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A Conceptual Framework for Collaborative Development of Intelligent Construction and Building Industrialization

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Digitalization drives the arrival of the era of intelligent construction, which greatly affects the development of construction industrialization. Due to the collaborative barriers between intelligent construction and building industrialization (ICBI), it is difficult for construction enterprises to participate in the actual engineering projects in this work. Achieving the collaborative development of ICBI has become a way to transform and upgrade the construction industry, and it has attracted more and more attention. However, the existing literature lacks consensus on the collaborative development of ICBI affecting the construction industry. In order to promote the theoretical research on the collaborative development of ICBI, this paper proposes a "mi" shaped conceptual framework so that readers can understand the operation law of ICBI collaboration and promote its healthy development. Therefore, based on the synergy theory, this paper extracts the contents of stakeholders' collaboration, industrial collaboration, structural collaboration, construction technology upgrading, factor endowment upgrading, innovation service upgrading, and construction process upgrading. These seven items are summarized into four dimensions: dual drive, resource supply, collaborative operation, and trust guarantee, which indicate the direction of ICBI collaborative development. The research results will help to realize the industrialization of new buildings and promote the sustainable development of the construction industry.

Keywords: digitization, intelligent construction, building industrialization, collaborative development, construction enterprises, dimensions, synergy

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1 INTRODUCTION

In recent years, digitization has brought an industrial revolution to the construction industry (Watson, 2011; Buchli et al., 2018; Tetik et al., 2019). Such digital technologies, including the digital twin, building information modelling (BIM), and the internet of things, have driven Construction 4.0 and brought the construction industry into an intelligent construction era (Craveiro et al., 2019; You and Feng, 2020). Intelligent construction has a significant impact on the development of the construction industry. For example, building a multi-stakeholder management and control platform can integrate smart factories with the internet of things and locate prefabricated components intelligently through digital collaborative design (Kozlovska et al., 2021; Turner et al., 2021; Yuan et al., 2021). Construction robotics play an important role in human-robot coordination and self-learning, making construction more efficient (Yan and Zhang, 2021). In particular, to promote intelligent construction in engineering construction, high-quality development requires the construction industry to take building industrialization as a carrier (Li et al., 2018). Intelligent construction is an innovative construction model that combines digitalization and engineering construction, which helps break through the bottleneck of information integration and interaction in prefabricated buildings (Wang et al., 2020; Wen, 2021). A priority for intelligent construction to assist in the development of construction industrialization.

According to China's commitment to carbon-peak and carbon-neutral at the United Nations General Assembly in 2020, energy conservation and emission reduction in construction are crucial contributors (Wong et al., 2013; Zhang et al., 2019; Li et al., 2020). The high-quality development in the construction industry has intensified the competition among construction enterprises, changing the industrial chain's traditional competition and cooperation mode. Construction enterprises urgently need to promote green and low-carbon development through the in-depth integration and innovation with intelligent construction technology, from the whole life cycle of building material production, construction, operation, and maintenance (Shi et al., 2019; Li et al., 2021). Relying on intelligent construction to carry out cross-disciplinary, cross-industry, and cross-department in-depth collaboration is also one integral approach for construction enterprises to enhance their independent scientific and technological innovation capabilities (Xue et al., 2018; Zhang et al., 2020). In the context of dual carbon, whether it responds to the call to promote mutual integration or actively seeks to improve its market competitiveness, the collaborative development of ICBI is imperative. However, such gaps in this work, including application scenarios and the management platform, have obstructed the healthy development of construction enterprises. Therefore, conceptual work is proposed for the collaborative development of ICBI to realize high-quality development in the construction industry. Three research questions were developed to shape this research:

RQ1. Which theories support or justify the collaborative development of ICBI within digitization?

RQ.2 What are the contributing paths to the effective collaborative development of ICBI in accelerating the transformation and upgrading of the construction industry?

RQ.3 What dimensions do the "mi"-shaped conceptual framework contribute to the effective collaboration of ICBI?

The remainder of this paper is organized as follows. **Section 2** reviews the research related to ICBI and synergy; **Section 3** constructs the "mi"-shaped conceptual framework associated with the collaborative development of ICBI; **Section 4** discusses the applicability of the conceptual framework in depth from four dimensions, and **Section 5** reports the conclusions.

2 LITERATURE REVIEW

2.1 Intelligent Construction and Building Industrialization

With intelligent construction in the engineering field, ICBI has been continuously improved for critical technologies such as engineering software, engineering internet of things, engineering machinery, and engineering big data (Liu et al., 2021). However, the collaborative development of ICBI is relatively slow. ICBI is an essential part of the fourth industrial revolution, and it did not show agglomeration development mode until 2017. Related literature research mainly focuses on digitization, cloud platform, and industrialization (Woodhead et al., 2018).

(1) As an advanced stage of digital construction, intelligent construction originates from the development of digital and intelligent technologies. It plays a vital role in standardized building, mechanized construction, and scientific organization and management (Rossi et al., 2019). ICBI improves the cost performance and reliability of the whole industry chain, which is a reliable methodology that guides construction to develop standardized design modules and component libraries (Bucchiarone et al., 2019).
(2) For fabricated construction industry chain and intelligent robotics, construction enterprises have established a BIM data management platform, which can realize the effective transmission and real-time sharing of BIM data in survey, design, production, construction, acceptance, and others (Edirisinghe, 2019). Such essential platforms, including the intelligent production platform for parts and components, the intelligent logistics platform for building materials, the intelligent installation and the intelligent park management service platform, and the building material centralized procurement platform, have solved the information flow integration problem in the construction industrialization supply chain and improved the intelligent construction degree (Ding et al., 2018).

(3) The deepen Industry 4.0 assists the stability of the collaborative development of ICBI, appearing the leading role of enterprises with advantages in intelligent construction (Kochovski and Stankovski, 2018). Project general contracting enterprises and whole-process engineering consulting enterprises have substantial impacts on improving the ability of intelligent construction solutions. For example, a multi-party collaborative intelligent construction work platform was established to strengthen collaborative work and gradually form an open industrial system that considers general engineering contracting enterprises the core (Zhou et al., 2018).

In short, scholars have conducted multi-angle and in-depth research on ICBI, focusing on the specific application and engineering practice in this work. Relevant theories, key technologies, and development systems have not yet been formed. Collaborative development is a hot topic and gradually becoming an essential research node related to ICBI. Intelligent construction is the basis for construction industrialization, and construction industrialization supports the development of intelligent construction. It is the key to realizing the collaborative development of ICBI.

2.2 Synergy Theory

Synergy theory started from Haken's work. It has previously been used to form a mode of action in which the matter, information, and energy in the system spontaneously generate an orderly organization through the transformation among variables (Haken, 2000). Haken believes that synergy is the main factor of the system beyond the fusion linkage produced by a single element. After that, synergy is considered a common goal: a network of self-motivated personnel to form a collective vision and exchange ideas, information, and working conditions through the network (Baldwin and von Hippel, 2011; Hartley et al., 2013). Tracing the evolution of synergy theory, it aims to expound the connotation from stakeholders' perspectives, action path, and operation process.

(1) Synergy is a non-linear organizational behavior that discusses stakeholders' complementary advantages, shared resources, and interaction among elements (Paulus et al., 2018; Anzola-Román et al., 2019). Through system integration, stakeholders promote organizational activities from disorder to order (Najafi-Tavani et al., 2018; Hong et al., 2019). Stakeholders usually do not act in isolation. They realize cross-field and cross-industry cooperation through multiple subjects, including "enterprise-enterprise," "enterprise-government," "enterprise-intermediary institution," and "enterprise-government-university-intermediary institution-financial institution-platform" (Feranita et al., 2017; Alford and Duan, 2018; Gao et al., 2019; Wang and Zhang, 2019; Zan et al., 2021). The cooperative or industrial alliance among construction enterprises, the knowledge innovation chain, and external innovation resources complicate collaborative activities.

