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Development of Key Domain-Relevant Technologies for Smart Construction in China

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Abstract: Smart construction integrates new-generation information technology with construction and is vital to the high-quality development of China's construction industry. We herein provide the basic concept and importance of smart construction and summarize four types of key domain-relevant technologies: engineering software for complete industrial chain integration, construction Internet of Things for smart construction sites, intelligent construction machinery for man–machine integration, and construction big data for intelligent decision making. Subsequently, we analyze the current status and weaknesses of these technologies in terms of market environment, enterprise deployment, and core resource reserves through questionnaire surveys and expert interviews. Moreover, we identify the development goals and propose important tasks, including establishing and improving the standards system; promoting cooperation among industries, universities, research institutes, and applications; improving intellectual property protection; and conducting pilot demonstrations of typical projects. Furthermore, suggestions are proposed from the perspectives of the government, enterprises, and universities.
Keywords: smart construction; engineering software; construction Internet of Things; construction machinery; construction big data

1 Introduction

The multiscalar relevance and localized effects of the construction industry are vital to the national economy in China. However, associated issues such as subpar product quality, rapid use of finite resources, and severe environmental pollution remain acute and unsolved. These issues are primarily due to the extensive but fragmented development models of China's construction industry, which results in a significant disparity between China's current position and its high-quality development mode [1]. Although these issues are serious, they are not unique to China. To address similar issues and consequent challenges, many developed countries have published different versions of construction development strategies, such as *Construction 2025* in the United Kingdom and *i-Construction* in Japan. These strategies emphasize the pivotal role of "3-lizations," i.e., industrialization, digitalization, and intellectualization, in strengthening both competitiveness and sustainability in construction. However, China is not among the earliest countries to emphasize and promote scientific and technological innovations in its construction industry. Hence, China must focus on innovations, particularly in artificial intelligence and digitalized economies, in future construction development to enhance the innovative ability of the construction industry and promote "smart construction" in a comprehensive manner.

Owing to its importance to the development of construction industries worldwide, smart construction has been extensively investigated in recent years. Rossi et al. [2] deployed smart construction machinery based on the installation

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of intelligent sensing equipment, which effectively supports the real-time evaluation of mechanical conditions. Similarly, Bucchiarone et al. [3] enhanced the interoperability of engineering elements using cyber–physical technologies, which upgrade the intellectualization level of construction. Kochovski and Stankovski [4] developed a framework for smart construction based on edge computing, which enables the efficient and effective management of project information and facilitate communication between project stakeholders. Furthermore, Edirisinghe [5] conducted a critical review of 114 relevant scholarly papers and provided suggestions regarding the developing trend of smart construction technologies. Ding et al. [6] successfully designed a method for the autoidentification of unsafe behaviors of construction workers using artificial intelligence technologies. Zhou et al. [7] were one of the earliest researchers to introduce a construction method for intelligent building sites based on a Chinese case—the Hong Kong–Zhuhai–Macau Bridge. Although smart construction has been investigated extensively, most of the related studies have focused primarily on problems associated with specific uses of smart construction technologies, whereas the concept of smart construction remains undertheorized, thereby resulting in a lack of systematic knowledge regarding smart construction theories and key techniques. As such, a clear route for smart construction development is hindered both abroad and in China.

The aim of this study is to identify the status quo of four key smart technologies in China's construction industry: engineering software, construction Internet of Things (IoT), construction machinery, and construction big data. In this regard, the authors first conducted a broad questionnaire survey with experts and professionals from representative architectural design companies, contractors, and engineering consultancies in China. The survey was conducted for 6 months, generating a total of 635 valid responses, among which 367 pertained to the development status of engineering software, 109 to construction IoT, 38 to construction machinery, and 121 to construction big data (Table 1). The Delphi method was used to refine the information obtained by conducting in-depth interviews with 23 professionals possessing vast experience in technology application and research and development (R&D). Each interview was conducted for 45–60 min. Based on information obtained from the questionnaire survey and results derived from the Delphi method, both key targets and viable routes for the key techniques in smart construction are provided herein to facilitate smart construction development in the country.

Table 1. Years of work experience of survey participants.

	5 years	5–12 years	13–20 years	> 20 years
Engineering software	108	164	73	22
Construction IoT	39	43	18	9
Construction machinery	12	19	5	2
Construction big data	32	81	6	2

2 Overview of smart construction

As an advanced landmark of next-generation information technology and construction [8], smart construction begins with the digitalization of engineering elements that can materialize canonical modeling, networked interaction, visualized perception, efficient computing, and intelligent decision-making support. These factors contribute to the efficient integration and coordination of activities such as planning, design, construction, maintenance, and operation in the lifecycle of a construction project. Hence, smart construction is widely recognized as an essential basis for people-oriented, sustainable, and intelligent deliveries of construction products and services [9].

