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A Study of Collaborative Innovation Mechanism of Prefabricated Construction Enterprises Using Order Parameter

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In innovation-driven development, collaborative innovation is gradually becoming a critical sustainable way for prefabricated construction enterprises (PCEs). However, academia and industry do not have a deep understanding of the collaborative innovation of prefabricated construction enterprises (CIPCE), and there is a lack of quantitative-driven research. This study aims to analyze the composition of the CIPCE and measure the operation process and results of the mechanism based on the order parameter. First of all, this study uses semi-structured interviews to analyze the mechanism of CIPCE in the current construction environment. Next, combining structured interviews and literature analysis, the original data was obtained through a questionnaire survey from 15 PCEs in Shenyang, China. Finally, according to the order parameter method, the operation process and results of the CIPCE mechanism are further measured, that is, the synergy and innovation performance that affects its decision-making. The results show that the CIPCE includes four sub-mechanisms: dual drive, resource supply, collaborative operation, and trust guarantee. The orderliness of enterprises has risen overall with partial fluctuations, and the synergy is low. Enterprise innovation performance generally presents a relatively high, but local fluctuations lead to continuous changes. These findings point out the direction for PCEs to maintain their competitiveness in response to the climate crisis and provide action guidelines for the future construction industry to minimize the negative impact on the environment.

Keywords: low-carbon, prefabricated construction enterprise, collaborative innovation, synergy, innovation performance

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1 INTRODUCTION

In recent years, tackling climate change has become an important issue for global development. Urbanization has promoted the large-scale growth of the worldwide construction industry and brought challenges to contain climate change (Lai et al., 2019). 2020 Global State Report for Building and Construction indicated that building carbon emissions account for 35%–38% in total. The proportion of high carbon emissions has brought resistance to the construction industry (Hou et al., 2021). Due to the enormous construction scale, China committed to achieving carbon peak and carbon neutrality (namely double carbon) Two study questions were developed: at the United Nations General Assembly in 2020 to better respond to climate change. Based on this goal, it is indispensable to use carbon emission reduction technologies to optimize the built environment at all stages, such as manufacturing, transportation, construction, maintenance, repair, and end-of-life (Kong et al., 2020).

Prefabricated buildings (PBs) have outstanding benefits in life-cycle carbon reduction, which are essential for the construction industry to achieve the double carbon goal (Zhang et al., 2019; Li et al., 2020). PBs produce carbon emission saving advantages through intensive, large-scale, mechanized production and on-site construction (Kong et al., 2020). For example, prefabricated construction enterprises (PCEs) adopt an intensive construction mode to reduce material consumption, water and sewage discharge, noise disturbance, and dust pollution at the construction site through large-scale production. The mechanized installation avoids the occurrence of large-scale construction waste.

China's government has issued many policies to stimulate innovation in PCEs to reduce carbon emissions. In parallel, such digital technologies, including the digital twin, building information modelling (BIM), and the internet of things, have promoted the PBs to develop green and low-carbon (Shi et al., 2019; Li et al., 2021). With the advent of the intelligent construction era, intelligent construction can effectively solve the inherent defects of PBs and further reduce carbon emissions, making PCEs more resilient in their supply chains (Watanabe et al., 2004). The PBs market has generated diversified demands for innovation related to carbon emissions. Facing the complicated built environment, PCEs focus on the invention of carbon emission reduction, which has become a hot spot of the competition (Wang and Sinha, 2021). Once a PCE achieves innovation, the company has core competitiveness. Therefore, PCEs must use breakthrough crucial core technologies and active innovation to seek ecological and economic benefits. However, due to the weak ability of PCEs to undertake projects, it is difficult for a company to complete an entire project alone (Du et al., 2019; Liu et al., 2019). Few PCEs have mastered all advanced technologies at the same time. Even leading companies need to link upstream and downstream companies in the industry chain to improve their innovation capabilities through collaboration. There are specific barriers among PCEs, which make innovation activities difficult. Collaborative innovation (CI) has become the key to the sustainable development of PCEs.

In the past 20 years, a series of studies focused on the collaborative innovation of prefabricated construction enterprises (CIPCE) from various aspects, such as intelligent construction (Wang et al., 2020; Wen, 2021), building industrialization (Kochovski and Stankovski, 2018; Zhou and Zeng, 2018), as well as an industrial chain (Zeng et al., 2020; Zhang et al., 2020). These studies highlighted the significance of collaboration in construction through cross-disciplinary, cross-industry, and cross-sector innovation activities. Specifically, PCEs established a BIM data management platform to realize the effective transmission and real-time sharing of BIM data in the survey, design, production, construction, acceptance, and others (Edirisinghe, 2019). Such primary platforms, including the intelligent production platform for parts and components, the intelligent logistics platform for building materials, the brilliant installation and the innovative park management service platform, and the building material centralized procurement platform, solved the information flow integration problem in the industrial chain and improved the competent construction degree (Ding et al., 2018). PCEs formed a collaborative organization network to realize the deep integration and innovation of intelligent construction and construction industrialization (Hartley et al., 2013; Howard et al., 2016). However, most previous studies usually adopted a qualitative-driven approach to explaining collaborative innovation from specific aspects, such as information, organization, and platform. There is a shortage of research taking quantitative-driven methods into the studies. Despite a growing awareness of the importance of CIPCE, the complex operating mechanism, process, and results of the system have remained unclear. To fill these gaps, an in-depth analysis of how PCEs work together to promote collaborative innovation and measure the process and results of system operation. Two study questions were developed:

RQ1: What is the potential mechanism for the CIPCE?
RQ2: In the current built environment, what is the operational process and results for the CIPCE?

The CIPCE mechanism has the characteristics of complexity and is affected by many parameters in the evolution process. When the various sub-mechanisms of CIPCE move together to a certain critical point, they usually produce some connection. This close connection may produce cooperative cooperation or competition and control the movement of the sub-mechanisms, resulting in the appearance of order parameters within the system (Yang et al., 2021). The order parameter is not only the representation of the degree of coordination of the sub-mechanisms but also the result of any form of cooperation between the sub-mechanisms, and it has crucial guidance for the internal research of the mechanism (Berasategi et al., 2011). Therefore, this study adopted the order parameter method to analyze the mechanism, operational process, and results of the CIPCE, including the following four steps:

(1) he study extracted CIPCE data in Shenyang, including order parameters such as type, scale, output value, scientific research investment, and others, through the official website and questionnaire.
(2) CIPCE in Shenyang was deeply analyzed to explore the mechanism composition.
(3) Synergy and innovation performance were explored to explain the operational process and results. The order parameter order degree, mechanism synergy degree and innovation performance of the base period and the inspection period were calculated.
(4) Targeted policy implications were proposed to guide the sustainable development of PCEs. More specifically, the findings of this study shed new light on ways to promote carbon emission reduction in the whole life cycle of PBs and improve the innovation performance of PCEs.