(2) Synergy network is an essential carrier for stakeholders to carry out collaborative activities (Hadjimanolis, 1999). Synergy network has different structures, such as vertical collaboration, horizontal collaboration, and structural holes (Wang et al., 2014; Maietta, 2015). According to the formation of associated nodes by innovation stakeholders, it is found that there are significant differences in the impact of synergy networks on innovation performance, and vertical synergy is more significant than horizontal synergy (Zeng et al., 2020). The structural holes of enterprise synergy and knowledge networks are positive and negative in different situations. In reality, knowledge sharing is also an important way of collaborative development. Taking knowledge as the center, the collaborative open management and agglomeration effect among enterprises (Connell et al., 2014; Knoke et al., 2017). Collaboration among stakeholders begins with communication and cooperation, which will generate spillover information. It will bring spillover effects that have good or bad economic effects for the industry and even other industries. The transmission and digestion of information can promote technological innovation and achieve optimal benefits (Howard et al., 2016).

(3) Synergy activities have affected various factors, driving stakeholders to achieve sustainable development (Su et al., 2018). The organizational scale, the organizational object, and the organizational background are potential moderators that affect the achievement of collective goals (Vega-Jurado et al., 2008; West and Bogers, 2013; Dooley et al., 2016). Shorter technical and management knowledge distances are conducive to the collaboration of the whole process and improve collaboration performance (Schulze and Brojerdi, 2012). In-depth thinking on technological research, integration, and industrialization innovation plays an essential role in improving the competitiveness of stakeholders (Huizingh, 2011; Anzola-Román et al., 2019).

Overall, the concept of synergy theory revolves around groups and organizations. The existing literature lacks a comprehensive and systematic discussion, and the conceptual framework research needs to be increased. Under the integration pattern of the knowledge economy, enterprises have entered the management mode with complex people as the background. Enterprise benefits are more and more dependent on the collaborative operation. However, there are gaps in the research on construction enterprises under the guidance of synergy theory. Therefore, it is of great significance to construct a conceptual framework in architecture based on synergy theory, stakeholders' synergy, paths' synergy, and processes' synergy.

3 RESEARCH METHODS

3.1 Data Sources

Since the beginning of the 21st century, ICBI has gradually become the focus of academia, enterprises, and governments. In order to gain an in-depth understanding of the current status of ICBI in China, this paper mainly adopts two methods to obtain data resources.

On the one hand, the "Intelligent Construction and Building Industrialization" was searched in the China Social Science Index Core Database, with a period of 2001–2021, and a total of 120 valid documents were retrieved. Using CiteSpace for visual analysis, the co-occurrence graph, timeline graph, and time zone graph of domestic ICBI research keywords are obtained. Through an in-depth analysis of these maps, we can further explain the basic principles of China's ICBI collaborative framework construction.

On the other hand, the web crawler technology is used to automatically crawl a large amount of text information on the websites of the Ministry of Housing and Urban-Rural Development of China and the Ministry of Housing and Urban-Rural Development of various provinces and cities and

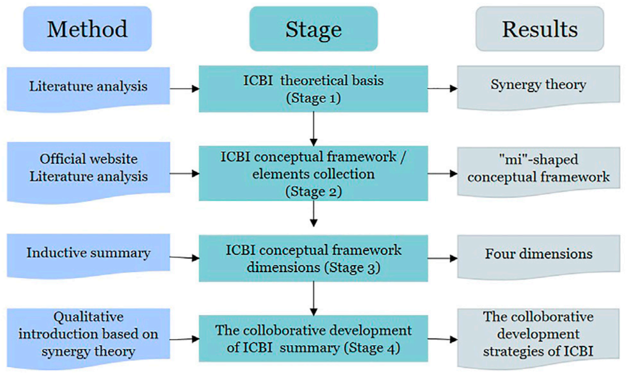

FIGURE 1 | Research flowchart.

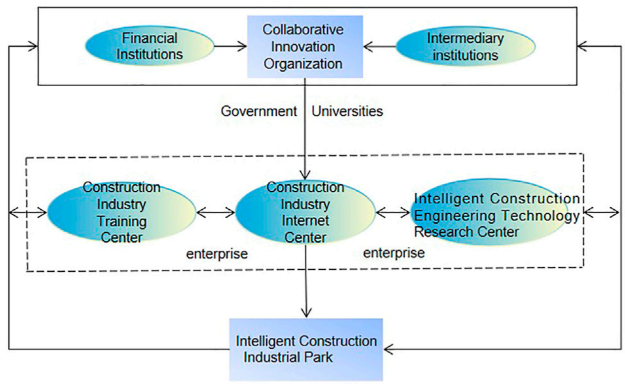

FIGURE 2 | Stakeholders' Collaboration in the collaborative development of ICBI.

conduct text analysis and advanced processing, keyword extraction, and word cloud analysis. Finally, the essential elements of the collaborative framework of ICBI are summarized.

3.2 Research Process

In China, the integration of ICBI is regarded as a new production method that promotes the flow of building data, improves the quality and efficiency of the entire industry chain, and maximizes the value of resources. Under the influence of the internal and external environment, construction enterprises can produce synergies that a single construction enterprise cannot achieve. Based on the synergy theory, this paper obtains the "mi"-shaped conceptual framework by analyzing the mechanism of the collaborative development of ICBI. The framework shows the complex relationship among the construction enterprises interacting, cooperating, and restricting each other. The research flowchart in this study is shown in **Figure 1**.

Firstly, based on the literature analysis method, the research status of ICBI and synergy theory are analyzed. This paper clarifies the research hot spots and directions of ICBI and points out the guiding significance of synergy theory to the sustainable development of construction enterprises. This work illustrates the critical role of synergy theory in the full text.

Secondly, according to literature analysis and web crawling results, this paper constructs a mi-shaped conceptual framework. The framework is obtained based on the ICBI synergistic development mechanism. Under the guidance of synergy theory, combined with the development practice of the construction industry, the discussion will be carried out from the direction of stakeholders' collaboration, industrial collaboration, structural collaboration, construction technology upgrading, factor endowment upgrading, and innovation service upgrading, and construction process upgrading.

Thirdly, this paper conducts an in-depth analysis of the conceptual framework of "mi"-shaped and summarizes the seven research contents into four dimensions from the perspective of synergy theory. Further in-depth analysis of the influence of each element in these dimensions on the collaborative development of ICBI will help identify the direction and improve the degree of synergy and innovation performance of ICBI.

Fourthly, a qualitative study is carried out to summarize this paper's research results, innovations, and future research directions.

4 CONCEPTUAL FRAMEWORK

4.1 Stakeholders' Collaboration

Generally speaking, there are many stakeholders in the collaborative development of ICBI. Specific chain-type technical and economic correlations are formed based on specific logical and space-time layout relationships. Due to the application of intelligent construction in engineering construction, the whole industry chain covers scientific research, design, production and processing, construction assembly, and operation, which can improve construction mechanization. In order to break through the innovation barriers of the entire industry chain, stakeholders require docking interaction and integration union. These behaviors are conducive to identifying and detecting unsafe behaviors in construction and promoting communication and cooperation among all parties involved in the project.

The design enterprises are committed to promoting full-professional collaboration, BIM cheerful design, and a standardized module library for BIM applications that cooperate with scientific research enterprises and decoration enterprises. Research institutions and development enterprises jointly establish a technology innovation alliance to research BIM underlying software and construction robotics. The construction enterprises continue to promote the inheritance and innovative application of new technologies in on-site construction links, such as distributing steel, processing steel, spraying, laying floor tiles, installing partition panels, and high-altitude welding, to achieve system integration and linkage development.

Construction enterprises have adopted a new digital and intelligent integrated development model to build many national-level prefabricated construction industry bases.

