Intelligent Construction Factory for Transportation Infrastructure in Construction 4.0

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Abstract. Currently, the integration of the construction industry and Industry 4.0 is facing a series of opportunities and challenges. This paper explores the concept, characteristics, and structure of intelligent construction factories within the context of Construction 4.0, with a focus on transportation infrastructure. And examines the functional zoning, organizational structure, and intelligent modules that define these factories, highlighting their role in optimizing production and reducing environmental impact. The study concludes by discussing the future trends of intelligent construction factories, emphasizing their potential for further automation, data-driven decision-making, and global collaboration. Intelligent construction factories are key drivers of innovation and efficiency in modern transportation infrastructure development. This study can help to further promote the efficient development of transportation infrastructure industrialization and orderly promote the construction industry towards Construction 4.0.

Keywords: transportation infrastructure; connotation and characteristics; industrialization; intelligent construction factory; intelligent module; Construction 4.0

1 Introduction

The construction industry relies heavily on labor. Based on the modular production approach used in the manufacturing industry, prefabrication has been introduced in the construction industry to mitigate the drawbacks of traditional cast-in-situ construction methods. The efficiency could be increased and urban built environment could be improved due to the automation in production and assembly[1, 2]. Prefabrication refers to a production process carried out in dedicated factories. [1]. In terms of transportation infrastructure, prefabrication factories mainly engaged in the prefabrication and processing of concrete and steel elements. To finalize the entire construction project, prefabricated elements are delivered to the construction site, where they are assembled, connected, and partially integrated with on-site cast-in-place construction. Compared with conventional construction methods, prefabrication-based construction has several advantages, such as short construction time, superior quality, safer construction, environmental friendliness and reduced cost[3]. As a result of these benefits, prefabrication

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has seen widespread adoption in construction across various countries and regions, including China[4], Singapore[5], Europe, and America[6].

The Industry 4.0 initiative promotes intelligent manufacturing as a driving force behind global economic growth[7]. A key focus in this initiative is the development of smart factories, seen as essential for realizing Industry 4.0 in the manufacturing sector. Advanced countries are actively developing smart factories to address challenges such as short product lifecycles, workforce shortages, environmental regulations, fragmented manufacturing processes, and increasing customer demands.[8]. For example, Li et al. paid attention to the middle and low voltage switchgear assembly industry, proposed a smart factory system architecture model for reference[9]. Mabkhot et al. proposed a framework for analyzing current research and exploring the elements and features of smart factory systems[10]. Wan et al. presented the architecture of an AI-driven smart factory designed to support new production modes involving multiple varieties and small batches[11]. Yi et al. examined the components of major smart factory architectures and developed a security model and response strategies to address cybersecurity issues[12]. Zhou et al. proposed a fog computing framework to schedule and allocate tasks in smart factory[13].

Originally designed for manufacturing, Industry 4.0 has since been adapted to other fields, including construction. Various construction-specific concepts have emerged in different countries[14]. For example, Li [15] first introduced Construction 4.0, while terms such as ‘Smart Construction’ have also emerged as broader terms encompassing Construction 4.0[16]. Currently, there is no universally accepted definition of Construction 4.0. Rastogi [17] noted that the primary objective of Construction 4.0 is to establish a digital construction site that tracks project progress throughout its lifecycle using various technologies. The European Industry Construction Federation (FIEC) described Construction 4.0 as the construction industry's equivalent of Industry 4.0, focusing on the digital transformation of the construction sector[18]. Although definitions vary, there is consensus that adopting Construction 4.0 will not only transform the construction process but also reorganize and integrate the traditionally fragmented construction industry[19].

As factory prefabrication is one of the most important steps in industrial construction of structures, smart factories are the foundation of Construction 4.0 and a critical step towards digital and intelligent construction. From another perspective, the production operations of prefab elements in factories are similar to those of a manufacturing industry[20]. In addition, the high level of standardization in prefabricated elements facilitates the use of digital technologies and information management throughout the design, production, transportation, and assembly stages. Therefore, the Industry 4.0 method could be introduced in prefabrication factories. Overall, the research on smart factories in the construction industry is imperative, which will bring about more predictable planning, improved process reliability, and easier cost control.