The remainder of this study is organized as follows. **Section 2** reviews the innovation in the realm of PBEs, along with the CI in the enterprises. **Section 3** provides an overview of the CIPCE and its research methods and processes. **Section 4** A detailed analysis of CIPCE is presented, including the mechanism composition, operational process, and operational results. **Section 5** discusses the results of this study, followed by policy implications. **Section 6** reports the conclusions and suggestions for future research.

2 LITERATURE REVIEW

2.1 Innovation of the PCEs

Due to the outstanding benefits of PBs in reducing carbon emissions, a series of studies have been discussed (Han et al., 2012; Yu et al., 2013; Kalasapudi et al., 2015). With the development of PBs, PCEs encounter obstacles in construction, such as policy requirements (Pittaway et al., 2004; Choi et al., 2008), enterprise competition (Bygballe and Ingemansson, 2014), and market demand (Buchli et al., 2018; Wang et al., 2021). Innovation is the critical strategy for PCEs to address these issues (Gann and Salter, 2000).

PCEs usually rely on innovation to expand their market share from different aspects. For example, they were combining natural materials with prefabricated components (Walker and Thomson, 2013), researching new building materials (Telesca et al., 2013), optimizing construction robotic hoisting technology (Martinez et al., 2008), and innovating the application of BIM in PBs (Poirier et al., 2015; Edirisinghe, 2019). Such as talent, information, knowledge, policy have a substantial impact on innovation for PCEs (Han et al., 2012; Connell et al., 2014; Knoke et al., 2017). These factors hinder the sustainable development of PCEs. In order to break through the innovation barriers between PCEs and external enterprises, network behaviours play a role in risk-sharing and technology complementarity (Hadjimanolis, 1999; Wang et al., 2014; Maietta, 2015). CI is considered an effective way for PCEs to realize innovation. The spontaneous and orderly organization of materials, information, and energy for PCEs is conducive to improving the construction industry's resilience (Haken, 2000; Lee et al., 2012). Despite the importance of CIPCE, there is still a lack of research on this issue. CIPCE not only on theoretical study but also needs to be measured to clarify the innovation ability, which can improve the competitiveness among PCEs (Vega-Jurado et al., 2008b; West and Bogers, 2013; Dooley et al., 2016a; Wang et al., 2020a).

2.2 CI of the Enterprises

CI has become an essential concept concerning the development of enterprises (Walsh et al., 2016). It was found that when the aggregation state of the material reaches a particular critical value under the influence of the external construction environment through tracking the evolution trajectory of CI, there will be synergy among various sub-mechanisms (Zhao et al., 2018). Synergy causes the sub-mechanisms to produce qualitative changes at the critical point, making a synergistic effect and forming an orderly structure. CI is dynamic. Innovation stakeholders continue to evolve to realize the interaction of material, information, and energy with the construction environment (Fang et al., 2018; Jiao et al., 2019). There are competitive and cooperative relationships among enterprises. Enterprises improve synergy and innovation performance through social interaction and network innovation activities (Schulze and Brojerdi, 2012; Maietta, 2015; Senghore et al., 2015).

Synergy represents the operational process of the sub-mechanism. Various factors affect corporate resilience during the operation of the sub-mechanism (Maietta, 2015). The scale of the organization and the diversity of the organizational objects will influence whether the CI goals can be achieved (Dooley et al., 2016b). Organizational background factors are considered potential moderators of CI (Vega-Jurado et al., 2008a; West and Bogers, 2014). Such a short distance of technology and management knowledge helps the whole-process innovation (Schulze and Brojerdi, 2012). These factors work together to promote enterprises improve synergy by enhancing market competitiveness (Anzola-Roman et al., 2019).

Innovation performance represents the operational results of the sub-mechanism. The collaborative network influences the innovation performance of sub-mechanisms through vertical and horizontal collaboration, which has found that the former is more significant than the latter on innovation performance (Hadjimanolis, 1999; Wang et al., 2014). Collaborative networks of different industries and regional levels improve corporate innovation performance by integrating resources (Chesbrough and Garman, 2009; Shapiro et al., 2010; Woodhead et al., 2018).

These approaches can all contribute to CIPCE.

(1) Innovation helps PCEs overcome obstacles.
(2) CI is one integrated approach to promote the sustainable development of PCEs.
(3) The CIPCE consists of several sub-mechanisms.
(4) The operational process and results of the sub-mechanism of CIPCE are characterized by synergy and innovation performance.

3 RESEARCH METHODS

3.1 Data Sources

Although PBs are still in their infancy in China, the government pays more attention to the development. In China, Shenyang, Liaoning province, is the pioneer of PBs, which became the only pilot city for the modern construction industry in 2011 and the first demonstration city for PBs in 2017. Over the years, Shenyang has built several prefabricated construction industry bases through an external introduction and internal cultivation. To facilitate the sustainable development of the PCEs, the Ministry of Housing and Urban-Rural Development of the People's Republic of China launched the National Prefabricated Construction Industry Base in 2017 and 2020. Specifically, Shenyang has four prefabricated construction industry bases: China Northeast Architectural Design & Research Institute Co., Ltd., Sanxin Group, Shenyang Zhongchen Steel Structure Engineering Co., Ltd., and Shenyang Zhaohuan Modern Building Components Co., Ltd., Liaoning Province also launched a provincial prefabricated construction industry base to

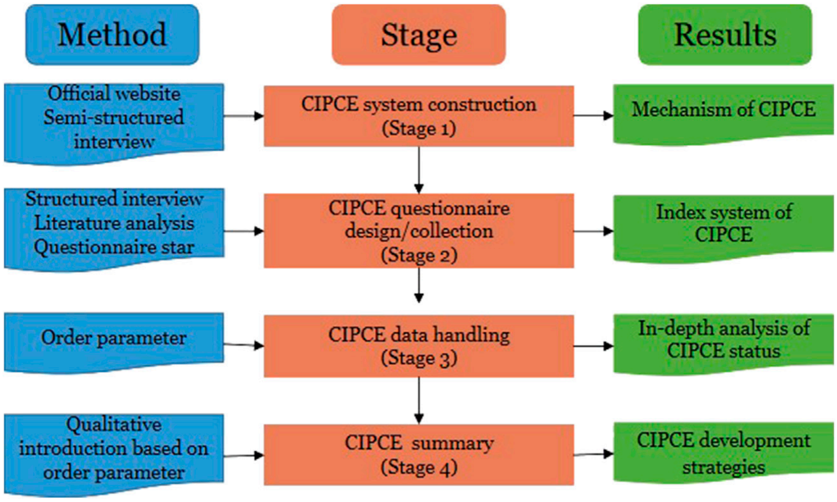

FIGURE 1 | Research flowchart.

commend PCEs that have made significant contributions to the promotion of PBs. There are 11 prefabricated construction industry bases in Shenyang, including Shenyang Weide Technology Group, Shenyang Jiuhong Construction Technology Co., Ltd., Therefore, there are 15 prefabricated construction industry bases in Shenyang. They cover the entire industrial chain of development, construction, design, scientific research, decoration, consulting and supervision, production of prefabricated components and parts, and material and equipment supply. With the launch of the "Thirteenth Five Year Plan" and industry conferences and forums, they built the brand for PCEs in Shenyang by actively adopting CI, introducing innovative talents, optimizing resource allocation, proposing innovative ideas, and increasing industry-university-research cooperation. These leading enterprises are typical of the CIPCE in Shenyang to a large extent.

