15	2	II
S_3	1,2,3,7,9,10,12,13,14,15,16,17,18,19,20,21,22	3,11,15	3,15	V
S_4	1,4,5,6,7,8,9,10,13,14,16,17,19,20,21,22	4	4	VI
S_5	1,5,6,7,8,9,10,13,14,16,17,19,20,21,22	4,5	5	V
S_6	1,6,7,8,9,10,13,14,17,19,20,21,22	4,5,6,8	8,6	IV
S_7	1,7,9	1,3,4,5,6,7,8,9,10,11,12,15,16,18,19,20,21,22	1,9,7	I
S_8	1,6,7,8,9,10,13,14,17,19,20,21,22	4,5,6,8	8,6	IV
S_9	1,7,9	1,3,4,5,6,7,8,9,10,11,12,15,16,18,19,20,21,22	1,9,7	I
S_{10}	1,7,9,10	3,4,5,6,8,10,11,12,15,16,18,19,20,21,22	10	II
S_{11}	1,2,3,7,9,10,11,12,13,14,15,16,17,18,19,20,21,22	11	11	VI
S_{12}	1,7,9,10,12,13,14,17,19,20,21,22	3,11,12,15	12	IV
S_{13}	13	2,3,4,5,6,8,11,12,13,14,15,16,17,18,19,20,21,22	13	I
S_{14}	13,14	3,4,5,6,8,11,12,14,15,16,18,19,20,21,22	14	II
S_{15}	1,2,3,7,9,10,12,13,14,15,16,17,18,19,20,21,22	3,11,15	3,15	V
S_{16}	1,7,9,10,13,14,16,17,19,20,21,22	3,4,5,11,15,16	16	IV
S_{17}	13,17	3,4,5,6,8,11,12,15,16,17,18,19,20,21,22	17	II
S_{18}	1,7,9,10,13,14,17,18,19,20,21,22	3,11,15,18	18	IV
S_{19}	1,7,9,10,13,14,17,19,20,21,22	3,4,5,6,8,11,12,15,16,18,19,20,21,22	19,20,21,22	III
S_{20}	1,7,9,10,13,14,17,19,20,21,22	3,4,5,6,8,11,12,15,16,18,19,20,21,22	19,20,21,22	III
S_{21}	1,7,9,10,13,14,17,19,20,21,22	3,4,5,6,8,11,12,15,16,18,19,20,21,22	19,20,21,22	III
S_{22}	1,7,9,10,13,14,17,19,20,21,22	3,4,5,6,8,11,12,15,16,18,19,20,21,22	19,20,21,22	III

The low-carbon transitions driving factors can be classified into six levels, as shown in Fig. 3.