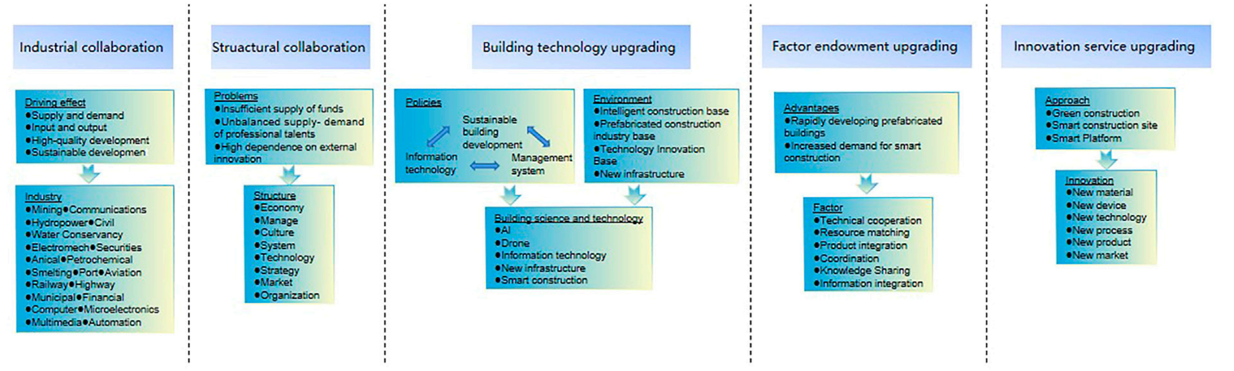

FIGURE 3 | Collaborative Paths in the collaborative development of ICBI.

Integrate the source of innovation of prefabricated construction enterprises with universities, form a collaborative organization network with intermediaries, and promote the industrialization development of new technologies and new products of prefabricated construction. The government and financial institutions are actively creating leading-level intelligent construction industrial parks, giving intelligent construction industrial parks a core position in the layout of modern construction industry clusters, including Construction Industry Training Center, Construction Industry Internet Center, and Intelligent Construction Engineering Technology Research Center. **Figure 2** shows the specific content of stakeholders' collaboration.

4.2 Collaborative Paths

The stakeholder network relationship is the fundamental driving force for collaborative activities. These relational networks are viewed as complex adaptive systems. Under the guidance of systematic methodology, there are interactions among and within systems. With the evolution of the network structure, **Figure 3** illustrates the collaborative paths in the collaborative development of ICBI, including industrial collaboration, structural collaboration, building technology upgrading, factor endowment upgrading, and innovative service upgrading.

4.2.1 Industrial Collaboration

The long industrial chain and the significant driving effect are the main characteristics of the collaborative development of ICBI. Therefore, its changes usually significantly impact other industries, driving multiple industries to seek development. From the perspective of supply and demand, large-scale and diversified buildings in society depend on the technology and services of intelligent construction. They cannot be separated from mining, communication, hydropower, water conservancy, petrochemical, and smelting. From the perspective of input and output, the growth rate of real estate investment in China has slowed down under the supply-side reform policy. The government work report pointed out that the proportion of real estate investment in GDP will continue to decline during the "14th Five-Year Plan" period. As an integral approach to stabilizing growth, the investment growth rate of construction enterprises in ICBI is expected to increase, further radiating ports, civil aviation, railways, municipalities, highways, and other industries. From the perspective of high-quality development, when construction companies adopt the general contracting model, they establish a multi-party collaborative intelligent construction work platform, which can, to a certain extent, clear up PPP projects for financing purposes and "pseudo" PPP projects packaged in disguised form. The proportion of projects that conform to the essential characteristics of PPP, green environmental protection, and people-benefiting has increased significantly, which is of great significance to the development of finance, securities, and other industries. From the perspective of sustainable development, construction enterprises are changing from cost-driven to innovation-driven. With the rapid penetration and diffusion of intelligent construction into building industrialization, construction companies are committed to using the Internet of Things technology to realize the online linkage of production equipment. Through promoting the practical experience of intelligent construction robotics in the pilot projects, the connection is gradually increased, such as computer, microelectronics, multimedia, automation, and other fields.

4.2.2 Structural Collaboration

Affected by the diversified development model of the construction industry, insufficient capital supply, imbalanced supply and demand of professional talents, and high dependence on external innovation have restricted the diversified and sustainable development of construction enterprises, including economy, management, culture, system, technology, strategy, market, and organization. First, the growth rate of total profits of China's construction enterprises has been declining since 2018 and has shown a downward trend in the past 5 years. Economic benefits reduce the enthusiasm of stakeholders in resource sharing and advantage integration, resulting in a shortage of funds for ICBI's coordinated development. It is urgent to establish a sound, intelligent construction, diversified investment system, and diversified financing model. Second, the proportion of personnel engaged in scientific activities in construction is relatively low compared with other industries during the same period. In addition, investment in scientific research innovation and new technologies is less than 1% of the total income for construction enterprises, and the supply and demand of intelligent construction talents are seriously unbalanced. Establishing a talent mechanism for the introduction, training, and development related to ICBI and cultivating new highly integrated talents, such as engineering construction + digitization, engineering construction + intelligence, engineering construction + information, are the support to promote the collaborative development of ICBI. Third, the core technology in China's construction enterprises is still highly dependent on foreign countries. More than 50% of the intelligent construction equipment needs to be imported. Critical technical problems need to be overcome urgently. It is necessary to develop prefabricated buildings vigorously, promote intelligent building technologies such as construction robots, intelligent factories, RFID, and QR codes, and realize the traceability of the whole process of quality responsibility. Stakeholders have established an advanced and applicable standard system for ICBI to strengthen BIM forward design and integration optimization. Also, it can promote the efficient sharing of various resources in the entire construction industry chain.

4.2.3 Building Technology Upgrading

Since 2016, the collaborative work of ICBI has been carried out in an orderly manner in the top-level design. China has introduced many policies to gather resources and strengthen the deep integration of information technology with the construction industry. Lean construction and intelligent construction are the primary means of building technology upgrading for construction enterprises, which help to comprehensively improve the quality, performance, and efficiency of engineering projects. In order to achieve the development goals of high efficiency, high quality, low consumption, and low emissions, intelligent construction and building industrialization application scenarios are encouraged to build, such as prefabricated building industry bases, intelligent construction bases, technology innovation centers, and critical laboratories. According to the 34 trillion new infrastructure plan jointly released by 13 provinces in China in 2020, the deep integration of digitization and intelligence associated with construction sites has provided opportunities for accelerating intelligent construction. One substantial contribution to the new infrastructure is that upgrading the traditional construction method can boost the modernization of China's construction industry into the fast lane. Under new infrastructure, construction enterprises play the main innovation body, focusing on innovative application scenarios, such as fabricated buildings and construction sites. Construction enterprises are committed to targeting cutting-edge international technologies, such as developing and applying construction robots and intelligent construction equipment, constructing industrial Internet platforms based on BIM digital technology, and establishing intelligent construction standard systems and evaluation systems. Through the continuous exploration of intelligent building technology, the contribution of scientific and technological progress to economic growth will be enhanced, and the sustainable and healthy development of the economy will be promoted.

4.2.4 Factor Endowment Upgrading

Based on information integration and knowledge sharing, construction enterprises gradually realize the organic synergy of ICBI, relying on the factor endowments upgrading. Such as technical cooperation, resource matching, product integration, and coordination have promoted joint research and demonstration applications for core technologies of intelligent construction, which help build an excellent industrial innovation ecology. On the one hand, it showed that the total area of newly started prefabricated buildings in China would be 630 million square meters in 2020, accounting for about 20.5% of the new construction area. Compared with the newly started prefabricated buildings in 2019, the total area of newly started prefabricated buildings has increased by 50%, and the integration of prefabricated steel structures is advancing rapidly. The development of prefabricated buildings is a significant change in the construction industry, conducive to promoting the deep integration of the construction industry and industrialization. The integrated application of the internet of things in intelligent construction sites guides information sharing. It establishes a prefabricated building development system that integrates the entire industrial chain from scientific research, design, production, construction, and assembly to operation.

On the other hand, the scale of China's artificial intelligence core industries accounted for more than 15% in 2017. Large public and commercial buildings' energy-saving needs have contributed to intelligent construction. Based on this, the market has cultivated many intelligent construction enterprises. They have realized the data sharing and effective transmission of the whole process and built the prefabricated construction industry chain with the support of the market. It helps to innovate and breakthrough core intelligent technologies, enabling construction enterprises to gain and maintain development advantages.

