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Application of CPS Under the Background of Intelligent Construction

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Abstract: The advent of the fourth industrial revolution (Industry 4.0) has brought about new opportunities for the intelligent transformation and upgrading of the construction industry to achieve high-quality and sustainable development. On the basis of analyzing the background of the industry and the development status of the corresponding technologies used in intelligent construction, the application of cyber-physical system (CPS) is proposed. The CPS intelligent construction platform is created in response to the demands of the construction industry's current growth to provide digital solutions. The drawbacks and challenges in the current construction development process have aided in the industry's transformation and upgrading.

Keywords: CPS; Digital twin; Cyber-physical system; Smart building

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1. Background research

1.1. Construction industry

At present, China's construction industry is in the early stages of industrialization; prefabricated concrete structures are developing relatively quickly, precast concrete components hold the largest market share, and the construction process of prefabricated concrete structural systems is relatively mature. However, there are still many issues in its design standardization and management informatization; thus, its industrialization transformation has a long way to go. The construction industry has historically relied heavily on factor inputs and large-scale investments to spur development; however, the degree of industrialization and information technology as well as the proportion of investment for scientific and technological research and development are low, the integration of advanced manufacturing technology, information technology, and energy-saving technology is insufficient, and the capabilities of robots and intelligent construction equipment are weak. In the same way, the informatization of the construction industry is an important part of its development strategy and also an inevitable requirement for the industry to transform its development mode, improve its quality and efficiency, as well as save energy while reducing emissions. At present, China's construction industry has made progress in office automation, professional software, customer management systems, data systems, and other aspects. However, there is still a significant gap in the actual realization of digitalization, networking, and intelligence. The future still requires the enhancement of the integration and application of information technology, such as BIM, big data, intelligence, mobile communications, cloud computing, and the internet of things.

1.2. Intelligent construction industry

1.2.1. Policy

In 2020, the Ministry of Housing and Urban-Rural Development in China issued the "Guiding Opinions on Promoting the Coordinated Development of Intelligent Construction and Building Industrialization," which points out the direction of industrialization and intelligence for developing the engineering construction industry, stipulating the necessity to promote building industrialization as the carrier, take digitalization and intelligent upgrading as the driving force, innovate and break through relevant core technologies, promote the application of intelligent construction in all aspects of engineering construction, as well as form a cover for scientific research and design. The intelligent construction industry system integrating the entire industry chain, including production and processing, construction assembly, and operation, is of far-reaching significance to promoting the transformation and upgrading of the construction industry.

In January 2022, the "14th Five-Year Development Plan for the Construction Industry" was issued, asserting that the construction industry should speed up the promotion of intelligent construction and building industrialization, as well as integrate the two to maximize their respective benefits. It shifted the core goal of the construction industry from the pursuit of high-speed growth to the pursuit of high-quality development.

The "14th Five-Year Development Plan for the Construction Industry" clearly points out that by 2035, China's construction industry must improve its overall quality and efficiency, the innovation ability of enterprises, and the quality of construction; the industrialization of the construction industry must be fully realized, and the core competitiveness and overall advantages of the construction industry must be enhance; additionally, there should be an established independent echelon of high-quality talents; its intelligent construction must be known to the world, thus improving its rank among construction powers. All these will help China's construction industry to reach the world's leading level.

1.2.2. Industry

China's intelligent construction is now in the start-up and exploratory stage, having a certain gap with developed countries. Under the premise of improving the intelligent construction policy, combined with the layout of the construction industry system, its standardization and digital foundation still require consolidation, and the research and development of its information platform must be closely integrated with the actual construction of projects.

Based on the intelligent construction system, the collaborative intelligent construction equipment and the construction of industrial logic are important ways to promote the healthy development of intelligent construction.