Owing to its advanced and various capabilities, smart construction can empower and revolutionize engineering production systems and their organizational forms. This enables the in-time or even real-time communication of construction processes, online and offline incorporation, and resource coordination, as well as facilitates the integration of construction, manufacturing, and information industries. Hence, smart construction is a viable method for achieving high-quality industrial development and for transforming a labor-intensive industrial approach to a technology-intensive one. Furthermore, it is a timely response to the policies of "accelerating the development of digitalization and promoting the digitalization-driven revolution of the projection function, lifestyle, and governance" specified in the *Outline of the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Long-Range Objectives Through the Year 2035*.

The development and promotion of smart construction will forge an upgraded version of "Construction in China." Considering the current globalization era along with intense international competition in science and technology, China's

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construction industry would benefit from early exposure to the international development tendency of "3-lizations" and hence be the global leader before smart construction becomes a new normal in the global construction industry.

3 State-of-art developments of smart construction technologies

Smart construction utilizes next-generation information technology featured in "3-lizations" and "computing power, data, and algorithm." The essential goals of China's smart construction progress are to develop smart construction technologies, including effective engineering software for the integration and interoperation of the entire construction supply chain, IoT for intelligent construction sites, smart construction machinery for human–machine integration, and advanced computing technologies for intelligent decision-making based on construction big data. The availability of these technologies and the associated achievements can support the coordination of the total process, all factors, and all participants in a construction lifecycle, thereby effectively facilitating the transformation and upgrading of the entire construction industry [10]. Therefore, smart construction technologies are critical links between underlayer general technologies and parent businesses; they are undoubtedly vital to the ultimate materialization of smart construction.

3.1 Software for industrial chain integration

Along with the continuous development of computer technology and its wide application in the current era, an engineering software system centered around building information modeling (BIM) has emerged in engineering and construction fields [11]. Engineering software includes software for design and modeling, engineering analysis, and project management. These types of software facilitate collaboration at different project stages to ultimately enable the automation of project deliveries and intelligent decision-making across the construction lifecycle [12].

Engineering software exhibits the following critical features: In terms of service target, engineering software facilitates building, municipal, bridge, tunnel, and all other types of construction projects. In terms of professional content, engineering software effectively reflects the professional knowledge derived from the long-term accumulation of both experience and expertise during the development process of China's construction industry. Furthermore, engineering software enables professionals to satisfy the actual requirements of the construction industry. In its simplest terms, engineering software transforms the knowledge and experience gained from practices into models and algorithms and then further develops these transformed models and algorithms into decision-supporting information to facilitate the smart and efficient accomplishment of multiple tasks. Hence, it is important to link the development of engineering software to actual practices such that the capability and efficacy of engineering software can be improved continuously.

Currently, a few problems exist in the engineering software system in China, among which the most prominent include the weak overall strength and the lack of core technologies. These problems have shaped the complexion of "strong management software, weak technological software, and few high-end software". Therefore, the engineering software used in the industry is primarily those developed from other countries. Using the software for design and modeling as a specific example, Chinese-developed software is affected by the increasingly severe problem of "lacking engines." In fact, 71.78% of our interviewees admitted that they primarily used the foreign software AutoCAD to perform design drawings, whereas over 50% of our interviewees reported that they primarily used Autodesk Revit and Civil 3D as BIM modeling software. More than 60% of the most popular software for engineering analysis used in China is developed abroad, since foreign software is extremely robust for computing and managing complex models. It is extremely difficult for Chinese-developed software to enhance its competitive edge within a short time to confront the significant competition from foreign software, such as the products produced by Autodesk. In summary, Chinese-developed engineering software necessitates significant developments.

3.2 Construction IoT for intelligent construction sites

As an expansion of the IoT in the construction field, construction IoT perceives and acquires real-time information regarding engineering elements via various types of sensors and then constructs a data channel through a standardized interface and middleware [13]. Hence, construction IoT can revolutionize the entire managerial process on construction sites, enabling comprehensive supervision of "unsafe behaviors of the human, unsafe status of the object, and unsafe factors of the environment." [14]

Supported by construction IoT, an intelligent construction site exhibits three main features. The first is the Internet of Everything (including man, machine, material, method, environment, and product), which is enabled by the multilayered connection of mobile internet and smart IoT. The second feature is the efficient integration of information, which is enabled by real-time data acquisition and communication, as well as forms the basis of an intelligent construction site. The third feature is the collaboration of participants. An intelligent construction site provides a general platform for information sharing, which can significantly enhance the sharing capability among multiple levels (e.g., interdepartment, interproject, and interregion).