4.2.5 Innovation Service Upgrading

The certification application of new green building materials is considered an important strategy to help the green development in construction under double-carbon. To promote the application of new intelligent green building materials with good functions, construction enterprises focus on the innovative application of green construction to further promote a green energy-saving system. China's construction enterprises are leading in the world in intelligent construction, especially in applying intelligent construction methods in large and complex projects, such as construction robotics, intelligent building machines, and integrated intelligent construction equipment. The primary urban information model platform and the full-life-cycle project management platform associated with technological innovation, factory production, and intelligent applications have been established to apply the intelligent technology to the construction industrialization projects, such as digital component

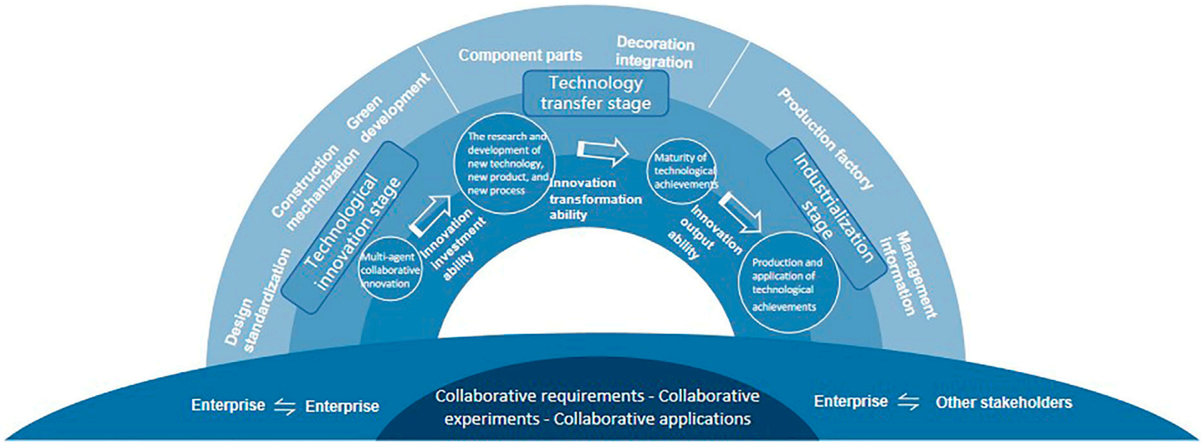

FIGURE 4 | The whole process in the collaborative development of ICBI.

factories, virtual construction, and installation, and on-site remote supervision. New technologies and products for intelligent buildings bring competitive advantages to construction companies and drive stakeholders to explore new markets actively. Construction enterprises gather various industrial resources, actively guide engineering projects to achieve innovative service upgrades, and promote the application of new materials, new equipment, new technologies, new processes, new products, and new markets.

4.3 Construction Process Upgrading

The collaborative development of ICBI is a dynamic process that consists of two chains. The internal chain is collaborative demand-collaborative experiment-collaborative application. The external chain is technological innovation-technology transfer-industrialization. **Figure 4** illustrates the collaborative effect between the internal chain and external chain. The collaborative objectives guide stakeholders to generate the demand for collaborative operation, then enter the technological innovation stage. New technologies have to undergo repeated trials from development to application to realize technology transfer with the joint efforts of stakeholders, thereby promoting the implementation of the results. The intelligence and industrialization level of the whole process in construction has been dramatically improved. A new generation of information technology and engineering construction technology is integrated through industry-university-research cooperation, guiding the transformation of scientific and technological achievements in three steps.

In the technological innovation stage, the bold design and integration optimization of BIM promotes one-click drawing of standardized design plans, establishes a standard component library, and realizes design standardization. The internet of things and intelligent technology ensure construction mechanization, promoting the online linkage of machinery, such as measurement robotics, innovative measurement tools, parts production robotics, construction robotics, and intelligent engineering equipment. Construction enterprises, universities, and scientific research institutions are conducive to accelerating the elimination of outdated equipment and technologies through the development of platforms, including integrated construction platforms and data management platforms, guiding green development.

In the technology transfer stage, the pilot application of intelligent construction was launched in several engineering projects to promote the smooth transformation of intelligent construction technology. Leading prefabricated construction enterprises help to realize the integrated development of decoration. The advantages of integration and cooperation are crucial to vigorously develop prefabricated buildings and enhancing the transformation capacity of intelligent construction technology.

In the industrialization stage, in the production of general components, supporting the production of building parts, and essential process production, prefabricated construction enterprises will increase the number of patents and expand the market share and scale of use of components through knowledge sharing, information integration, coordination, and cooperation. With the help of scientific management methods, the internet platforms in construction are built to realize a few or even factories without workers and gradually reduce the production costs of components and parts.

To sum up, the study proposes a "mi"-shaped conceptual framework for the collaborative development of ICBI. The findings of the descriptive analysis are summarized in **Figure 5**. The conceptual framework shows the complex relationship among stakeholders in the interaction, cooperation, and mutual restriction, clarifying the collaborative development path of ICBI. First, the diversified development of intelligent construction acts on industrial collaboration and forms a linkage development mechanism with multiple industries. Second, problems such as insufficient funds, unbalanced supply-demand of professional talents, and high dependence on external innovation promote the structural collaboration for construction enterprises from three aspects: driving force, innovation resources, and industrial chain

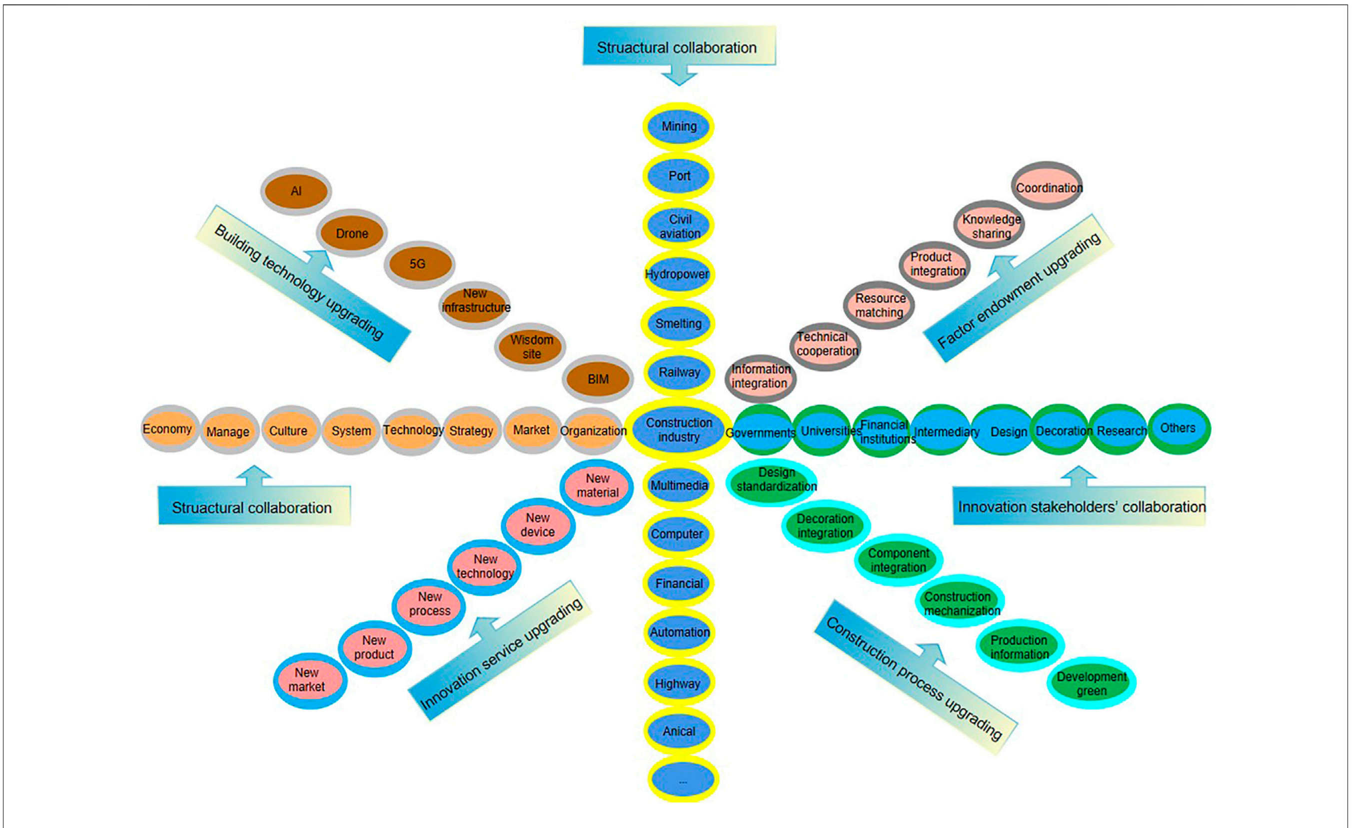

FIGURE 5 | "mi"-shaped conceptual framework in the collaborative development of ICBI.