Some studies have been made on prefabrication factories of Construction 4.0 and have achieved some research results. Some scholars focus on the mobility of factories, for instance, Martínez et al. presented the concept, and conducted the layout design and the application evaluation performed of a flexible field factory for construction industry, verifying the economic feasibility of flexible on-site factories[21]. Stuart et al.

presented the concept of a compact, affordable, and movable micro-factory that can be relocated to temporary sites or construction areas for the production of prefabricated panels[22]. The above research results are primarily applied in building construction, and the corresponding element sizes are also small, which is not suitable for the manufacture of larger-sized elements in transportation infrastructure.

Some scholars have also conducted research on the application of relevant intelligent technologies in precast plants based on the needs of Construction 4.0. For example, Kasperzyk et al. introduced a robotic prefabrication system that utilizes a novel approach known as "re-fabrication", focused on the disassembly/assembly of precast element models during structural design in precast plants[23]. Zöller et al. created a method for parametric 3D modeling and path planning for robotics, aimed at achieving digitalization and Industry 4.0 in the design and production of precast reinforced concrete elements[24]. Zhang proposed a genetic algorithm based optimization model for prefabricated production, providing a better decision-making method for prefabricated element manufacturing[25]. Kosse et al. proposed a framework for implementing a digital twin in the mass production of precast concrete elements, utilizing the asset administration shell (AAS) concept within the Industry 4.0 framework[26]. They also examined how the combination of Building Information Modeling with methods from the context of Industry 4.0[27], and introduced a DS framework to optimize precast element production[28]. Overall, relevant research mainly focuses on a certain technology or a certain module of intelligent construction factories, often verifying the role of Construction 4.0 in enhancing production efficiency and quality of prefabricated elements. However, none of these studies address the complete definition and architecture of intelligent construction factories for transportation infrastructure in Construction 4.0. Some scholars have also indicated that upcoming studies will focus on expanding the Industry 4.0 concept to encompass the entire manufacturing facility, aiming to develop a digital factory specifically for precast concrete production[26]. This aligns closely with the research focus of this article.

Therefore, this article is based on the relevant requirements of Construction 4.0, combined with the development needs of transportation infrastructure, conducting a comprehensive study on the definition and architecture of intelligent construction factories, provide a systematic summary of the architecture of an intelligent construction factory. The rest of this paper is organized as follows. Section 2 provides an overview of the connotation and characteristics of industrial intelligent construction factories. In Section 3, the architecture of industrial intelligent construction factories is summarized. Finally, Section 4 concludes this research.

2 Connotation and Characteristics of Industrial Intelligent Construction Factory

2.1 Connotation of Intelligent Construction Factory

Currently, there are some application cases of Construction 4.0, but they mainly focus on the application of BIM technology. For example, a building in Pakistan successfully conducted energy analysis and optimization using BIM technologies such as Autodesk Revit and Autodesk Insight based on the concept of Construction 4.0[29], verifying BIM's capabilities in sustainability, adaptability, higher productivity, cost efficiency, and mastering the complexities of technology-driven construction. Regarding the integrated application of Construction 4.0 technologies, most case studies are still at the stage of questionnaire surveys [30] or interviews with relevant construction industry practitioners[31, 32].Based on these typical cases, this paper further explores the concept and characteristics of intelligent construction factories under Construction 4.0.

The aim of traditional prefabrication factories is only to achieve design intent, with service objects corresponding to design and construction. To further enhance the intensive utilization of resources, improve construction quality and efficiency, the industrial intelligent construction model has emerged. Based on the new construction mode, the concept of Construction 4.0 is introduced, resulting in the birth of the concept of intelligent construction factories. The origin of intelligent construction factories is presented in Fig 1.