3.2 Research Methods and Processes

CIPCE is a complex organizational behaviour, and the non-linear relationship between elements drives the innovation process. There is a correlation between various functional departments within an enterprise, and the ability to coordinate and participate in practice is an essential guarantee for the realization of collaborative innovation. Through the organic integration of technology, capital, resources, talents, and other elements, various innovation stakeholders interact to produce synergy, and the order parameter promotes collaborative innovation development from disorder to order structure. Therefore, this study uses qualitative and quantitative methods to determine the order parameters to clarify the indicators and measure the synergy and innovation performance based on the order parameter method. The research flowchart in this study is shown in **Figure 1**.

Firstly, a preliminary understanding of CI is done through the official website of PCEs. After analyzing the relevant text content, the mechanism of CIPCE is discussed. The semi-structured interview is based on a semi-open dialogue model to collect qualitative representations, which is convenient to collect qualitative data. This study selected 3 PCEs executives and three experts as interview objects familiar with the work and have a long working experience. Based on the CIPCE related literature and materials, the following questions were listed as the interview outline to optimize the mechanism of CIPCE:

(1) How familiar are you with CIPCE?
(2) What do you think is the driving force for CIPCE?
(3) Do you think the supply of PCE resources is sufficient in the CIPCE process in Shenyang? Why?
(4) What do you think is the current status of CIPCE?
(5) What areas do you think the CIPCE in Shenyang needs to improve?
(6) What do you think should be the layout and planning of CIPCE in Shenyang?
(7) In your opinion, which country regions are currently performing well in CIPCE? What are the lessons learned?

Secondly, Citespace is an essential tool for literary analysis, which displays the keyword clustering graph and clustering sequence graphs helpful for constructing the index system. This study selects the core collections in Web of Science as the data source of CIPCE research. According to the research topic, the subject word segment "collaborative innovation of enterprises" is limited, the period is 2001–2020, and the document type is Article& Review. Combined with semi-structured interviews about the mechanism of CIPCE and systematic analysis of 362 representative kinds of literature, the index system of CIPCE was initially designed. The index system in this work is somewhat subjective. To further improve the rationality and science of the CIPCE index system, this study develops the first round of questionnaires for stakeholders. The respondents of this round of questionnaires are mainly experts, scientific researchers, and business leaders in related work. A total of 45 questionnaires were distributed, and 39 questionnaires were returned.

Based on the first round of questionnaires, structured interviews were conducted with the previous six interview objects to adjust and screen the indicator system. Based on the prior round of empirical screening of indicators, the second questionnaire took the personnel engaged in CI-related work in 15 PCEs as the object of this study. Questionnaire stars are used for distribution and collection. One hundred forty-seven valid questionnaires were obtained, satisfying the questionnaire's required sample requirements. The prefabricated components accounted for at most 21.1%, and consulting & supervision enterprises accounted for 8.8%.

Thirdly, based on the order parameter, this study constructs the sub-mechanism order degree model, the overall mechanism synergy model, and the innovation performance measurement model to deeply explore the operational process and results of the mechanism of CIPCE.

CIPCE consists of several sub-mechanisms, assuming that the order parameters of the sub-mechanisms are $X_i=(X_{i1}, X_{i2}, X_{i3}, ..., X_{in})$, $n\in[1,+\infty)$, $n\in N$, $\alpha_{ij}\leq X_{ij}\leq\beta_{ij}$, $i\in[1,n]$, β and α respectively represent the upper and lower bounds of the order parameter X_{ij} for the sub-mechanism of CIPCE at the critical point. The order degree for the order parameter of sub-mechanism X_{ij} is calculated as follows:

$$U_i\left(X_{ij}\right) = \begin{cases} \dfrac{\left(X_{ij}-\beta_{ij}\right)}{\left(\alpha_{ij}-\beta_{ij}\right)}, j\in[1,t] \\ \dfrac{\left(\alpha_{ij}-X_{ij}\right)}{\left(\alpha_{ij}-\beta_{ij}\right)}, j\in[t+1,n] \end{cases} \quad (1)$$

Assuming that the initial time is T_0, and the synergy of the sub-mechanism is $U_i^0(X_i)$ $i = 1, 2, 3, ..., n$, for a sure time T_1, if T_1, $U_i^1(X_i)$ $i = 1, 2, 3, ..., n$, defined Synergy of Collaborative Innovation Mechanism (SCM):

$$SCM = \mu\sum_{i=1}^{n}\tau_i\left|U_i^1(X_i) - U_i^0(X_i)\right| \quad (2)$$

Entropy-topsis is the typical approach for enterprises to measure innovation performance. As a limited scheme multi-objective decision-making method, it has universal applicability, which calculates the Euclid distances D_i^+ and D_i^- between each index and the positive and negative ideal solution to measure the closeness of each unit to the perfect solution C_i:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(i_j^+ - z_{ij}\right)^2}, D_i^- = \sqrt{\sum_{j=1}^{n}\left(i_j^- - z_{ij}\right)^2} \quad (3)$$

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (4)$$

$Z_{ij} = \omega_j \times Y_{ij}$, $I_j^+ = \max(z_{1j},z_{2j},z_{3j},\bullet\bullet\bullet,z_{mj})$, $I_j^- = \min(z_{1j},z_{2j},z_{3j},\bullet\bullet\bullet,z_{mj})$

Based on the academic synergy and innovation performance grade division, this study divides synergy and closeness values into continuous intervals to determine the grade classification (see **Table 1**).

TABLE 1 | Grade of CIPCE.

Synergy	Collaboration level	Closeness	Innovation level
(−1, 0]	Non-cooperative	[0, 0.25]	Low performance
(0, 0.4]	Low synergy	(0.25, 0.5]	Moderate performance
(0.4, 0.7]	Moderate synergy	(0.5, 0.75]	Higher performance
(0.7, 1]	Highly synergy	(0.75, 1]	Highest performance

Finally, a qualitative study is carried out according to the calculation of the operation process and results for the CIPCE mechanism. This study discusses the countermeasures for improving the ability for CIPCE.

4 SYSTEMATIC ANALYSIS

4.1 Mechanism Analysis

The mechanism of CIPCE is composed of relevant data and facts. According to the data from the PCEs official website and the conclusions of the semi-structured interviews, it is clear to preliminarily analyze the current situation of CIPCE in Shenyang, which helps to further definite the CIPCE mechanism in Shenyang. This paper divides CIPCE into four sub-mechanisms through in-depth analysis, including dual drive, resource supply, collaborative operation, and trust guarantee (Baldwin and von Hippel, 2011; Hartley et al., 2013; Alford and Duan, 2018).