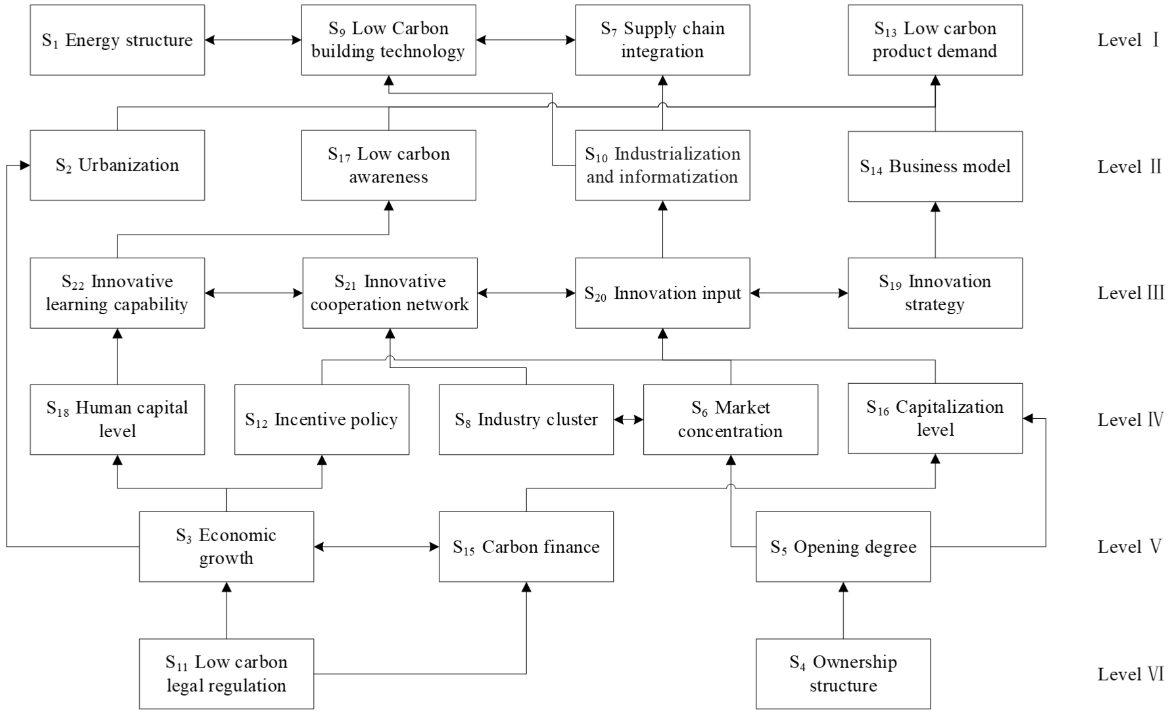

Fig. 3. Hierarchical structure model.

According to the driving and dependence power in the RM (Table 5), the MICMAC of low-carbon transitions driving factors is shown in Fig. 4.

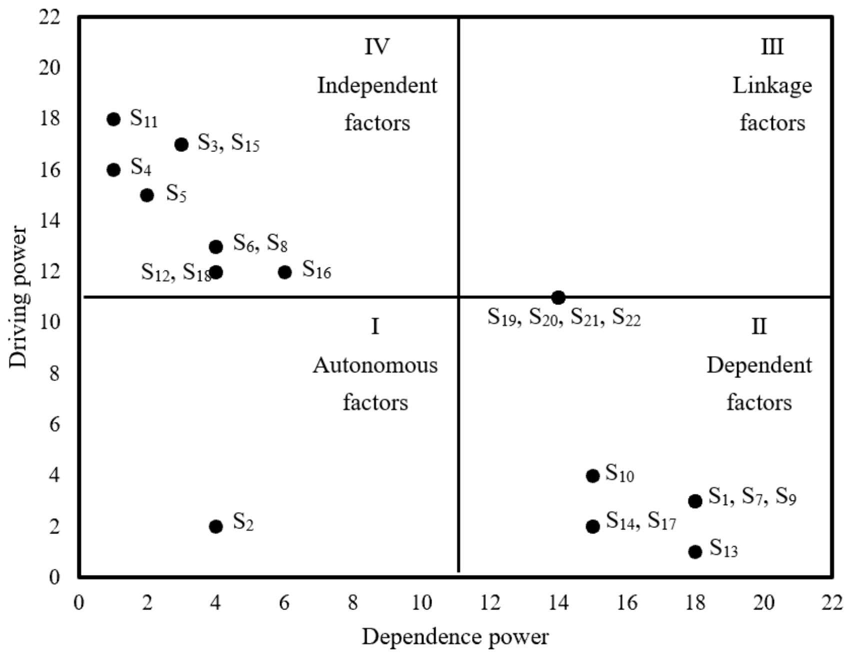

Fig. 4. Driving and dependence power diagram.

5. Results and discussion

Fig. 3 and Fig. 4 show that the drivers of low-carbon transitions can be divided into six levels, with the driving and dependence power of the factors distributed in four quadrants. Combined with the MICMAC result, the hierarchical structure can be further split into three groups: level I-level II are upper-level direct driving factors; level III-level IV are intermediate-level indirect driving factors, and level V-level VI are deep-level fundamental driving factors. Following is a detailed description of the three levels:

First, the low-carbon transitions are most directly affected by upper-level driving factors, which include energy structure (S_1), urbanization (S_2), supply chain integration (S_7), low-carbon building technology (S_9), low-carbon awareness (S_{10}), low-carbon product demand (S_{13}), industrialization and informatization (S_{14}), and business model (S_{17}). In the MICMAC analysis, urbanization (S_2) is the only autonomous factor that is relatively stable within the system and has a negligible effect on the low-carbon transitions. The remaining factors of the ISM model are dependent factors that others can affect and will improve significantly if other factors are developed.