2. Cyber-physical system

CPS is a multidimensional, complex cyber-physical system that integrates computing, networking, and the physical environment. It constitutes a mutual mapping of human, machine, object, environment, information, and other physical and cyberspace information resources through a highly complex system, the 5C hierarchical architecture (Intelligent Perception Layer Connection, Information Mining Layer Control, Network Layer Cyber, Cognitive Layer Cognition, and Configuration Execution Layer Configuration), which promotes timely interaction and efficient collaboration, thus achieving a high degree of resource integration [1]. The basic model is "perception-analysis-decision-execution," as shown in **Figure 1**.

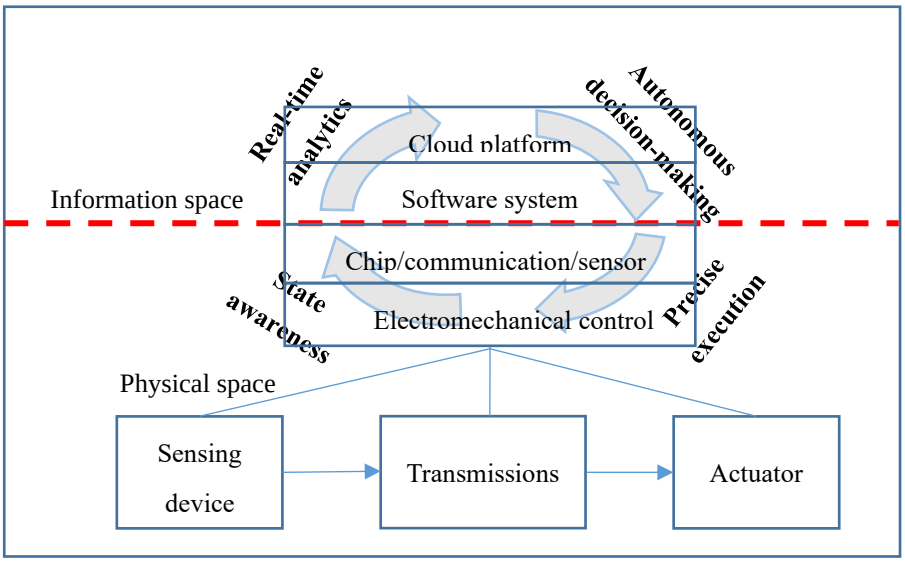

Figure 1. CPS "perception-analysis-decision-execution" model

3. Analyzing the development status of CPS

3.1. Current situation of domestic development

In 2016, China's State Council issued the "Guiding Opinions on Deepening the Integration and Development of Manufacturing and the Internet," which proposed to build a reference model and comprehensive technical standard system for cyber-physical systems, a test and verification platform, and a comprehensive verification test bed, as well as support the development of compatibility, interconnection, and interoperability test and verification. Subsequently, various industries began researching and innovating the CPS technology, and with the deepening of CPS research, a general consensus has been achieved. CPS has become a comprehensive technology system that supports the deep integration of virtual spaces, such as information, communication, environment, society, and other resources, with the entities of the physical world [2]. There will be great potential for development in various industries, including energy, transportation, medical, aerospace, and construction. The development of CPS will be a transformative change that will have an immeasurable and far-reaching impact [3-5].

At present, with the rapid development of CPS and its application, CPS has been widely used in many fields, such as industrial manufacturing, energy and electricity, transportation, medical, and health.

3.1.1. CPS + industrial manufacturing

The concept of CPS is most prevalent in the industrial sector, especially in manufacturing. For instance, the well-known "Industry 4.0" concept in Germany is epitomized by the cyber-physical production systems (CPPS).

The full cycle, including the design, production, service, application, and so on, has been included in the CPS concept and application scenarios in the industrial field. Based on the actual operation data of physical entities, production environment, and manufacturing process, CPS can be accurately mapped to the virtual space, so as to achieve real-time control and the optimization of industrial production processes, which can improve the intelligence and efficiency of industrial production [6].