Dual driving aims to form a driving force based on the integration and complementation of valuable resources of PCEs. Government guides PCEs to increase the initiative of CI actively. Such stakeholders, universities, intermediaries, and financial institutions, jointly create the core competitiveness of the market and provide the driving force for technological innovation and sustainable development in the realm of PBs. The total usage of prefabricated concrete components and the proportion of PB area in Shenyang during the "Thirteenth Five-Year Plan" period has increased rapidly for 2 years under the leadership of PCEs. The internal and the external driving forces of PCEs work together to drive upstream and downstream enterprises in the modern construction industry chain to invest and build factories in Shenyang.

Resource supply is the basis for the effective operation of CIPCE. To optimize the allocation of resources in the realm of PBs and achieve industrial upgrading, Shenyang has released a variety of policy dividends and invested resources, such as capital, talents, and technology. PCEs, take the lead in establishing an expert database to promote the training and cultivation of industry professionals. It enables the seamless docking of technology and demand and the deep integration of technology and capital. In particular, PCEs in Shenyang participated in compiling several national and industry standards and were responsible for editing many local standards. Also, the top 500 companies worldwide are introduced to Shenyang for

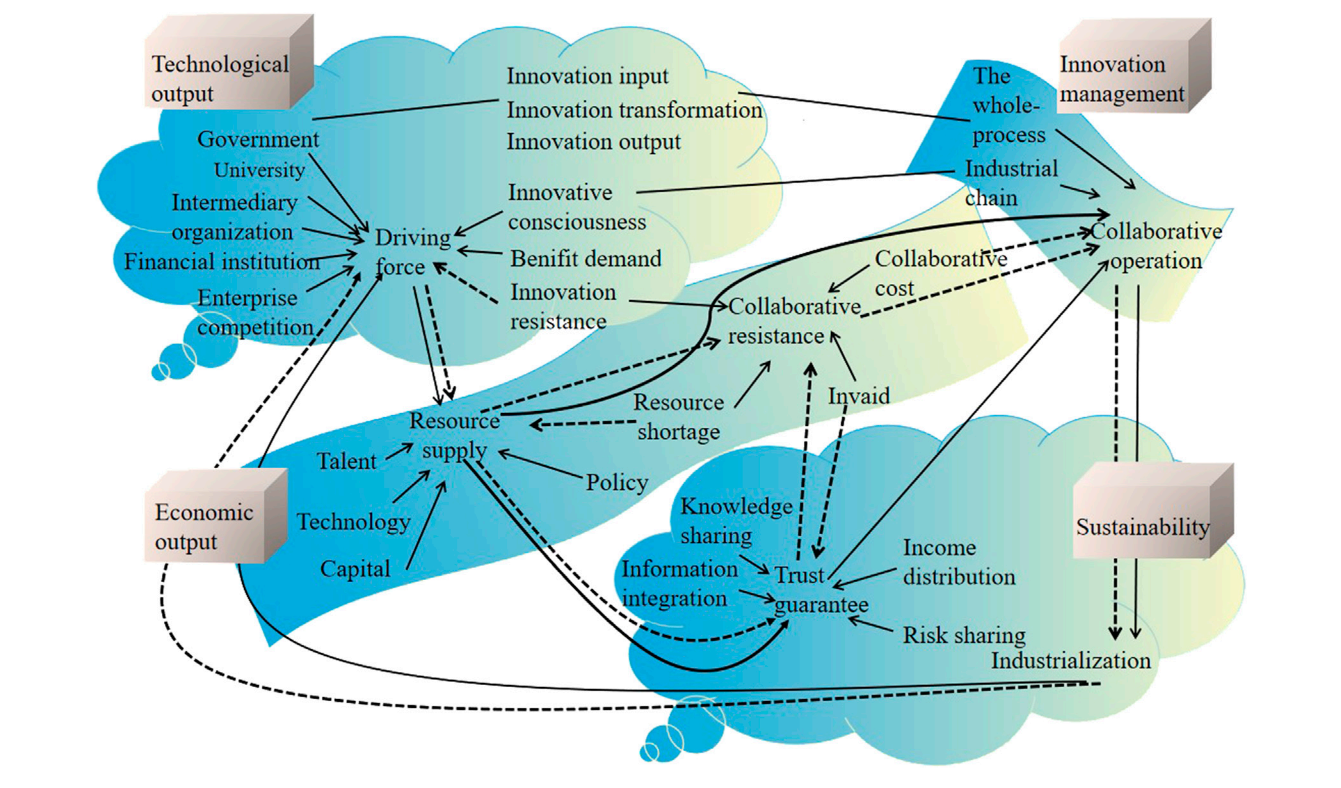

FIGURE 2 | The paths of the mechanism for CIPCE.

landing PBs to promote the integration of low-carbon buildings and new technologies.

Collaborative operation refers to injecting intangible assets such as new technologies into PCEs, improving construction enterprises' construction quality and efficiency, and realizing value increase. From the perspective of the whole process, PBs in Shenyang have created a lovely atmosphere for industry-university-research cooperation. PCEs in Shenyang have hundreds of core technology intellectual property rights, and they apply for authorization of invention patents, utility model patents, and computer software copyrights in dozens of them each year. They also pay great attention to the cultivation of independent research capabilities and the transformation of results. In addition, they have also carried out joint research on crucial technologies with other well-known manufacturers in the United States, Germany, Australia, and Japan. They have close ties with leading companies in other industries such as Mengniu Dairy Group and China Aerospace. From the perspective of the industrial chain, PCEs have promoted many EPC general contracting and BIM application projects and have been awarded multiple honorary titles under advanced design concepts and innovative strategies. They consistently pay attention to the latest development of PBs, boldly explore the application of scientific production models, and create a large number of classic representative projects. In order to promote the provision of modernized full-industry chain services for the construction industry, PCEs have established a good reputation in the industry and successfully built a strong brand of PBs in Shenyang.

The key to the smooth operation of CIPCE is the trust of innovation stakeholders and the multi-faceted guarantee. The government actively promotes the development of intelligent construction and joint research between PCEs and innovative construction industry chain companies such as robotics, drones, and software companies to reduce corporate investment risks. Integrating PBs, intelligent construction, and digital management, PCEs promote the innovative application of a new generation for information technology and advanced intelligent construction equipment and realize the collaborative development of intelligent construction and building industrialization. PCEs have participated in government-organized exchange meetings or hosted innovation conferences many times to solve the issues, such as knowledge sharing, information integration, profit distribution, and risk sharing, to enhance the trust guarantee ability.

4.2 Synergy Analysis

To further explore the mechanism of CIPCE, this study measures the synergy from the perspective of the mechanism operational process (see **Figure 2**). The synergy measurement includes eight order and 22 sub-order parameters (see **Table 2**).