Energy production and consumption are major sources of carbon emissions (Yang et al., 2021), which support the development of industrial and energy systems. The high carbonization of energy supply and consumption structures in the energy system would contribute to rising carbon emissions (Jiang et al., 2022). An effective way to encourage energy savings and emission reduction is to optimize the energy supply structure or alter the energy consumption structure. For the industrial system, low-carbon product project management, low-carbon technology development, and low-carbon product demand are the core of transitions (Hwang & Shan, 2018). The construction industry in China annually produces more than 30% of all buildings with high energy consumption characteristics. Consequently, low-carbon transitions depend on growing consumer demand for green and low-carbon buildings. It is essential to advance low-carbon building technologies to support low-carbon products, which can be achieved by updating related techniques. Furthermore, there is the potential to reduce carbon emissions at every stage of the building manufacturing process. Integrating the industrial supply chain and controlling the entire process can reduce carbon emissions.

Second, factors at the intermediate level are influenced by factors at the deep level and impact factors at the upper level. These factors include market concentration (S_6), industry cluster (S_8), incentive policy (S_{12}), capitalization level (S_{16}), human capital level (S_{18}), innovation strategy (S_{19}), innovation input (S_{20}), innovation cooperation network (S_{21}), and innovation learning ability (S_{22}). MICMAC considers innovation strategy (S_{19}), innovation input (S_{20}), innovation cooperation network (S_{21}), and innovation learning ability (S_{22}) as linkage factors. When these four extremely unstable factors interact with other factors, they will have an impact on themselves. It means that the formation of low-carbon innovation activities is unpredictable and highly reliant on human and financial resources and other elements. If innovative activities can be duplicated in social development, it will benefit the renewal and upgrading elements and contribute to the transitions to a low-carbon economy. Market concentration (S_6), industry cluster (S_8), incentive policy (S_{12}), capitalization level (S_{16}), and human capital level (S_{18}) are independent factors that can impact the whole system and must be prioritized during the transitions process.

Under the innovation-driven strategy, the spread and application of innovations, such as low-carbon building products, technologies, and business models, must be tested multiple times and matured in a particular environment before being put on the market. Innovation strategies, learning abilities, innovation inputs, and innovation cooperation networks can protect the growth of innovation activities (Wang et al., 2021a). Nevertheless, breakthrough innovations will not provide a competitive advantage over existing products in the early stages of development and will receive good performance feedback (Ilg, 2019). Therefore, the government should create incentives to encourage innovation within construction companies, major leading companies should take the initiative to carry out low-carbon projects and play a leading role in becoming better and stronger via independent research and development, and small and medium-sized businesses can grow in clusters to better integrate capital and human resources to support innovative activities (Xue et al., 2014). In addition, as the primary agent of innovation and the target of market development, enhancing human capital can improve the learning capacity of innovation subjects while contributing to the establishment of low-carbon consumption patterns and the development of low-carbon markets.

Third, the deep-level factors at the bottom of the hierarchical structure impact the intermediate-level and upper-level. Economic development (S_3), ownership structure (S_4), opening degree (S_5), low-carbon legal regulation (S_{11}), and carbon finance (S_{15}) are included in this level. All factors in MICMAC belong to independent factors that have a strong driving power and the foundation to the low-carbon transitions.

Transitions are guided by low-carbon rules and regulations, and tightening regulatory schemes and enforcement will accelerate low-carbon development. Carbon financing can provide financial support for low-carbon activities to increase the predictability of innovation (Agyekum et al., 2020). Ownership structure as part of the industry structure, the development of mixed ownership models can inspire the internal motivation of companies to enhance low-carbon practices (Yuan et al., 2021). In addition, encouraging the opening of construction companies from different regions or countries, both domestically and internationally, can eliminate local development protectionism and enable experienced construction companies to undertake projects, thereby drawing experience of the low-carbon transitions. Economic development and carbon financing will support innovative activities with money, human, and policy to bridge the gap between innovative products and industrial development.