The current development of construction IoT in China is lagging behind that of developed countries such as the United States, Japan, and Germany, which possess more than 20 000 types of sensors; cumulatively, they constitute more than 70% of the global market. In addition, along with the development of the micro-electromechanical systems, the capabilities of sensors have improved significantly. More than 90% of high-end sensors rely critically on imports. In addition to sensors, technologies such as onsite flexible networking and digital engineering are urgently required. In addition, Chinese-developed construction IoT are vital to the monitoring and supervision of personal identification, operation status of construction machinery, process management of high-risk major tasks, and monitoring of environmental indicators. However, our survey shows that in more than 88% of construction activities, construction IoT can only realize a low-to-middle level of potential targets. Hence, improving the value of construction IoT subject to limited resources is an important task in the future.

3.3 Smart construction machinery for human–machine integration

Smart construction machinery, which is based on conventional construction machinery, is a next-generation technique that integrates multiple technologies such as sensors, fault diagnosis, and global navigation satellite systems. The key features of smart construction machinery include self-inductance, self-adaptation, self-learning, and self-decision-making. Smart construction machinery can optimize its own performance through circular processes of self-learning, revision, fault diagnosis, and forecasting. Through these processes, smart construction machinery significantly surpasses conventional construction machinery, as the latter has long impeded construction work because of its resource-consuming, labor-intensive work, which is associated with not only low productivity, but also potential safety hazards [15].

Construction industries in many countries and regions have emphasized readjusting the industrial structure and the development of advanced technologies to move construction machinery forward toward “3-lization” and finally realize a system of smart construction machinery [16]. Simultaneously, China has realized a number of breakthroughs in the R&D of smart construction machinery. However, in many aspects, China still lags behind the international advanced level, particularly in the production of essential components of smart construction machinery, such as programmable logic controllers, electronic control units, and controller area networks. Such weaknesses have severely impeded the development of smart construction machinery in China, rendering China weak compared with its competitors. Therefore, the development of smart construction machinery in China can be described as “significant but not strong or refined.” As such, further improvements are necessitated.

3.4 Construction big data for decision making

Construction big data includes numerous types of data produced during different stages and multiple layers across a project lifecycle, as well as technologies associated with the acquisition, transformation, communication, and analysis of these data [17]. Construction big data are vast in volume, various in type, rapid in generation, and low in value density. Hence, the application of construction big data should focus on issues regarding the transformation from engineering experience to data-driven decisions. Subsequently, construction big data will be important in increasing industrial competitiveness and productivity, as well as improving the efficiency of industrial governance [18,19].

The value of construction big data is determined by the analytical process of the data. In this context, data analysis refers to the selection of data (whole or partial) and the mining of useful information and knowledge from data selected for decision making pertaining to different tasks. In addition to conventional statistical techniques, construction big data analytics relies on artificial intelligence, among which deep learning is one of the most important directions of development. Deep learning does not require excessive consumption and allows self-optimization based on input data. Hence, deep learning effectively solves problems of overfitting, difficulties in feature extraction, and training in early methods such as artificial neural networks [20]. In fact, it has been widely used in tasks such as behavior monitoring and identification of environmental hazards [21]. Although deep learning offers numerous advantages, because of its complexity, it tends to provide models in terms of black boxes and hence may render them unexplainable. By contrast,

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in terms of interpretability, the mechanistic model is better than deep learning because the former has a clear physical meaning for each of its parameters. Hence, it is important to construct a hybrid data analysis model that integrates big data analytics and mechanistic models. Such a model facilitates feature extraction from construction data, thereby enhancing the instantaneity and adaptability of the model.

Most developed countries regard big data as one of the most important and valuable resources for development. They have developed many different types of strategic plans with emphasis on the combination of big data and industrial development, including the *Federal Data Strategy 2020 Action Plan* (the United States) and *Data Strategy 2018–2020* (Australia). In fact, China has published a series of strategic plans, such as the *Action Plan for Big Data Development*. However, neither the development nor the application of construction big data has evolved in a desirable manner; in fact, both are still in their infancy. Specifically, the application process of construction data in China is lacking sophistication, i.e., data acquisition has not been digitalized and automatized, and data storage and analysis lack standardization. Furthermore, the major tools for data storage and management, such as HBase, MongoDB, and Oracle NoSQL, are primarily imported, similarly for flow computing architectures Storm and Spark. In terms of application areas, the construction big data used in China are primarily for labor management, material purchase management, cost management, and machinery management; hence, deep and wide applications are lacking.