4.2.1 Dual Drive

The dual drive includes internal driving force and external driving force. The former mainly consists of the interest

TABLE 2 | Index system of synergy.

Sub-mechanism	Order parameter	Sub-order parameter	Evaluation index
Dual drive (DD)	Internal drive	Benefit demand	The growth rate of total output value
		Innovative consciousness	Enterprise research investment
	External drive	Government promotion	Policy support
		University promotion	High-level research team
		Intermediary organization promotion	Intermediary service capacity
		Financial institution promotion	Financial support
		Enterprise competition	Industry competitiveness
Resource supply (RS)	Innovative resource	Talent supply	Number of scientific researchers
		Technology supply	Technology transformation service capability
		Capital supply	Investment in scientific activities
	Agglomerated resource	Policy supply	Policy implementation
Collaborative operation (CO)	The whole-process collaboration	Innovation input	Research investment intensity
		Innovation transformation	Maturity of scientific achievements
		Innovation output	Number of technical contracts
	Industrial chain collaboration	Supply-demand chain collaboration	Diversified financing system
		Value chain collaboration	Degree of corporate relevance
		Enterprise chain collaboration	Degree of technology gradient relevance
		Space chain collaboration	The brand effect of regional enterprises
Trust guarantee (TG)	Trust	Knowledge sharing	External communication
		Information integration	Information sharing degree
	Guarantee	Income distribution	Satisfaction with income distribution mode
		Risk sharing	Critical risk identification and control

demand and the willingness to innovate for the PCEs. The latter provides government promotion, university promotion, intermediary organization promotion, financial institution promotion, and enterprise competition.

Different PCEs have differentiated requirements, which drive companies to seek benefits with superior resources. As the innovation stakeholder of the construction industry, when it shows demand for new materials, new technologies, new processes, new products, new equipment, and new markets in the built environment, to maintain or increase the current profit, PCEs urgently carry out technical research. In the context of carbon emission reduction, the traditional construction mode in construction has been challenged, making the application of digital technology for PBs more widespread. It has become the sustainable focus for PCEs to combine virtual digital with engineering reality. The independent innovation consciousness in PCEs has been strengthened in the built environment. PCEs must rely on the joint role of innovation stakeholders to improve the development resilience of PBs.

The sustainable development of PCEs is affected by governments, universities, intermediaries, financial institutions, and other enterprises. The government has formulated many technologies, finance, and talents policies conducive to CIPCE. Universities are good at cutting-edge research on PBs based on original innovation. Market development is hazardous. It is challenging to realize universities' innovative research, transformation, and industrialization achievements. Universities and PCEs can effectively solve the problems of high original innovation cost, long cycle, and high risk through integrated innovation, digestion, absorption, and re-innovation. PCEs introduce innovative achievements into the market, which will help expand the market share. Universities, research institutes, and PCEs have communication barriers, and they have poor mobility in the sharing of technology, information, and resources. Intermediary agencies are just building a bridge between research and industrialization, and they can effectively promote the integration of technological innovation resources. Generally speaking, the automation of new technology needs to be strictly demonstrated. PCEs need many funds in this process, and financial institutions' support can effectively alleviate the financial pressure. Facing the development opportunities of low-carbon environment construction, PCEs are increasing. In the current competitive situation, CI has become a necessary means to ensure the sustainable development of enterprises.

4.2.2 Resource Supply

Resource supply mainly refers to the establishment of collaborative platforms to realize the regional carbon emission reduction goals, and innovation stakeholders focus on innovative resources and agglomerated resources.

In CIPCE, the supply of innovative resources is inseparable from talents, technology and funds. PBs talents participate in the innovation for high-precision and key technologies. Innovation stakeholders share the pressure to face uncertain technology and management innovation risks. Universities provide original, innovative technology for research through major theoretical innovation, use the transformation service platform of intermediary institutions to transform scientific achievements, and the government and financial institutions provide assistance from the perspective of funding.

The agglomerated resource is manifested in policy supply, regulating the potential risks in CIPCE. The realization of the dual carbon goal requires policies to help the healthy development of PCEs by gathering various resource advantages.

4.2.3 Collaborative Operation

Collaborative operation is mainly divided into whole-process collaboration and industrial chain collaboration. The whole-process collaboration includes innovation input ability, transformation ability, and output ability. Industrial chain collaboration includes value chain, supply-demand chain, enterprise chain and space chain.

PCEs use the practical resources of other innovation stakeholders to develop modern construction industry products and intelligent construction technologies. They strengthen joint research on vital technology issues through innovative investment. Innovation and transformation are carried out in the form of crucial laboratories, pilot test bases, and industrial parks, linking cutting-edge knowledge with the actual development of enterprises. The key to the competition of PCEs is often a highly applicable new technology. The industrialization of technological innovations is conducive to constructing the carbon emission reduction environment in construction.

PBs innovation stakeholders increase their value and adapt to the requirements of new industrialized production so enterprises can obtain the most extraordinary competitiveness. In the context of double carbon, the advantages of PBs have become more pronounced, and the demand for PBs in the construction market is increasing. The supply-demand chain collaboration requires PCEs to exchange human resources, financial resources, technology, and information to conduct in-depth cooperation from research to industrialization for new products, technologies, and processes. In the process of production and construction, it is difficult for a company to complete an entire project alone. Even leading companies need to collaborate through the enterprise chain to improve their innovation capabilities. PCEs in different regions are unevenly distributed and unbalanced in capacity development, which needs to combine the regional construction environment with building a chain of cooperation, complementary advantages, and joint development to achieve spatial chain coordination.

4.2.4 Trust Guarantee

In the current built environment, trust can ensure that PCEs carry out CI, and guarantee can ensure the smooth realization of CI.

Coordinating knowledge sharing and information integration behaviours help PCEs reduce sunk costs. Such activities, including organizing staff training, exchanges, learning, and the diffusion of knowledge among employees, are conductive to promote the sustainability of PCEs. Information integration requires PCEs to invest a large number of talents, technology, and capital as a necessary condition to increase the rate of information flow. Knowledge sharing and information integration ensure that innovation stakeholders reach a basic cooperative consensus and form a trusting and harmonious relationship.

Both the income distribution and risk-sharing provide an essential guarantee for the operation of CIPCE. Generally speaking, the expected return from the transformation of scientific achievements is relatively high, which involves innovation stakeholders' pricing and share conversion. Due to the certain risks in CIPCE, it is necessary to clarify the rights and responsibilities of enterprises and strengthen the protection of CI.