3.1.2. CPS + energy

In the energy industry, the deep integration of CPS and energy enables different energy systems to be online, realizing transformation in the direction of interconnection, common source, common network, and multi-

energy complementarity. At the same time, in various application scenarios such as electricity, heat, and natural gas, CPS-based technology is able to achieve mutual integration, which can improve the utilization rate of energy and provide convenient services for users' needs, such as safety, economy, and other aspects.

3.1.3. CPS + transportation

In the transportation industry, with the in-depth integration of CPS and various components of the transportation system, the planning and construction efficiencies of transportation facilities can be improved in terms of their technical levels.

In addition, in terms of transportation optimization, through CPS, transportation can refine real-time supervision based on a variety of monitoring sensors and hardware equipment and achieve real-time data interaction with the supervision platform, such as guiding vehicles and rail transit. Through the data algorithm of the virtual space, the optimal transportation scheduling calculation in the physical world can be carried out, so as to comprehensively improve the actual dynamic transportation performance.

3.1.4. CPS + healthcare

On the basis of the traditional health monitoring system, various types of data belonging to patients and medical institutions, such as patients' health records and daily drug purchase records, can be computed and analyzed using the CPS architecture and software system.

Through the mining and analysis of a small amount of health and medical data, the formulation of personalized and customized precision treatment and healthcare plan can be realized for patients. In addition, the system framework based on CPS can promote the development of telemedicine and remote emergency assistance. It is possible to share developed resources across the country and even in remote and medical resource-scarce areas.

3.2. Current situation of foreign development

In 1976, Don Woods created a small program called Colossal Cave Adventure on a Xerox console, which was probably the first computer game software, at Stanford's Artificial Intelligence Lab.

In 1993, hundreds of foreign special forces were besieged by thousands of Somali militiamen during military operations in Mogadishu, the Somali capital, killing 19 soldiers and wounding 73 others. This incident created a demand where terrorists can be fought without the direct involvement in battlefields.

Subsequently, foreign countries have borrowed the principle of game software and developed special combat software based on screen interaction. Virtual digital ammunition, which perfectly matches the drone's physical ammunition, is controlled on screen by the operator. The operation is entirely contactless, and no personnel will need to enter the battlefield. Just by aiming at the target from the screen, it is possible to make precise hits. This technique of controlling physical entity P by digital virtual C reflects the CPS-based technology (**Figure 2**).

The cyber-physical system interacts with physical processes through human-computer interaction interface, using a networked space to control the physical entities in a remote, reliable, real-time, secure, and collaborative manner.

CPS combines computation, networking, and physical processes, in which physical processes are controlled and supervised by the network. The computer receives feedback from the physical processes that it controls. In a CPS system, physical processes and other processes are closely related and interrelated, making full use of the characteristics of different system structures. CPS embodies the monitoring of each physical process and the execution of appropriate commands to change it. In other words, physical processes are monitored by computing systems. It is associated with many small devices that have wireless communication, sensory storage, and computing capabilities. In the real physical world, physical processes

occur naturally, and CPS is an anthropogenic physical system or a more complex system that unites humans and the physical world.

The management system is an information system that uses information technology to establish a complete set of project site management that supports on-site management, interconnection, and collaboration, intelligent decision-making, as well as knowledge sharing throughout the life cycle of the project. With the continuous deepening of information construction by construction enterprises and the development of internet technology, an increasing number of construction enterprises have a better grasp of the construction site.

In regard to project research in engineering project, as long as the virtual body management is the entity management, integrating the CPS system in the physical space of the construction project through various data and technologies in the virtual space to establish a digital twin engenders a quantum leap in the limitations of time and space. It not only enables real-time symmetrical management of the physical world and the information world, but also realizes data-based, systematic, visualization, and green construction management.