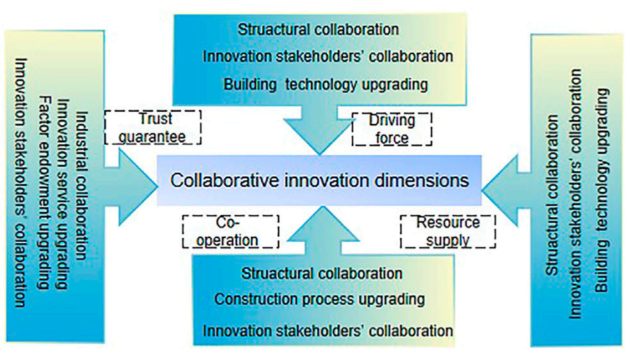

FIGURE 6 | Dimensions in the collaborative development of ICBI.

coordination. Third, the management system, the information technology, and the development of construction industrialization are deeply integrated to accomplish the construction technology upgrading for construction enterprises from the perspective of fabricated buildings and innovative construction sites. Fourth, the rapid development of prefabricated buildings and the increase in demand for intelligent construction will increase the factor of endowments upgrading. Fifth, intelligent construction promotes the construction industry's transformation to green, digital, and lean and ensures the innovative service upgrading smoothly in construction. Sixth, relying on standardization design, mechanization construction, green development, component integration, factory production, and scientific management, intelligent construction has achieved the construction process upgrading to industrialization in the whole process for the transformation of technological achievements.

5 DIMENSION ANALYSIS

Thus far, this study divides the conceptual framework of the "mi" shape into four dimensions, such as driving force, resource supply, collaborative operation, and trust guarantee, to further explore the collaborative development direction of ICBI, as shown in **Figure 6**.

1. In the process of mutual integration of valuable resources, the relationship between supply and demand has contributed to the collaborative development of ICBI, forming a synergistic driving force.
2. Resource supply focuses on innovation resources and agglomeration resources, which has built an integrated collaboration platform for intelligent construction enterprises and prefabricated construction enterprises.
3. Collaborative operation refers to injecting intangible assets into building industrialization, improving the construction

quality and efficiency of prefabricated buildings, and enabling multiple entities to achieve value increment.

It is mainly divided into whole-process collaboration and industrial chain collaboration. The key to the collaborative development of ICBI is trust among various subjects and a multi-dimensional guarantee. We discuss the four dimensions in more detail below.

5.1 Driving Force

There is differentiated demand for collaborative development of ICBI. Structural collaboration takes an interest in needs and innovation consciousness as internal driving forces to promote the sustainability of prefabricated buildings. The building technology upgrading expands the scale of collaborative competition among construction enterprises, affects the resource integration and information interaction for construction enterprises with universities, intermediaries, and financial institutions, and it drives the enthusiasm for intelligent construction as an external driving force (Guo and Li, 2022).

When prefabricated buildings show demand for new material, new technology, new process, new product, new equipment, and new market, construction enterprises urgently conduct intelligent technology research through coordinated development. It means to maintain existing profit levels and improve returns obtained interests. The experience center and education base of ICBI has increased society's attention to intelligent construction. The independent innovation awareness of construction enterprises has been increasingly strengthened (Skippari et al., 2017), which will improve the competitiveness among construction enterprises and guide the healthy development of the construction industry.

The government has formulated several development plans for ICBI and achieved lean management in construction by improving technology, finance, and talent policies. Universities have added ICBI-related majors, actively carried out universities-enterprise cooperation, and cultivated high-level talents. Intermediaries link universities, scientific research institutions, and enterprises to promote the optimal allocation and effective integration of various resources required in the transfer process of intelligent construction. The collaborative development of ICBI is a high-cost and long-term process, and market development is also hazardous. Construction enterprises play an essential role in the collaborative development of ICBI, which needs many funds. Financial institutions have vigorously carried out financial innovation through social funds, encouraged construction enterprises to participate in technology transfer actively, eased the financial pressure of construction enterprises in transformation, and improved transformation efficiency for scientific and technological achievements.

5.2 Resource Supply

To enable the collaborative development of ICBI and form a mutually beneficial pattern among stakeholders, such as government, universities, intermediaries, and financial institutions. Resource supply means investing resources to promote the development of construction enterprises towards technological innovation and resource agglomeration.

The supply of innovation resources includes talent, capital, and technology. The main body of talent supply is that construction enterprises and universities actively introduce outstanding talents in intelligent construction, and improve the skill evaluation system of construction practitioners from the perspective of ICBI. Focusing on the entire upstream and downstream industrial chain, such as digital design, intelligent production, and intelligent construction, connecting industrial parks with prefabricated construction enterprises and intelligent construction enterprises is an essential means to promote the establishment of prefabricated bases. Plot ratio incentives, appropriate relaxation of loan conditions, tax incentives following regulations, and services such as stock issuance and bond financing for construction industrialization enterprises will help build a sound capital financing mechanism.

Aggregated resources refer to the supply of macro policies, mainly from the government. Policy guidance, laws, and regulations play a role in the development process and risk prevention, conducive to optimizing the collaborative innovation structure for construction enterprises.

5.3 Collaborative Operation

The construction process upgrading drives the construction enterprises to conduct in-depth explorations of the whole collaborative innovation process. The technology innovation stage integrates design standardization, construction mechanization, and green development. The technology transfer stage focuses on the production of components and parts. Moreover, the industrialization stage implements production factories to produce general components, building parts, and key processes. Through the coordination of economy, management, culture, system, technology, strategy, market, and organization, construction enterprises with solid innovation and driving ability will be built from the perspective of the industrial chain.

Whole-process collaboration refers to how construction enterprises take necessary measures to improve their innovation input capability, transformation capability, and output capability at each stage of technological innovation, transformation, and industrialization (Persaud, 2005). Innovation investment refers to the research of modern construction industry products and intelligent construction technology by construction enterprises with the help of government technology management departments and scientific research funds. Innovation transformation is carried out in critical laboratories, pilot test bases, and industrial parks. Intermediary service agencies generally master the frontiers of technological development, which connect with universities and scientific research institutions to obtain cutting-edge scientific knowledge in technology. Construction enterprises take the industrialization of technological innovation achievements as the core and provide relatively mature technology applications for the technological development of construction enterprises. It contributes to increased competitiveness and economic benefits for stakeholders.

Industrial chain collaboration includes four aspects: capital chain, value chain, technology chain, and space chain. According to the advantages of construction enterprises, stakeholders provide whole-process financial support for new products, new technologies, and new processes and carry out in-depth cooperation in bank loans and equity transfers. Construction enterprises are adapting to the requirements of new construction industrialized production methods, and stakeholders continue to realize their own value-added. It is difficult for an enterprise to build a complete engineering project alone. Furthermore, a project needs to be jointly undertaken by several construction enterprises that master core technologies. Few enterprises can master all advanced technologies. Even leading enterprises need to coordinate with the upstream and downstream to improve their innovation capabilities. Construction enterprises in different regions are distributed and developed unevenly, which need to combine the actual development of the regional economy, society, and environment to build a chain of cooperation, complementary advantages, and joint development.