4.3 Innovation Performance Analysis

Innovation performance is the manifestation of the mechanism operational result. The mechanism of CIPCE influences the innovation performance of enterprises through interaction. The Balanced Scorecard is a management system that organically integrates financial indicators and three types of non-financial indicators and is usually used to measure corporate performance (Stanley et al., 2010; Chu and Chung, 2016; Shao et al., 2016). The Balanced Scorecard mainly covers four dimensions: financial, customer, internal process, learning, and growth. The continuous in-depth development of management theory has gradually developed into an organizational system framework for enterprise innovation management. The concept of a balanced scorecard not only builds a comprehensive index system of four dimensions for enterprises from a macro perspective but also designs a section that conforms to the sub-goals based on the characteristics of the enterprise from a micro perspective which provides a scientific and reasonable research method for the measurement of enterprise innovation performance. Based on the balanced scorecard theory, this study analyzes innovation performance from four dimensions, such as economic output, technological output, innovation management, and sustainability, to explore the results of the mechanism for CIPCE (Jarrar and Smith, 2014; Malesios et al., 2020; Sirin et al., 2020). The overall goal of the balanced scorecard can be decomposed into several sub-goals, linking each dimension to form a specific relationship. These sub-goals guide PCEs to achieve sustainability through the technical output and innovation management dimensions, which ultimately manifests as the improvement of indicator data in the economic output dimension, forming a causal relationship chain connecting various indicators, and providing specific ways for enterprises to CI (see **Figure 2**). This study further measures the ten innovation performance indicators (see **Table 3**).

4.3.1 Technical Output

The technological output dimension is extended from the perspective of the driving force for CIPCE. Innovation stakeholder encourages companies to focus on vigorously developing PBs, creating innovative construction technologies, such as construction robotics and building material smart logistics, to promote the construction industry to achieve low-carbon development through digital transformation. The independent innovation of PCEs is the most fundamental strategic measure for enterprise technological innovation. Under the combined effect of innovation awareness and interest needs, enterprises improve their core competitiveness through technological upgrading, making technological innovation a new driving force for the development of PCEs.

TABLE 3 | Index system of innovation performance.

Economic output	Innovation management
• Sales revenue of new products, new technologies, new processes, and new revenues • Tax incentives	• Industrial cluster competitiveness • Number of significant innovation projects introduced into the industrial chain
Technological output	Sustainability
• Brand recognition • Owner satisfaction	• Number of innovation teams • Employee satisfaction • Training hours • Information system processing capabilities

With high technology penetration into the construction industry, PCEs constantly upgrade and improve their technical level. These technologies help improve brand recognition and owner satisfaction through research, transformation and industrialization and ultimately serve as technological outputs to improve the innovation performance for PCEs.

4.3.2 Economic Output

The economic output dimension mainly assesses the profit and cost of PCEs. Investing resources from the four aspects, including policy, talent, capital, and technology, can promote the operation of the mechanism for CIPCE. PCEs focus on saving costs and improving innovation performance to allocate resources reasonably. Attaching importance to the products and services in construction industrialized brings about substantial results to maximize economic output, for example, increasing the sales revenue and tax incentives of new products, new technologies, and new processes.

4.3.3 Innovation Management

The innovation management dimension is the principal means to realize other dimensions. Through the whole process and the entire industrial chain of CIPCE, PCEs actively explore new organizational management models suitable for the collaborative development of intelligent construction and building industrialization to enhance their independent technological innovation capabilities and innovation performance. To this end, PCEs need to focus on the competitiveness of industrial clusters, the number of major innovation projects, and the competitive advantages of PCEs in the construction market.

4.3.4 Sustainability

The sustainability dimension is essential for measuring whether an enterprise can guarantee innovation stakeholders achieve sustainable development. The internet of things, building information modelling and other digital technologies are rapidly empowering the field of PBs with the number of PCEs continues to grow, driving the realization of architecture 4.0. It accumulates high-quality products and services and brings customers long-term consumption motivation. Growth requires companies to maximize the company's benefits through innovative research, knowledge sharing, information integration, profit distribution, and risk-sharing. The number of innovative teams, employee satisfaction, training hours, and information system processing capabilities will become the key to ensuring the innovation performance of PCEs.

5 RESULTS AND DISCUSSION

5.1 The Order Degree Measurement of the Sub-mechanism

According to the model, the order degree of various PCEs and the overall CI sub-mechanism in Shenyang during the "13th Five-Year Plan" period is calculated (see **Table 4** and **Figure 3**). The overall orderliness of the CIPCE sub-mechanism in Shenyang needs to be further improved, and the trend is increasing. The synergy of PCEs and the sub-mechanisms of PCEs show an overall upward trend and partial fluctuations. It rose slowly from 2016 to 2017 and declined from 2017 to 2018. After 2018, it appeared a rapid upward trend in general.

Firstly, DD has the highest degree of order overall, and RS has the lowest degree of order. Except for production and material & equipment supply companies, DD has the highest degree of order and fluctuations. Except for development companies, RS has the lowest degree of order with a relatively flat increase or even a downward trend, which inhibits the sustainable development of CIPCE in Shenyang.

Secondly, RS and TG have a low degree of order with a secondary position, DD and CO order in a significant position, forming a primary and secondary order form. The order of the four sub-mechanisms of the prefabricated components, materials & equipment supply companies is orderly. The order of the former sub-mechanism is DD, CO, RS and TG from high to low, and the latter's order is CO, DD, TG and RS.

Thirdly, the order degree of the sub-mechanism of the prefabricated component enterprises is consistent with the order degree of the overall sub-mechanism on the trend graph, and the former is greater than the latter. It shows that different PCEs may have the same or similar sub-mechanisms in measuring the order degree of the sub-mechanisms. Due to differences in enterprise types and development levels, the order of the sub-mechanisms will appear different. In particular, it is pointed out that the orderliness trend chart of the sub-mechanisms for

TABLE 4 | Synergy of the sub-mechanism of CIPCE in Shenyang.

Sub-mechanism		2016	2017	2018	2019	2020	Sub-mechanism		2016	2017	2018	2019	2020
Development	DD	0	0.0833	0.1287	0.2130	0.3498	Decoration	DD	0.0079	0.0912	0.1388	0.2209	0.3554
	RS	0	0.0526	0.0712	0.1433	0.1726		RS	0.0049	0.0558	0.0536	0.1433	0.1772
	CO	0.0077	0.0720	0.1560	0.1992	0.3097		CO	0.0080	0.0677	0.1614	0.2333	0.3100
	TG	0.0037	0.0207	0.0506	0.1058	0.1766		TG	0.0042	0.0246	0.0726	0.1268	0.1770
Construction	DD	0.0072	0.0627	0.1026	0.2179	0.3096	Consulting and Supervision	DD	0.0081	0.0614	0.1610	0.2407	0.3543
	RS	0.0049	0.0598	0.0999	0.1311	0.1777		RS	0.0045	0.0429	0.0321	0.1347	0.1770
	CO	0.0075	0.0859	0.1266	0.1950	0.3096		CO	0.0080	0.0516	0.1624	0.2438	0.3108
	TG	0.0043	0.0396	0.0803	0.1456	0.1772		TG	0.0045	0.0413	0.1002	0.1174	0.1767
Design	DD	0.0080	0.0831	0.1613	0.2103	0.3098	Prefabricated components	DD	0.0254	0.0598	0.1405	0.2429	0.3710
	RS	0.0049	0.0545	0.0870	0.1540	0.1753		RS	0.0045	0.0221	0.0493	0.1597	0.1773
	CO	0.0082	0.0842	0.1651	0.2309	0.3106		CO	0.0065	0.0748	0.1119	0.2179	0.2212
	TG	0.0046	0.0311	0.0870	0.1461	0.1776		TG	0.0049	0.0561	0.0990	0.1402	0.1348
Research	DD	0.0074	0.0541	0.1251	0.2269	0.3501	Material and equipment supply	DD	0.0076	0.0584	0.1452	0.2183	0.3541
	RS	0.0043	0.0384	0.0343	0.1203	0.1769		RS	0.0045	0.0423	0.0517	0.1170	0.1775
	CO	0.0075	0.0660	0.1266	0.2178	0.3097		CO	0.0084	0.0975	0.1811	0.2179	0.3111
	TG	0.0045	0.0577	0.0946	0.1028	0.1775		TG	0.0048	0.0551	0.0926	0.1407	0.1772
Overall	DD	0.0029	0.0712	0.1460	0.2575	0.4180	Overall	CO	0	0.1101	0.1122	0.2152	0.2959
	RS	0.0032	0.0196	0.0127	0.0927	0.1400		TG	0	0.0455	0.0777	0.0989	0.0565