In conclusion, reforming the building industry's structure and organization and establishing low-carbon legal standards are the driving forces behind economic progress and financial growth. The growth of the economy can further optimize the energy system, whereas innovation can drive updates to the industrial system. Innovative products with market-competitive characteristics, such as low-carbon building technologies, low-carbon products, and business models, will progressively develop and mature in the innovation protection space generated by policies, human and financial resources, thereby driving the development of low-carbon innovation in enterprises and boosting the transitions and upgrading of the industry.

A comprehensive identification of the drivers is required, as is a deep understanding of the responsibilities of the different stakeholders in the low-carbon transitions of the construction industry. Fig. 5 depicts the multi-stakeholder collaborative system for low-carbon transitions in the construction industry. The construction industry's low-carbon transitions are a dynamic change process driven by the transition environment, multi-stakeholder, and multi-dimension aspects in a co-evolutionary manner. The environment necessitates that the construction industry's transitions consider the low-carbon development of the economy, society, ecology, and civilization. The multi-stakeholder group, consisting of governments, construction companies, intermediary agencies, financial institutions, university research institutions, and end users, must coordinate. Multi-dimension aspects recommend more reforms in the construction industry regarding industrial structure, organization, policy, technology, market, finance, and workforce. Each stakeholder has different resources and skills, so the transition process must be controlled by constant self-adjustment and cooperation with other stakeholders. Following is a detailed analysis of various stakeholders.

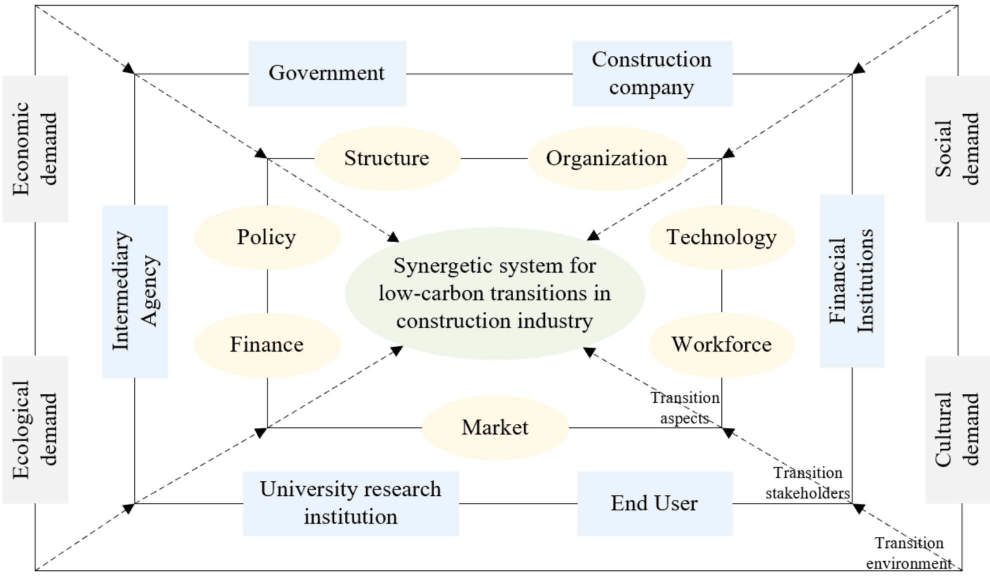

Fig. 5 Multi-stakeholder collaborative system for low-carbon transitions in the construction industry

(1) For governments. The governments should guide and stimulate the development of innovations in low-carbon building construction by formalizing low-carbon rules and regulations and establishing incentive policies. Additionally, as low-carbon construction products would have externalities in their early stages of development, the government should provide specific economic tools to eliminate or decrease the influence of externalities.

(2) For construction companies. The efficiency and quality of low-carbon transitions in the construction industry depend on companies' capital and personnel investments. Larger companies should take the lead in low-carbon transitions and actively engage in innovative activities. Small and medium-sized companies constrained by scale, capital, and technical strength generally lack the drive for transitions but can pool resources through clusters to support low-carbon innovation.