5.4 Trust Guarantee

A trust guarantee aims to enhance the trust among stakeholders and ensure members' enthusiasm to cooperate through incentive measures.

Factor endowments upgrading takes multiple factors as the core and relies on the trust mechanism to promote technical cooperation, resource matching, product integration, and coordination among construction enterprises. It helps to drive knowledge sharing and information integration among construction enterprises to solve the market competition problems. Intelligent construction promotes the digital transformation of the construction industry and brings together the strategic layout of "Internet + construction, finance + construction, investment + construction," guarantees the scientific nature of risk-sharing and income distribution with innovative service upgrading, and promotes the development of new materials, new equipment, new technologies, new process, new products, new market.

Trust is the foundation for the collaborative innovation operation of construction enterprises. Knowledge sharing, information integration, and other behaviors will help construction enterprises increase sunk costs and benefits (Wu et al., 2022). Knowledge sharing means that stakeholders promote the collaborative development of construction enterprises through knowledge diffusion among employees to achieve common goals. The primary way is to organize staff training and learn advanced scientific knowledge and construction technology from each other. Information integration invests talents, technology, and capital into cooperative innovation projects to form unified standards and reach basic cooperation consensus. Based on ensuring the trust of stakeholders, it can achieve a win-win or multi-win situation for stakeholders, thereby increasing the benefits of cooperation.

The dual incentive strategy of income distribution and risk sharing provides a fundamental guarantee for the operation of ICBI. Generally speaking, the expected benefits of transforming scientific and technological achievements are relatively high. Not only do construction enterprises gain industrialization profits, but participants such as universities and intermediaries that provide scientific research and transformation services for technology landing should also gain certain benefits. It involves issues such as valuation, share conversion, and financing. In parallel, risk and return are positively correlated, and the higher the expected return, the greater the potential risk. The risk factor for the collaborative development of ICBI is relatively significant.

The dimensions of the driving force, resource supply, collaborative operation, and trust guarantee cannot be studied in isolation. The collaborative development of ICBI is a composite system. In order to achieve the synergistic goal, **Figure 7** shows that there is a specific relationship between the four dimensions. These connections coordinate system elements to impact other elements or the whole to play better a synergistic effect, namely positive and negative loops.

The positive loop starts with the collaborative operation and develops technological innovation through whole-process collaboration and industrial chain collaboration. After the transformation of scientific and technological achievements, it realizes industrialized development, obtains economic benefits, increases the internal and external driving forces of collaborative innovation, promotes resource supply capacity, and stimulates the enthusiasm of ICBI, then acts on the dimension of collaborative operation. The positive loop is a collaborative operation—industrialization—driving force—resource supply—trust guarantee—collaborative operation.

The negative loop starts with collaborative resistance, which is a factor that hinders synergy in the collaborative process of ICBI. It may be caused by high coordination costs, invalid incentives, resource shortages, and innovation hindrance. By weakening the collaborative operation and reducing the transformation efficiency of scientific and technological achievements, the industrialization ability and dual driving ability are insufficient, resulting in tight resource supply and a low trust guarantee effect. This cycle will increase the collaborative resistance. The negative loop is collaborative resistance—collaborative operation—industrialization—driving force—resource supply—trust guarantee—collaborative resistance.

6 DISCUSSIONS

Collaborative development is a hot topic in the research of ICBI, and many stakeholders' behavior has been widely discussed around the world. Nevertheless, there is no theoretical framework to tell us how ICBI collaborative development explicitly. The primary purpose of the current research is to propose a "mi"-shaped conceptual framework to promote the collaborative development of ICBI through multi-path collaboration based on synergy theory. This paper analyzes the mechanism for effective implementation of ICBI on construction projects. In the mechanism, seven paths were studied, summarized into four dimensions. This study was applied to respond to three questions. The first asks: Which theories support

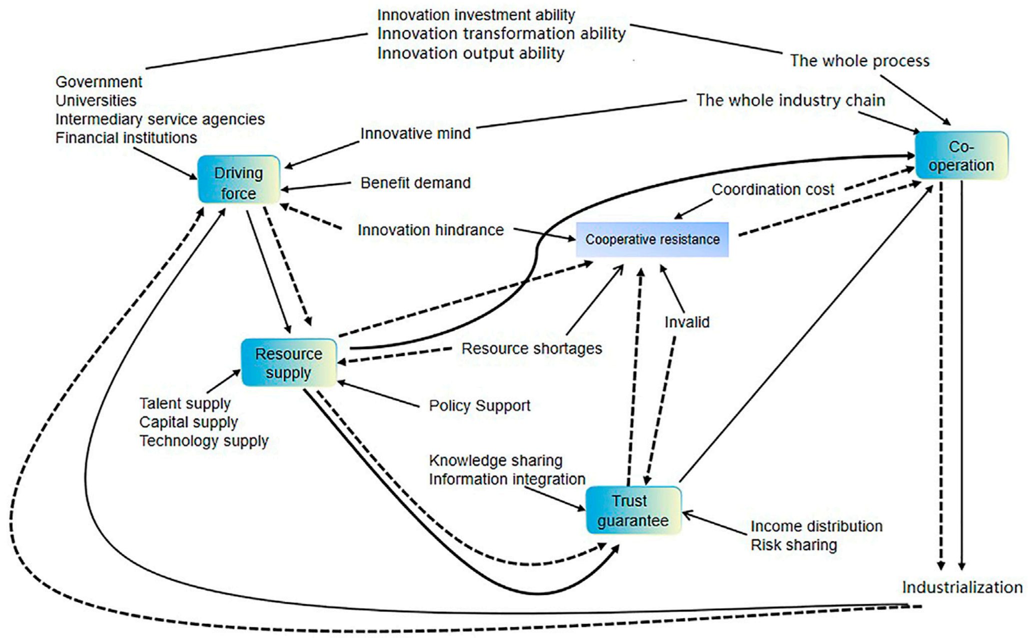

FIGURE 7 | The positive loop and negative loop in the collaborative development of ICBI.

or justify the collaborative development of ICBI within digitization? The answer, which is presented in **Section 2**, provides the foundation for the theoretical support. The second asks: What are the contributing paths to the effective collaborative development of ICBI in accelerating the transformation and upgrading of the construction industry? **Section 3** and **Section 4** explain the seven paths. The third asks: What dimensions does the "mi"-shaped conceptual framework contribute to the effective collaboration of ICBI? The answer is presented in **Section 5** to guide the direction for the collaborative development of ICBI. This paper has three principal theoretical contributions.

First, we have carefully reviewed the literature on ICBI and collaborative development. Research focuses on stakeholders, action paths, and operation processes. Theoretical research and practical discussion on the development of ICBI and other aspects are of great significance, which will help improve the construction industry's labor productivity, speed up the construction process, reduce the engineering cost, and improve the quality of the engineering project.

Next, combined with the development status of China's construction industry, a "mi"-shaped conceptual framework for the collaborative development of ICBI was established. The framework clarifies that stakeholders' collaboration, industrial collaboration, structural collaboration, building technology upgrading, factor endowment upgrading, innovative service upgrading, and construction process upgrading are the fundamental support for the collaborative development of ICBI. It explains the operating rules and principles for the interconnection of various elements under certain environmental conditions, which have essential theoretical significance.

Finally, to further explore the potential value of the conceptual framework and understand how to improve the level of ICBI, it is crucial to explore the four dimensions of the driving force, resource supply, collaborative operation, and trust guarantee, which are helpful to guide the development of ICBI.

7 CONCLUSION

This paper adopts synergy theory, applying it to the collaborative development of ICBI. It advocates for the development status of China's construction industry to consider stakeholders' collaboration, industrial collaboration, structural collaboration, building technology upgrading, factor endowment upgrading, innovative service upgrading, and construction process upgrading. Moreover, it proposes the potential value under four dimensions to improve the innovative performance of construction enterprises. In this regard, the "mi"-shaped conceptual framework could serve as a routine for construction enterprises to mitigate risks associated with the collaborative development of ICBI. There are three optional avenues to be explored in the future.