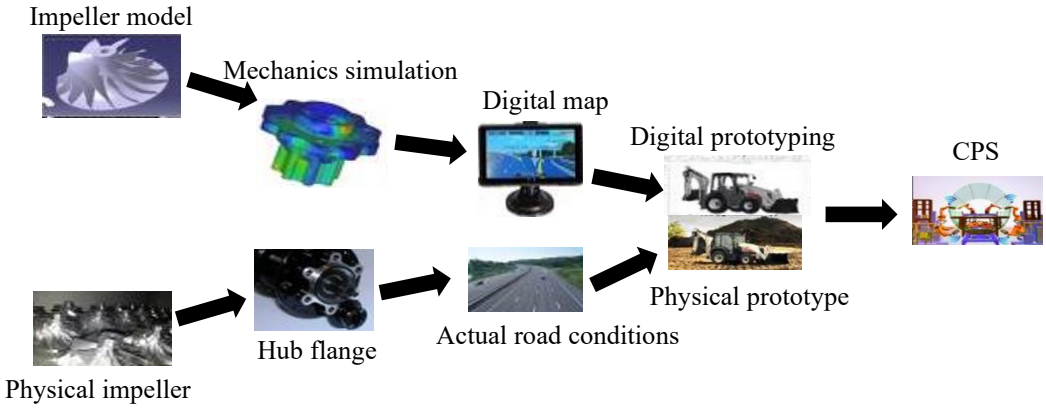

Figure 2. CPS digital twin evolution

At present, new technologies such as artificial intelligence (AI), wireless sensor networks, and building information models have been continuously integrated into construction management, and some progress has been made. For instance, radiofrequency identification (RFID) is widely used in personnel positioning and management, material tracking, equipment rights management, and other operations; computer vision, on the other hand, has played a huge role in structural deformation detection and unsafe behavior recognition; building information modeling (BIM) reflects the critical role of information integration and interaction platform. From the aforementioned technologies, a series of intelligent systems have emerged in the fields of construction safety management, construction labor management, construction equipment management, construction activity monitoring, and environmental management, forming the prototype of smart construction sites. The connotation and common traits of smart construction sites, however, are not properly understood, and the aforementioned achievements mostly rely on various software and hardware technologies to enable the informatization and intelligence of particular tasks [7].

In recent years, the United States has issued the “American Competitiveness Plan” through the NAS (National Academy of Sciences), which clearly lists CPS as a key support plan. Subsequently, the National Institute of Standards and Technology set up a CPS public working group to deploy and formulate a series of CPS standards.

4. Application research of CPS-based intelligent construction in the construction industry

With the current comprehensive development of CPS at home and abroad, the in-depth application of information technology in the field of industrial manufacturing, and the proposal of Industry 4.0, industrial digitalization has become an inevitable development trend [8,9].

For more than 40 years since the reform and opening-up, the construction scale and its technology have continued to expand, but the modernization process of the construction industry has been developing slowly. Still relying on demographic dividend, the business model is still managed by package. The industry's extensive production and organization methods and the poor overall cultural quality of the personnel are significant factors that lead to low production efficiency, waste of resources, and frequent safety accidents in the construction industry.

Therefore, China's construction industry is based on the goal of long-term development, which is very urgent and critical to the transformation and upgrading of traditional industries. At the same time, with the increasing maturity of basic technologies, such as the internet, cloud computing, big data, blockchain, and internet of things, the CPS-based intelligent construction of the construction industry will become an important research direction for digital upgrading [10].

4.1. Challenges in the construction industry

4.1.1. Fading of demographic dividend

After nearly 30 years of rapid development, China's construction industry has made great achievements. In recent years, with the acceleration of population aging and the impact from the development of other industries, the construction industry is seeing a "labor shortage" phenomenon. As a labor-intensive industry, the traditional construction industry is deeply affected by the fading demographic dividend [11].