4 Challenges associated with smart construction in China

China has achieved rapid and fruitful progress in smart construction after years of development and experience accumulation. However, with respect to the immediate necessity for industrial upgrading and transformation, as well as compared with the current relevant situations in developed countries, the development of smart construction in China is still hindered by various challenges.

In terms of market environments, many domestic construction companies have formed not only dependence on foreign techniques, but also dependence on data (i.e., the manner by which they are stored, acquired, communicated, and analyzed). Hence, it would be extremely difficult for companies to change their existing methods to Chinese-devised ones within a relatively short period. Consequently, Chinese-developed products would lag further behind foreign products, as demand for them is low since they are rarely used.

In terms of enterprise deployment, most domestic construction companies have not specified sophisticated development plans and provisions, resulting in a severe lack of communication between upper- and lower-reach enterprises. This situation undermines the development of Chinese-developed products, both in terms of scope and depth. In addition, domestic construction companies began late in developing smart construction; consequently, ecological foundations are weakened and resources are used unoptimally. Hence, Chinese-developed products are positioned at the bottom across the entire value chain. Moreover, domestic construction companies are not invested in innovations and do not produce sufficient internationally leading innovative products.

In terms of key resources, smart construction standards are insufficient, resulting in the absence of valid standards for relevant research. As such, the capabilities of market adaptation and services must be enhanced. Furthermore, the weak core technologies in China cause domestic smart construction R&D to be confined to secondary development based on foreign technologies. In addition, a fully equipped application ecosystem for smart construction does not exist; hence, the intellectualization of the entire project lifecycle cannot be supported. Finally, high-end interdisciplinary talent is lacking, whereas the associated plans for the introduction, fostering, and reserve of talent have not been established.

5 Major tasks of China’s development of smart construction

To promote China’s smart construction, independent R&D must be performed based on the rule of “setting fine examples, promoting gradually,” as well as by strengthening weaknesses in features, improving upgrading, and procuring advantages in R&D for the core technologies of smart construction.

As mentioned above, engineering software in China is affected by the problem of insufficient engines; hence, the associated disadvantages must be addressed. Several suggestions are proposed herein. First, based on a clear identification of the discrepancy between foreign software and Chinese-developed software, we should emphasize the R&D of Chinese-developed software, particularly bottleneck technologies, and domestic 3D graphic engines must be enhanced. Second, we should improve both the innovation and application of Chinese-developed software such that they precisely match the actual requirements of building and infrastructure projects for replacing foreign software. Third, we should accelerate the process in the design and development of engineering software standards systems, improve the associated evaluation mechanisms, and finally develop a self-controllable software ecosystem centered on BIM for the construction supply chain.

The development of construction IoT should focus on features that have the potential to become a global leader. First, feasible paths should include incorporating construction IoT into industrial IoT as well as defining application standards and standardized technical guidance for IoT technologies. Second, breakthrough should be realized in the R&D of technologies such as total factor sensing, flexible adaptive networking, and intelligent fusion of multimode heterogeneous data. Third, the scale advantage of the construction market in China should be fully utilized to perform a high-quality demonstration of engineering IoT and strengthen its application value.

The development of construction machinery requires emphasis on upgrading the levels of intellectualization, sustainability, and humanization. Hence, researchers and practitioners should strive to develop and enhance the system of construction machinery strands to improve market adaptation, as well as to remove bottlenecks in component technologies and raw materials to improve the reliability of products. Finally, the previous simplex model and pure sales must be abandoned; in fact, innovative, integrated sales services should be provided by focusing on aftermarket services.

The development of construction big data should be based on the current advantages to provide a solid data basis for continuous innovation. First, the development of fundamental theories should be improved in big data and key technologies for data acquisition, storage, and mining should be further developed. The first rule is to satisfy the demands of actual engineering projects. Second, an organic system for construction big data management must be established, including policies and regulations, standardized evaluation approaches, and corporate institutions, such that the vast volume of construction big data can be effectively managed and utilized. Third, regarding the availability of a production system for construction big data and the improvement of its application and service, the next key task is to drive the development of correlative industries and foster a new ecosystem of construction services.

6 Countermeasures and suggestions

The development of smart construction is a systematic, strategic, and long-term process. During this process, the progress of key smart construction technologies is significantly affected by the macroscopic administration, market environment, and R&D deployment, where multiple industries, stakeholders, and agents are involved. Hence, countermeasures and suggestions should be provided accordingly by considering different stages, production systems, organizational structures, and cooperation between companies and industries to empower the construction industry in all aspects.