(3) For intermediary agencies. Intermediary service agencies are commonly

prevalent among governments, companies, and university research institutes, providing services for both supply and demand. To accelerate the spread of information, intermediary agencies should discover and collect information on low-carbon innovation from various sources and deliver the most current technical knowledge to companies and university research institutions.

(4) For university research institutions. To accelerate the transitions to low-carbon building, university research institutions should offer relevant courses on low-carbon construction to train professionals and technicians, challenge the conventional paradigm through academic research, and collaborate with companies engaged in industry-university research.

(5) For financial institutions. Construction companies are likely to incur high opportunity costs and earn low profits for investments in low-carbon research and team training during the transitions. Financial institutions must create effective financial products (e.g., low-carbon financing funds, trusts, etc.) to provide finance support.

(6) For end users. Users are the final consumers of innovative low-carbon products. They can represent market demand and provide original suggestions and feedback on product use for low-carbon construction innovation. Improving low-carbon user awareness and developing consumption concepts should be prioritized to increase the proportion of low-carbon building products and encourage the establishment of a low-carbon building market.

6. Conclusion

The construction industry is one of the most significant contributors to China's carbon emissions, and achieving a low-carbon transitions in the construction industry is critical to the sustainable development of society. Therefore, it is essential and valuable to investigate the direction of an effective low-carbon transitions. Low-carbon transitions in the construction industry is a complex system and a type of socio-technical transition influenced by multi-dimension factors such as industry, technology, market, policy, and the general public. However, most prior research had concentrated on a single aspect of the complex system and lacked a systematic approach for in-depth analysis. Thus, this study aimed to identify the drivers of low-carbon transitions in the construction industry and understand their interrelationships and impacts. In order to achieve the goal, this study introduced MLP as a heuristic structure that identifies 22 significant factors through a systematic literature review and expert survey. A hierarchical assessment of the factors and their degrees of impact was provided using ISM and MICMAC analyses.

The results reveal that the 22 drivers can be categorized into six levels of hierarchy. Moreover, combined with MICMAC analysis, low-carbon legal regulation (S_{11}) has the most vital driving force and is more influential on other factors. In addition, the growth of carbon finance will also provide a powerful driving force for the transitions. Energy structure (S_1), supply chain integration (S_7), low-carbon building technology (S_9), and low-carbon product demand (S_{13}) are the most dependent and multiple performances of the low-carbon transitions of the construction industry, which must be accomplished with the accumulation of other factors.

The following are managerial and policy implications for the construction industry's transitions to low-carbon practices: (1) establishing specific low-carbon legal regulation and clarifying the direction of transitions for each step is the fundamental task; (2) developing the economy and implementing relevant financial policies can provide financial support for low-carbon innovation and enhance stakeholders' motivation; (3) optimizing the industry's structure and organization can reshape the construction industry's character and profoundly drive its revolution; (4) providing sufficient financial and personnel resources to help develop and protect low-carbon innovation activities that could make the final low-carbon products or technologies competitive in the market; (5) clarifying the tasks and responsibilities of the multi-stakeholder involved in the low-carbon transitions of the construction industry and raising low-carbon awareness to help the transitions happen collaboratively.

In terms of theoretical implications, this study contributes to the existing knowledge system on low-carbon transitions in the construction industry. Based on the current state of low-carbon carbon growth in the construction industry, MLP was utilized to assess the transition driving mechanism, which extended the research scope of MLP. Additionally, the applicability of the ISM-MICMAC approach in other fields was improved.

A few limitations should be acknowledged for future studies. First, the reliability of the judgment of the relationships of factors depended on the knowledge and cognition of the interviewees. Therefore, future research opportunities can be conducted on the effectiveness, dynamics, and quantifiability of the drivers for low-carbon transitions in the construction industry. Second, this study is an exploratory analyze and lacks regional specificity. There are regional differences in the low-carbon transitions of the construction industry result from the influence of factors, including geographic location, resource allocation, and economic development. Future studies can be done based on the state of low-carbon development in the construction industry in various provinces to propose particular transition strategies.

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