4.1.2. Weak efficiency growth

With outdated operation methods and a low degree of informatization, the traditional construction industry relies on traditional management methods to manage the construction process. Due to the impact of the overall industry environment in recent years, the profit margin of the construction industry is seeing a decline, and the project's resource input cost is essentially unchanged. Hence, it is necessary to rely on management to increase efficiency [12]. Against the backdrop of years of traditional management, the efficiency of projects has grown at a slow pace. The following are the primary issues with the existing building construction project management system:

(1) the industrial chain is not integrated, and it is difficult to share information, resulting in huge communication and construction costs;
(2) the construction organization scheme faces difficulties in obtaining the optimal solution due to the complex building construction process; the advantages and disadvantages of the construction organization design largely depend on the experience and level of the designer, thus creating contingency and uncontrollability;
(3) the construction process lacks efficient control mechanisms, and the information transmission at the construction site is noticeably slow, including real-time collection of work status, real-time intelligent decision-making, and completion of corrective control;
(4) the whole industry chain's construction data is not structured, and enterprises lack their own knowledge base.

4.1.3. The demands for development

With the rapid development of the construction industry, consumers' requirements for construction products are gradually increasing. Green buildings, green construction, double carbon policies,

prefabricated construction, digital transformation, and other new requirements for the development of the construction industry at the national level have also been put forward. All participating units need to improve the comprehensive strength of enterprises in order to meet and adapt to the development requirements of the construction industry.

4.2. Resolution

In view of the development of the construction industry and its new requirements for industrialization transformation and intelligent upgrading, new construction industrialization has become the only way for the transformation and upgrading of China's construction industry.

In accordance with the requirements for the development of the industry, this paper proposes a smart construction platform based on CPS combined with industrial internet to provide digital services for the entire industrial chain. Through the CPS intelligent construction platform, it is possible to realize the digital management of the whole construction production process from supply chain to delivery.

4.2.1. System architecture

The intelligent construction platform proposed in this paper is based on the "three-in-one" software + hardware + BIM, with BIM as the basis for visualization, accessing project management software data and intelligent hardware data, as well as creating a construction site that is in synchrony with the actual construction site, so as to visualize and realize the symmetrical management of digital twin on the site.

4.2.2. Scenarios

When all data is concentrated in the smart platform by providing data access of the physical factory in the corresponding data platform to open up the physical factory and the construction site, creating a model through BIM in the intelligent platform, using the sensor equipment for automatic data input, and advocating auxiliary data entry of the software system, the CPS intelligent construction system is able to access information processing technologies, such as cloud computing, to provide digital solutions for current use scenarios.

4.3. Technical support

4.3.1. BIM

BIM originated from the United States in the 1970s, and compared with two-dimensional computer-aided design (2D CAD) and charting technologies, its main advantages include visualization, simulation, and coordination. Based on the information and data carried by BIM, it can be used in all stages of an engineering project's construction process [13].

With the development and application of BIM, this technology has gained widespread attention, becoming an indispensable tool in the construction process. At the same time, the number of technicians who are familiar with BIM and its applications are also increasing year by year. On the other hand, many BIM software manufacturers have gained maturity in terms of their software development, and the majority of software is now compatible and interoperable even among different brands.

In short, the implementation conditions for the popularization and expansion of BIM are now mature.

4.3.2. Big data

The amount of data generated by the engineering project management process itself is extremely large, and its data collection, storage, analysis, and sharing can be applied to numerous applications based on big data. Compared with traditional data, big data has the following characteristics:

(1) the total amount of data is large, and the accumulation of data volume at any time, from gigabyte (GB), to terabyte (TB), petabyte (PB), or even to exabyte (EB), increases geometrically;
(2) data has shifted from the original structured data to unstructured data, such as pictures, audios, videos, and other forms, with the development of smartphones, microcomputers, applications, and professional application software;
(3) the speed is fast, data is generated on a daily basis, its transmission speed has far exceeded that of traditional data, and the speed of different types of data transmission can be improved with 5G technology, putting forward higher requirements for timeliness in big data processing;
(4) with the development of big data and the enrichment of industry data models, the mining and analysis of big data has far-reaching significance, as it can be used to extract valuable information and transform and integrate the knowledge of enterprises and industries; it is more valuable that a single data, which has limitations to a certain extent [14].