6.1 Suggestions for macroscopic administration

First, in terms of macroscopic administration, favorable policies should be issued to accelerate the construction of industrial innovation platforms, particularly for the in-depth integration of smart construction technologies and industrial practices. Such policies will significantly benefit the collaborative development mechanism in science and technology industries. Furthermore, the construction of industrial innovation platforms that incorporate the state, industry, and individual companies can form a worth-learning model for industrial innovation, thereby fully utilizing the driving and accelerating power of scientific institutions. Such relevant policies and industrial innovation bases will be important in realizing breakthroughs, enabling the transformation of key smart construction technologies, improving the agglomeration economy of industrial innovation, and ultimately promoting the upgrading and high-quality development of China’s construction industry.

Second, policies should widen and strengthen routes and financial resources to support industrial innovations. Governments at multiple administrative levels should enhance their financial support by developing a valid financial mechanism that ensures both stable capital resources and competitiveness. This will allow for a more rapid and effective transformation of technologies into products and further enable industrialization. Moreover, it is necessary to develop an innovation input mechanism in which governments are crucial in establishing a supportive environment, companies function as key agents, and multiple social participants are important sources of financial aid. Through these measures, the efficiency of resource allocation will be improved significantly, and the creation of new technologies and products will be further promoted.

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The third suggestion is to develop systems for smart construction standards and standardized evaluation approaches. In this regard, emphasis should be directed toward the application of multiple types of engineering data across a project lifecycle, the development of technological frameworks and the associated standards, and the objective evaluation of the development and application levels of smart construction based on the existing national certification testing system. In particular, performing international comparative analyses by period is crucial for the identification, correction, and improvement of potential weaknesses.

The fourth suggestion is to develop a standardized and orderly market environment to construct a business system with fair competition, during which associated authorities should strive to improve relevant laws and regulations, as well as strengthen the protection of intellectual property rights. Furthermore, it is equally important to fully utilize industry associations in the self-regulation of industries and ordering of markets. The anti-trust, anti-dumping, and strengthening and protection of intellectual property rights should be emphasized.

6.2 Suggestions for firms

First, firms should first focus on BIM and digital design, smart building sites, and unmanned construction systems, followed by application-centered R&D. Hence, firms should closely monitor the market demand, intensify their market investigation, and further develop coping mechanisms. Additionally, they should enhance the market feedback mechanism for the continuous upgrading of product capability, quality, and service. These endeavors would benefit the production of both goods and services that effectively match market requirements and gradually expand customer segments.

Second, individual firms must increase their R&D inputs and deploy particular strategic development plans based on their own features. Regarding R&D, firms should effectively allocate equipment, people, etc. and ensure that resources are synergized to increase product quality. For small- and medium-sized manufacturers, it is preferable to focus on specific technologies in a particular field and perform increasingly specialized and in-depth instead work instead of pursuing “significant and broad” endeavors. Larger manufacturers are comparatively more suitable in proposing general solutions for specialized small- and medium-sized manufacturers. Hence, they are suitable in forming integrated approaches for interfirm cooperation and the shared but staggered growth of different types of firms.

Third, firms that focus on technology applications should collaborate closely with R&D firms (e.g., hardware manufacturers and industrial automation manufacturers) to achieve industrial chain cooperation and develop a collaboration ecosystem for smart construction. Additionally, it is necessary to reap the technological advantages of key R&D units and exploit the effect of demand traction based on actual applications. Through in-depth cooperation, different types of firms can facilitate resource complementarity and value co-production. Therefore, an integrated solution plan and cooperation system can be established, thereby enabling the systematic development of smart construction.

6.3 Suggestions for universities and R&D institutions

Owing to the importance of talent in China’s development of smart construction, universities and R&D institutions should exploit their education specialties and develop a school–enterprise cooperative education mode for cultivating young talent to further develop smart construction. Important measures for the cultivation of multitalented individuals that excel in construction management, engineering technologies, and information technologies should be included in the development of university research bases, college–enterprise training plans, cultivation of emerging disciplines, and emphasis on the development of “new engineering disciplines,” including the majority of smart construction and the implementation of educational reform in engineering majors.

Additionally, universities and R&D institutions are suggested to fully utilize their advantages in fundamental research in supporting young talents to conduct independent, original research. The novelty, seriation, systematicness, and integrity of research products must be emphasized. In addition, it is important to focus on the leading role of R&D in the development of the engineering field and fully acknowledge that R&D itself should be based on services for actual engineering problems. The current key direction of development involves fundamental technologies of engineering software, construction IoT, construction machinery, and construction big data. The progressive development of breakthroughs is critical in these specified directions.

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