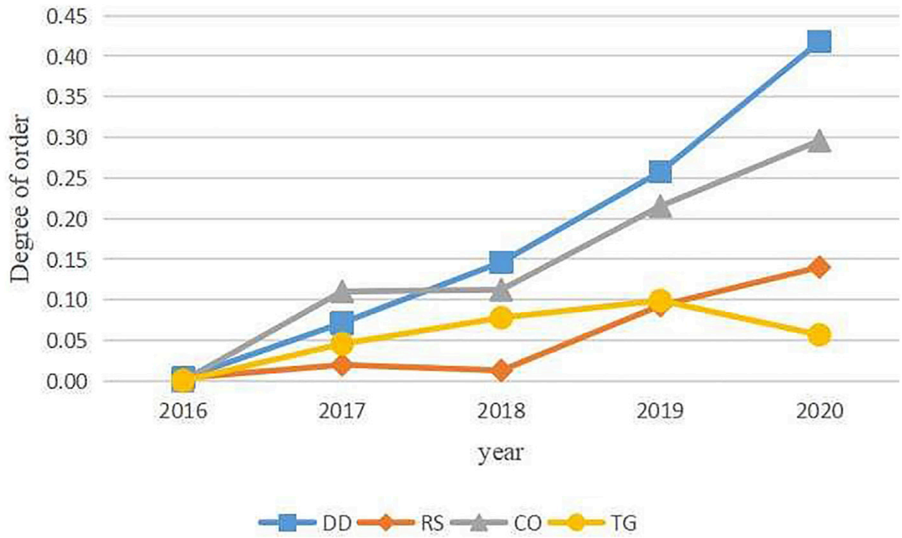

FIGURE 3 | Trends of sub-mechanisms order in PCEs.

consulting & supervision enterprises is similar to the overall. RS orderliness is higher than the overall and is lower in other aspects. It shows that the consistency of the order degree of the sub-mechanism affects the overall order degree of the sub-mechanism to a certain extent.

5.2 The Synergy Measurement of the Overall Mechanism

Based on the questionnaire data, the overall mechanism synergy of PCEs was calculated, and the trend chart was drawn (see **Figure 4**). This study found that the synergy of enterprises all fluctuates in [0, 0.4], and the level of synergy is not high, indicating that PCEs in Shenyang need to form a more resilient CI trend. Taking the overall mechanism synergy of PCEs in Shenyang as the standard, the synergy of various enterprises during the "Thirteenth Five-Year Plan" period has generally shown an upward trend, and the dynamic changes have been consistent in time. The fluctuation ranges from 2016 to 2019 is large, and the synergy of various enterprises in 2019–2020 changes slowly or even shows a downward trend. Affected by COVID-19, PCEs in Shenyang will be impacted in 2020. There

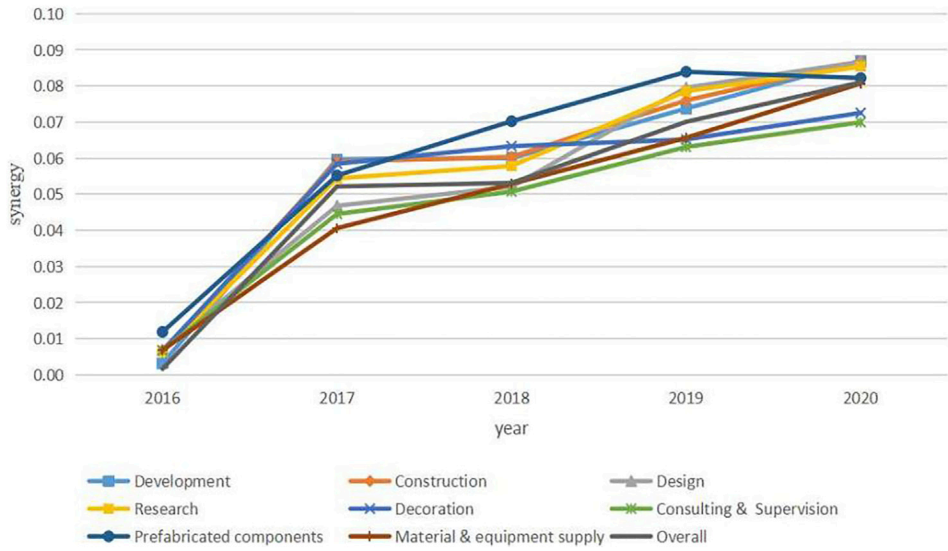

FIGURE 4 | Synergy among various enterprises and overall PCEs in Shenyang.

will be many issues such as a significant reduction in corporate management efficiency, forced adjustment of branding, and damage to the benefits of enterprises and employees, which will bring the development resistance of PCEs.

The synergy of the three types of enterprises, including development, scientific research, and prefabricated components, is higher than the overall mechanism. Development enterprises actively integrate and gather the upstream and downstream resources of the entire industry chain, such as technological research, digital building design, intelligent construction, advanced component manufacturing, and talent training, to connect industrial parks with intelligent manufacturing enterprises. Scientific research enterprises focus on vigorously developing PBs and continue to promote the deep integration of government, industry, university, research, and funding. Prefabricated components have extremely high requirements for lean management. In particular, the stacking and transportation of prefabricated concrete components have brought certain incremental costs to the enterprise. In order to increase profits and obtain higher benefits, enterprises are actively constructing intelligent production lines for prefabricated components.