4.3.3. IoT

The internet of things was first proposed at the end of the 20th century by the Massachusetts Institute of Technology in the United States. Through a variety of information sensing equipment networking, the formation of an intelligent data sensing network that purports to achieve real-time data interconnection between people and things, things and things has been realized.

At present, in the construction process, large-scale equipment operation monitoring, face recognition, license plate recognition, environmental monitoring, AI recognition, as well as special safety and quality monitoring have been widely used. The construction site environment is complex and changeable. Through IoT, the use of sensors instead of manual data collection methods engenders more efficient data collection and monitoring for various on-site construction activities [15].

4.3.4. Mobile internet

Through the link between mobile communication device and the internet, mutual data transmission can be realized. The Research Institute of the Ministry of Industry and Information Technology stipulates that mobile internet constitutes the internet and services that use the mobile network as the access network, such as mobile terminals, mobile networks, and application services.

At present, smartphones, tablets, and other convenient handheld devices can be very convenient, fast, and efficient in connecting to the internet, such as the traditional 2G and 3G networks, and now the 4G and 5G networks. The development and comprehensive application of mobile internet have broken the constraints of time and space of construction sites, meeting the application needs of project managers for data, including obtaining information anytime and anywhere, real-time recording, and querying, thus greatly improving the efficiency of project management.

In the future, with the popularization of 5G, it will further provide technical support for the development of intelligent technology at construction sites.

4.3.5. Cloud computing

At present, cloud computing services have developed into a three-level service model [16,17].

(1) Infrastructure as a service (IaaS) refers to hardware infrastructure that provides provisioning and configuration services for virtualized computing and storage resources.
(2) Platform as a service (PaaS), which refers to the platform environment for program development and operation, providing resource management and data processing services.
(3) Software as a service (SaaS), which refers to application software that provides internet software access and application services for end users.

4.3.6. Artificial intelligence

The concept of artificial intelligence (AI) was born during the Dartmouth Conference in the 1950s. Through computer technology, data processing and analyses are carried out, simulating complex processes, such as human judgment, reasoning, and learning.

With AlphaGo triumphing over professional Go players, as well as the open source of AI algorithms, AI services have emerged in various fields.

(1) Business intelligence

AI programs can make accurate predictive insights as well as analyze and collect data for enterprises to develop strategies.

(2) Transportation and inventory automation

AI may resolve the issues of transportation backlog and inventory shortage by programming the application that analyzes procurement data and inventory, so as to automatically purchase new goods. In this way, having excessive or insufficient inventory can be avoided, and enterprises will not miss delivery deadlines, thereby saving costs.

(3) Customer service artificial intelligence

Intelligent chatbots can provide customers with real-time suggestions.

(4) Marketing

Artificial intelligence can be used to search large data sets to produce more accurate and insightful customer profiles.

In addition to the basic applications of AI in helmet detection, photonic textiles, fire detection, and hazard identification for industrial operations, it will continue to develop for various applications in the construction industry, such as on-site safety and quality automatic identification by unmanned aerial vehicle algorithms [18].

5. Development prospect of CPS-based intelligent construction

5.1. Informatization

Bringing the construction process online is a prerequisite for the development of intelligent construction, so that the construction process can be solidified and transmitted through information tools (software, hardware). Upgrading the traditional management modes of escrow package and offline document management is the basis and premise for intelligent construction [19].

From the positions of various departments of the project, to the information linkage between the participants and suppliers, and subsequently to the upstream and downstream interaction of the industry, it is necessary to popularize informatization. Moreover, with the intensification of the population aging phenomenon, the transformation and upgrading of the construction industry have become an inevitable development trend, in which informatization is the prerequisite for the development of industrial digitalization [20].

5.2. Digitalization

The essence of digitalization is to format information, transform chaotic and complex information into formatted data that can be recognized and calculated by computers, and subsequently build a mathematical model of the industry based on the industry's characteristics and data types. The actual formatted data are calculated by computers in accordance with the corresponding rules for unified processing.