First, this study conducts a preliminary analysis of the stakeholders in the collaborative development of ICBI. It is necessary to conduct detailed research on certain two types. A "government-construction enterprise" decision analysis can be performed assuming limited rationality in future research. The evolution game model for "government and construction enterprise" is constructed to analyze both sides' evolution and stability strategy in collaborative innovation. Based on this, the study should change the simulation parameters to determine the stable equilibrium of evolution and propose countermeasures and suggestions for the collaborative development of ICBI.

Second, this framework is preliminary based on a literature review and status analysis. More empirical studies should be conducted in the future to develop it further. For example, the study will analyze the macro environment, existing problems, and development trends of the collaborative development of ICBI in different regions. Through data processing and result analysis, the applicability of this research framework should be verified. At the same time, it is also possible to provide a theoretical reference for the collaborative development of ICBI.

Third, the collaborative development of ICBI is a complex system. According to the positive loop and negative loop among various dimensions, the process and results for the collaborative development of ICBI can be further measured. 1) Several sequences and sub-sequence parameters are set up to build the synergy and innovation performance index system. 2) The synergy and innovation performance indicators are determined according to the entropy weight method. 3) Redefine the concept of the collaborative development of ICBI, and build a subsystem order model and an overall system synergy model. 4) According to the synergy and innovation performance of the collaborative development system of ICBI, the collaborative evaluation grades are divided to provide a method for measuring the collaborative development level of regional ICBI.

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.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. LL performed material preparation and conceptualization; ZG wrote the first draft of the manuscript, 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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REFERENCES

Alford, P., and Duan, Y. (2018). Understanding Collaborative Innovation from a Dynamic Capabilities Perspective. *Ijchm* 30, 2396–2416. doi:10.1108/ijchm-08-2016-0426

Anzola-Román, P., Bayona-Sáez, C., and García-Marco, T. (2019). Profiting from Collaborative Innovation Practices: Identifying Organizational Success Factors along the Process. *J. Manag. Organ.* 25, 239–262. doi:10.1017/jmo.2018.39

Baldwin, C., and von Hippel, E. (2011). Modeling a Paradigm Shift: From Producer Innovation to User and Open Collaborative Innovation. *Organ. Sci.* 22, 1399–1417. doi:10.1287/orsc.1100.0618

Bucchiarone, A., Sanctis, M. D., Hevesi, P., Hirsch, M., Abancens, F. J. R., Vivanco, P. F., et al. (2019). Smart Construction: Remote and Adaptable Management of Construction Sites through IoT. *IEEE Internet Things M.* 2, 38–45. doi:10.1109/IOTM.0001.1900044

Buchli, J., Giftthaler, M., Kumar, N., Lussi, M., Sandy, T., Dörfler, K., et al. (2018). Digital *In Situ* Fabrication - Challenges and Opportunities for Robotic *In Situ* Fabrication in Architecture, Construction, and beyond. *Cem. Concr. Res.* 112, 66–75. doi:10.1016/j.cemconres.2018.05.013

Connell, J., Kriz, A., and Thorpe, M. (2014). Industry Clusters: an Antidote for Knowledge Sharing and Collaborative Innovation? *J. Knowl. Manag.* 18, 137–151. doi:10.1108/jkm-08-2013-0312

Craveiro, F., Duarte, J. P., Bartolo, H., and Bartolo, P. J. (2019). Additive Manufacturing as an Enabling Technology for Digital Construction: A Perspective on Construction 4.0. *Automation Constr.* 103, 251–267. doi:10.1016/j.autcon.2019.03.011

Ding, L., Fang, W., Luo, H., Love, P. E. D., Zhong, B., and Ouyang, X. (2018). A Deep Hybrid Learning Model to Detect Unsafe Behavior: Integrating Convolution Neural Networks and Long Short-Term Memory. *Automation Constr.* 86, 118–124. doi:10.1016/j.autcon.2017.11.002

Dooley, L., Kenny, B., and Cronin, M. (2016). Interorganizational Innovation across Geographic and Cognitive Boundaries: Does Firm Size Matter? *R&D Manage* 46, 227–243. doi:10.1111/radm.12134

Edirisinghe, R. (2019). Digital Skin of the Construction Site. *Ecam* 26, 184–223. doi:10.1108/ecam-04-2017-0066

Feranita, F., Kotlar, J., and De Massis, A. (2017). Collaborative Innovation in Family Firms: Past Research, Current Debates and Agenda for Future Research. *J. Fam. Bus. Strategy* 8, 137–156. doi:10.1016/j.jfbs.2017.07.001

Gao, S., Yin, F., Chen, J., and Guo, Y. (2019). The Mechanism of Inter-organizational Collaboration Network on Innovation Performance: Evidences from East Coastal Enterprises in China. *J. Coast. Res.* 94, 945–949. doi:10.2112/si94-186.1

Guo, Z., and Li, L. (2022). A Study of Collaborative Innovation Mechanism of Prefabricated Construction Enterprises Using Order Parameter. *Front. Built Environ.* 8, 8. doi:10.3389/fbuil.2022.858650

Hadjimanolis, A. (1999). Barriers to Innovation for SMEs in a Small Less Developed Country (Cyprus). *Technovation* 19, 561–570. doi:10.1016/S0166-4972(99)00034-6

Haken, H. (2000). Information and Self-Organization: A Macroscopic Approach to ComplexSystems. *Am. J. Phys.* 57, 262. doi:10.1119/1.15809

Hartley, J., Sørensen, E., and Torfing, J. (2013). Collaborative Innovation: A Viable Alternative to Market Competition and Organizational Entrepreneurship. *Public Admin Rev.* 73, 821–830. doi:10.1111/puar.12136

Hong, J., Zheng, R., Deng, H., and Zhou, Y. (2019). Green Supply Chain Collaborative Innovation, Absorptive Capacity and Innovation Performance: Evidence from China. *J. Clean. Prod.* 241, 118377. doi:10.1016/j.jclepro.2019.118377

Howard, M., Steensma, H. K., Lyles, M., and Dhanaraj, C. (2016). Learning to Collaborate through Collaboration: How Allying with Expert Firms Influences Collaborative Innovation within Novice Firms. *Strat. Mgmt. J.* 37, 2092–2103. doi:10.1002/smj.2424

Huizingh, E. K. R. E. (2011). Open Innovation: State of the Art and Future Perspectives. *Technovation* 31, 2–9. doi:10.1016/j.technovation.2010.10.002

Knoke, B., Missikoff, M., and Thoben, K.-D. (2017). Collaborative Open Innovation Management in Virtual Manufacturing Enterprises. *Int. J. Comput. Integr. Manuf.* 30, 1–9. doi:10.1080/0951192x.2015.1107913

Kochovski, P., and Stankovski, V. (2018). Supporting Smart Construction with Dependable Edge Computing Infrastructures and Applications. *Automation Constr.* 85, 182–192. doi:10.1016/j.autcon.2017.10.008

Kozlovska, M., Klosova, D., and Strukova, Z. (2021). Impact of Industry 4.0 Platform on the Formation of Construction 4.0 Concept: A Literature Review. *Sustainability* 13, 2683. doi:10.3390/su13052683

Li, B., Han, S., Wang, Y., Wang, Y., Li, J., and Wang, Y. (2020). Feasibility Assessment of the Carbon Emissions Peak in China's Construction Industry: Factor Decomposition and Peak Forecast. *Sci. Total Environ.* 706, 135716. doi:10.1016/j.scitotenv.2019.135716

Li, C. Z., Xue, F., Li, X., Hong, J., and Shen, G. Q. (2018). An Internet of Things-Enabled BIM Platform for On-Site Assembly Services in Prefabricated Construction. *Automation Constr.* 89, 146–161. doi:10.1016/j.autcon.2018.01.001

Li, D., Huang, G., Zhu, S., Chen, L., and Wang, J. (2021). How to Peak Carbon Emissions of Provincial Construction Industry? Scenario Analysis of Jiangsu Province. *Renew. Sustain. Energy Rev.* 144, 110953. doi:10.1016/j.rser.2021.110953