The synergy between consulting & supervision and material & equipment supply enterprises is lower than the overall mechanism. The consulting & supervision enterprise aims to provide technical support for training PBs talents and consulting & supervision services to society. Few studies are exploring the frontier science of PBs, such as new structural systems of PBs, and building information technology. Material & equipment supply enterprises have room for improvement in on-site construction links, such as material distribution and high-altitude welding, and critical production processes, such as moulds, concrete, construction robotics and intelligent control machines. Moreover, the level of innovation and integration of on-site assembly technology is low.

TABLE 5 | Closeness of evaluation index.

Index year	2016	2017	2018	2019	2020
D^+	0.294	0.264	0.208	0.196	0.170
D^-	0.101	0.119	0.127	0.144	0.172
C	0.5285	0.4926	0.5583	0.6277	0.4131

The changing trend of the synergy between construction and design companies is the same. The decoration company is coordinated with construction and design. They take advantage of the industrialization of new buildings to promote the integrated design of multiple disciplines. Modern industrialized organization methods and production methods can enhance the integrity and systemic of the entire industrial chain of modern architecture in Shenyang, guide various elements to gather together, and avoid secondary design.

5.3 The Measurement of Innovation Performance

In measuring the innovation performance of Shenyang PCEs, this study calculates the closeness of the actual vector and the ideal vector value of each indicator (see **Table 5**). From the perspective of the closeness of the evaluation index, the innovation performance of PCEs in Shenyang did not show an increasing trend during the “13th Five-Year Plan” period, and the overall innovation performance was relatively high. In 2017 and 2020, it is at a medium performance level, and in 2016, 2018 and 2019, it is at a high-performance level.

The innovation performance of PCEs in Shenyang continued to increase in 2018 and 2019, indicating that CI is showing a good trend, and it has brought a particular promotion effect to the development of PCEs. The decrease in the closeness index in 2020 is closely related to the sudden outbreak of COVID-19. It affects the exchanges and cooperation, production, construction, and information interaction among PCEs.

5.4 DISCUSSION

In achieving the double carbon goals, CIPCE will help allocate resources rationally, reduce the life-cycle carbon emissions, and guide the sustainable development of PCEs. Based on the research results, this study discusses the countermeasures to improve the capability of CIPCE.

Firstly, considering the homogeneity characteristics of Shenyang's modern construction industry products, the government actively carries out innovation activities, focusing on cultivating enterprises' sense of independent innovation. By driving PCEs to increase research investment in fundamental technology research, expand more market shares. The government strengthens cross-departmental overall coordination, regularly studies the difficulties of CIPCE, and promotes the solution of bottlenecks. Relying on the Large Northeast Science Market promotes the interconnection of the related achievements for PBs on the platform.

Next, the government prioritizes credit support from financial institutions for PCEs that introduce, digest, absorb, and independently develop large-scale special advanced equipment. PCEs strengthen cooperation with provincial-level scientific achievements transformation guidance funds to increase the turnover of technology contracts. PCEs improve the awareness of invention patents and intellectual property protection and clarify property rights ownership. Also, PCEs continue to optimize the capital management system and carry out a reasonable division of economic benefits.

Then, the government establishes a long-term mechanism for introducing, training, and developing talents for technological innovation in PBs and strengthens the reserve of high-level talents. PCEs also attach importance to the introduction and training of high-level talents and fully mobilizes the passion for scientific research of high-level talents. Relying on the government and industry associations to carry out professional technical training, organize experts to guide the knowledge of CIPCE, and promote the integration of academic qualifications and skills certificates.

Finally, PCEs will work together to complete the assembly construction process from research and design to operation and maintenance of the entire life cycle, integrating upstream and downstream industrial chains for integrated development. PCEs focus on the upstream and downstream information of the industrial chain, builds an information service platform for real-time information exchange and sharing and publishes relevant data and complete information. It should actively explore a new organization and management model suitable for the collaborative development of intelligent construction and PBs and study its application to Shenyang's service and decision-making information system. By increasing the promotion of new technologies, we can achieve early warning, dynamic monitoring, and linkage management to improve the ability of enterprises to bear risks.

6 CONCLUSION

Affected by policy and demand, CI has become the key to maintaining the competitiveness of PCEs. Furthermore, many stakeholders' behaviours have been widely discussed around the world. Nevertheless, there are no quantitative conclusions to explicitly tell us how to verify and measure the mechanism behind it. This study profoundly analyzes the CIPCE mechanism and measures its operation process and results to fill this gap. This study explored the complex relationship of CIPCE interaction and developed the synergy and innovation performance indicator system of CIPCE operation. Specifically, this study has three principal theoretical contributions.

First, this study deeply discusses the mechanism of CIPCE through analyzing the status quo of CIPCE in Shenyang. It found that CIPCE is composed of four sub-mechanisms: dual drive, resource supply, cooperative operation and trust assurance, which provides action guidelines for stakeholders to formulate specific measures to improve the capabilities of CIPCE in the built environment.

Second, the CIPCE index system is constructed in this study. From the perspective of the operational process and results of the CIPCE mechanism, the synergy index system and the innovation performance index system based on the balanced scorecard are constructed to provide a methodological reference for further in-depth measurement.

Third, the synergy and innovation performance of CIPCE in Shenyang show that there are differences in the degree of order for the sub-mechanisms of CIPCE in Shenyang during the "13th Five-Year Plan" period, and the overall level of synergy is low. In parallel, the innovation performance of PCEs in Shenyang is relatively high, but fluctuating with the stability needs to be improved. It will help explore the countermeasures for CIPCE capability improvement and promote PCEs to maintain their long-term competitive advantages.

After summarizing the conclusion, some limitations should be noted. There are three optional avenues to be explored in the future regarding the study. First, digitization can have a substantial impact on CIPCE. Realizing CIPCE has become one approach for the construction industry's transformation and upgrading, attracting growing attention. Due to the lack of application scenarios and the imperfect management platform, it is difficult for PCEs to participate in the practical engineering project in this work. The literature lacks consensus on CIPCE to affect the construction industry. To respond to this problem, a conceptual framework applicable for CIPCE, which reflects the current status of China's construction industry, is required for PCEs. The conceptual framework will help improve the mechanism of CIPCE in this study.

Next, this study explores CI with a focus on PCEs. Other stakeholders, such as governments, intermediaries, financial institutions, also contribute to carbon reduction in the built environment. There is a need for a detailed study of CI with both types of stakeholders. For example, "government-PCEs" decision analysis can be carried out under the premise of bounded rationality. A "government-PCEs" evolutionary game model is constructed to analyze the evolution and stabilization strategies in CI between the stakeholders. Based on this, research should change the simulation parameters to determine the stable equilibrium of evolution and propose suggestions for the development of CIPCE.

Last but not least, this study is a quantitative study based on literature review and status analysis. More empirical studies should be conducted in the future to develop it further. For example, the research will analyze the macro environment, existing problems and development trends of PCEs in different regions. The universality of the index system in this study is verified through data processing and analysis results. At the same time, it can also provide theoretical references for CIPCE.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by ZG. The first draft of the manuscript was written by ZG, and all authors commented on all versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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