The essence of digitalization is also to classify, analyze, and process the project data generated based on informatization, as well as generate key indicators that are conducive to management decisions. It embodies the process of data processing and application.

5.3. Intelligent

With the rapid development and iteration of informatization and digitalization, as well as the emergence and popularization of intelligent equipment, terminals, and algorithms in various projects, there will be an increase in the use of smart devices with a reduction of human involvement in the construction process. Especially with the intensification of the aging population, the construction industry will face a severe shortage of laborers.

With the maturity of intelligent equipment, such as construction robots, drones, and building machines, the intelligent development of the construction industry will be further promoted. The restricted labor force can be upgraded and liberated from repetitive, inefficient labor. While promoting the transformation and development of the intelligent construction mode, the integration of intelligent equipment and various information technologies will also play a certain role in promoting the development of overall social intelligence.

5.4. Visualization

With the adjustment and development of basic technologies, such as intelligent terminals and rendering engines, as well as the popularization of visualization technologies, such as BIM, virtual reality (VR), and augmented reality (AR), the traditional two-dimensional presentation methods, such as document reports and data reports, will also move toward new technologies, such as three-dimensional visualization and immersive experience.

Data can be visualized in the form of three-dimensional visualization, aiding in the decision-making process and improving its efficiency and accuracy. With the CPS-based intelligent construction system, non-construction professionals can understand the project information better and participate in project decision-making.

5.5. Integration

With the continuous exploration and development of CPS-based intelligent construction technology, there will be a gradual unification of standards in each participating unit, from the original single-point application and single enterprise internal management to multi-unit system integration application and cross-departmental collaborative management.

Secondly, the functions and data of the CPS system will be standardized, and the data specification and data interface standards of each enterprise will also be unified to achieve integration and scalability between systems. The systems have been fully integrated in terms of high-level design, and data are organically shared at the application layer.

Through the intelligent construction of the CPS system in the upstream and downstream of the industrial chain, from raw materials to production and processing, from factory production to logistics transportation and on-site assembly, as well as other operations, the CPS-based intelligent construction runs through the whole life cycle of engineering construction and further realizes data mining, integrated intelligent construction, as well as the fine control of projects.

5.6. Greening

Based on the “double carbon” goal of carbon peaking and carbon neutrality, the development model of the construction industry has been redefined, in which “green and low carbon” will become one of the core goals of the industry’s future development.

In order to achieve green and low-carbon construction, it is necessary to begin with planning and design, integrating production suppliers and various construction enterprise departments, and fully implementing the concept of green development from the perspective of research, construction, operation, and

maintenance. The specific green construction measures are as follows:

(1) the comprehensive and in-depth application of BIM-based technologies, the advanced overall planning and key technology simulations through BIM-based technologies, as well as the optimization of technical solutions and other measures to prevent rework and repetitive operations in the construction process;

(2) the continuous development of prefabricated construction methods, the improvement of assembly rates, and the deepening of industrialization will engender an increase in prefabricated components; a large number of centrally-established buildings in PC component factories will be conducive to carbon emission reduction through production efficiency improvement and on-site construction work and material loss reduction;

(3) the application of a CPS-based intelligent construction system improves project management efficiency, reduces construction waste, quantifies the energy consumption index of the construction process, and provides accurate data support for the evaluation and optimization of green construction.

6. Conclusion

CPS is the key technology for intelligent construction and an important direction for the transformation and upgrading of the construction industry. Through the in-depth integration and continuous innovation of the construction industry, intelligent construction technologies will continue to improve and iterate on the basis of existing information of digital, intelligent, and visual technologies.

The application of CPS-based intelligent construction technologies will assist participating enterprises in scientific management, provide a strong guarantee for cost reduction and engineering project efficiency, improve the quality of engineering projects, and ultimately promote the development and progress of the entire construction industry in the direction of intelligence, integration, and greening.

Disclosure statement

The authors declare no conflict of interest.

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