Liu, Z., Meng, X., Xing, Z., and Jiang, A. (2021). Digital Twin-Based Safety Risk Coupling of Prefabricated Building Hoisting. *Sensors* 21, 3583. doi:10.3390/s21113583

Maietta, O. W. (2015). Determinants of University-Firm R&D Collaboration and its Impact on Innovation: A Perspective from a Low-Tech Industry. *Res. Policy* 44, 1341–1359. doi:10.1016/j.respol.2015.03.006

Najafi-Tavani, S., Najafi-Tavani, Z., Naudé, P., Oghazi, P., and Zeynaloo, E. (2018). How Collaborative Innovation Networks Affect New Product Performance: Product Innovation Capability, Process Innovation Capability, and Absorptive Capacity. *Ind. Mark. Manag.* 73, 193–205. doi:10.1016/j.indmarman.2018.02.009

Paulus, P. B., Baruah, J., and Kenworthy, J. B. (2018). Enhancing Collaborative Ideation in Organizations. *Front. Psychol.* 9, 2024. doi:10.3389/fpsyg.2018.02024

Persaud, A. (2005). Enhancing Synergistic Innovative Capability in Multinational Corporations: An Empirical Investigation. *J. Product. Innov. Man.* 22, 412–429. doi:10.1111/j.1540-5885.2005.00138.x

Rossi, A., Vila, Y., Lusiani, F., Barsotti, L., Sani, L., Ceccarelli, P., et al. (2019). Embedded Smart Sensor Device in Construction Site Machinery. *Comput. Industry* 108, 12–20. doi:10.1016/j.compind.2019.02.008

Schulze, A., and Brojerdi, G. J. C. (2012). The Effect of the Distance between Partners' Knowledge Components on Collaborative Innovation. *Eur. Manag. Rev.* 9, 85–98. doi:10.1111/j.1740-4762.2012.01031.x

Shi, Q., Ren, H., Cai, W., and Gao, J. (2019). How to Set the Proper Level of Carbon Tax in the Context of Chinese Construction Sector? A CGE Analysis. *J. Clean. Prod.* 240, 117955. doi:10.1016/j.jclepro.2019.117955

Skippari, M., Laukkanen, M., and Salo, J. (2017). Cognitive Barriers to Collaborative Innovation Generation in Supply Chain Relationships. *Ind. Mark. Manag.* 62, 108–117. doi:10.1016/j.indmarman.2016.08.002

Su, Y., Zheng, Z., and Chen, J. (2018). A Multi-Platform Collaboration Innovation Ecosystem: the Case of China Article Information: A Multi-Platform Collaboration Innovation Ecosystem: the Case of China. *Manag. Decis.* 54, 00. doi:10.1108/MD-04-2017-0386

Tetik, M., Peltokorpi, A., Seppänen, O., and Holmström, J. (2019). Direct Digital Construction: Technology-Based Operations Management Practice for Continuous Improvement of Construction Industry Performance. *Automation Constr.* 107, 102910. doi:10.1016/j.autcon.2019.102910

Turner, C. J., Oyekan, J., Stergioulas, L., and Griffin, D. (2021). Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities. *IEEE Trans. Ind. Inf.* 17, 746–756. doi:10.1109/tii.2020.3002197

Vega-Jurado, J., Gutiérrez-Gracia, A., Fernández-de-Lucio, I., and Manjarrés-Henríquez, L. (2008). The Effect of External and Internal Factors on Firms' Product Innovation. *Res. Policy* 37, 616–632. doi:10.1016/j.respol.2008.01.001

Wang, C., Rodan, S., Fruin, M., and Xu, X. (2014). Knowledge Networks, Collaboration Networks, and Exploratory Innovation. *Amj* 57, 484–514. doi:10.5465/amj.2011.0917

Wang, C., and Zhang, G. (2019). Examining the Moderating Effect of Technology Spillovers Embedded in the Intra- and Inter-regional Collaborative Innovation Networks of China. *Scientometrics* 119, 561–593. doi:10.1007/s11192-019-03084-1

Wang, X., Wang, S., Song, X., and Han, Y. (2020). IoT-Based Intelligent Construction System for Prefabricated Buildings: Study of Operating Mechanism and Implementation in China. *Appl. Sci.* 10, 6311. doi:10.3390/app10186311

Watson, A. (2011). Digital Buildings - Challenges and Opportunities. *Adv. Eng. Inf.* 25, 573–581. doi:10.1016/j.aei.2011.07.003

Wen, Y. (2021). Research on the Intelligent Construction of Prefabricated Building and Personnel Training Based on BIM5D. *Ifs* 40, 8033–8041. doi:10.3233/jifs-189625

West, J., and Bogers, M. (2013). Leveraging External Sources of Innovation: A Review of Research on Open Innovation. *Soc. Sci. Elec. Pub.* 31, 814–831. doi:10.1111/jpim.12125

Wong, J. K. W., Li, H., Wang, H., Huang, T., Luo, E., and Li, V. (2013). Toward Low-Carbon Construction Processes: the Visualisation of Predicted Emission via Virtual Prototyping Technology. *Automation Constr.* 33, 72–78. doi:10.1016/j.autcon.2012.09.014

Woodhead, R., Stephenson, P., and Morrey, D. (2018). Digital Construction: From Point Solutions to IoT Ecosystem. *Automation Constr.* 93, 35–46. doi:10.1016/j.autcon.2018.05.004

Wu, Z., Yang, K., Xue, H., Zuo, J., and Li, S. (2022). Major Barriers to Information Sharing in Reverse Logistics of Construction and Demolition Waste. *J. Clean. Prod.* 350, 131331. doi:10.1016/j.jclepro.2022.131331

Xue, X., Zhang, X., Wang, L., Skitmore, M., and Wang, Q. (2018). Analyzing Collaborative Relationships Among Industrialized Construction Technology Innovation Organizations: A Combined SNA and SEM Approach. *J. Clean. Prod.* 173, 265–277. doi:10.1016/j.jclepro.2017.01.009

Yan, X. Z., and Zhang, H. (2021). Computer Vision-Based Disruption Management for Prefabricated Building Construction Schedule. *J. Comput. Civ. Eng.* 35, 04021027. doi:10.1061/(asce)cp.1943-5487.0000990

You, Z., and Feng, L. (2020). Integration of Industry 4.0 Related Technologies in Construction Industry: A Framework of Cyber-Physical System. *Ieee Access* 8, 122908–122922. doi:10.1109/access.2020.3007206

Yuan, Y., Ye, S., and Lin, L. (2021). Process Monitoring with Support of IoT in Prefabricated Building Construction. *Sensors Mater.* 33, 1167–1185. doi:10.18494/sam.2021.3003

Zan, A., Yao, Y., and Chen, H. (2021). University-Industry Collaborative Innovation Evolutionary Game and Simulation Research: The Agent Coupling and Group Size View. *IEEE Trans. Eng. Manage.* 68, 1406–1417. doi:10.1109/tem.2019.2908206

Zeng, W., Li, L., and Huang, Y. (2020). Industrial Collaborative Agglomeration, Marketization, and Green Innovation: Evidence from China's Provincial Panel Data. *J. Clean. Prod.* 279, 123598. doi:10.1016/j.jclepro.2020.123598

Zhang, D., Liu, G., Chen, C., Zhang, Y., Hao, Y., and Casazza, M. (2019). Medium-to-long-term Coupled Strategies for Energy Efficiency and Greenhouse Gas Emissions Reduction in Beijing (China). *Energy Policy* 127, 350–360. doi:10.1016/j.enpol.2018.12.030

Zhang, R., Wang, Z., Tang, Y., and Zhang, Y. (2020). Collaborative Innovation for Sustainable Construction: The Case of an Industrial Construction Project Network. *Ieee Access* 8, 41403–41417. doi:10.1109/access.2020.2976563

Zhou, H., Wang, H., and Zeng, W. (2018). Smart Construction Site in Mega Construction Projects: A Case Study on Island Tunneling Project of Hong Kong-Zhuhai-Macao Bridge. *Front. Eng. Manag.* 5, 78–87. doi:10.15302/j-fem-2018075

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