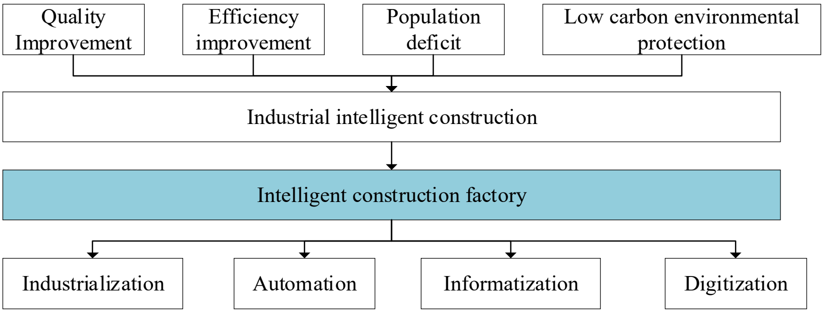

Fig. 1. The origin of intelligent construction factories

The concept of an intelligent construction factory in Construction 4.0 represents a highly advanced and digitized production facility designed to manufacture elements for transportation infrastructure. This factory integrates advanced technologies like big data analytics, artificial intelligence (AI), Building Information Modeling (BIM), the Internet of Things (IoT), and cloud computing to improve the efficiency, precision, and sustainability of the construction process[33].

In essence, an intelligent construction factory is not just a place for production but a comprehensive digital ecosystem. It enables seamless data flow across all phases of construction, from design and production to logistics and installation. The factory operates with a high degree of automation, utilizing robotics, smart production lines, and advanced monitoring systems to minimize human intervention, reduce errors, and optimize resource utilization. This factory model supports mass customization, allowing for flexible production that can quickly adapt to varying project demands. It also emphasizes sustainability, leveraging intelligent resource management and waste reduction strategies to minimize the environmental impact. The connotation of intelligent construction factory is shown in Fig 2.

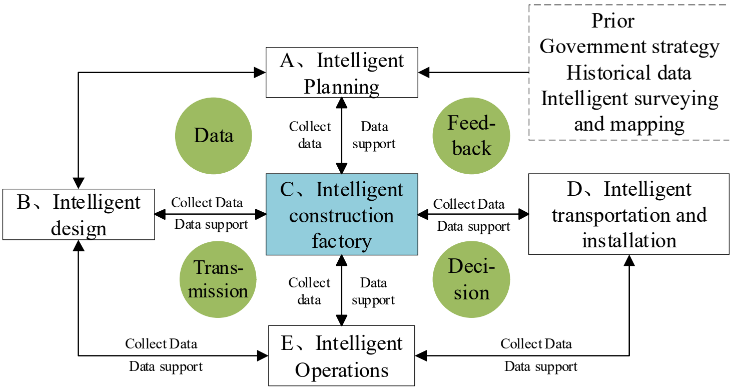

Fig. 2. Connotation of intelligent construction factory

2.2 Characteristics of Intelligent Construction Factory

According to the target positioning of the factory, it should have the following characteristics. The first characteristics is progressiveness of technology. According to a survey about off-site construction from China in 2020, More than 90% of respondents from construction companies believe that the lack of advanced technology is the main constraint on the development of off-site construction[34]. The application of advanced technologies in off-site construction can realize higher efficiency and quality assurance[35]. To realize the automation, informatization and digitalization while enhancing quality and efficiency, minimizing energy consumption, reducing labor input to the greatest extent, advanced technology, materials, processes and equipment should be used in intelligent construction factories as far as possible.

Secondly, the mobility of intelligent construction factories should be considered. Factory-based prefabrication demands a significant upfront investment and a skilled local workforce[22]. Mobile factories differ from traditional ones, which involve large investments and fixed locations, as they are designed to align with Lean principles, leveraging industrialized practices without incurring the high fixed costs of stationary factories[21]. Therefore, construction of the factory should adhere to modularization and dismantling, so that the factory can be reconstructed in different locations as needed.

Thirdly, the functions of intelligent construction factories should be expandable. It is widely acknowledged within the industry that "the main drawback of prefabrication is its lack of flexibility in adapting to design changes"[36]. To address this limitation, current construction practices focus on enhancing flexibility through mass customization[37]. Thus, the characteristics of intelligent construction factories should comply with the development direction of prefabricated technology, the products produced by the factory should be able to be quickly adjusted according to market needs.

Finally, the individuality should be one of the characteristics of intelligent construction factories. Further research should be conducted on design flexibility while meeting standardization requirements. The products produced by the factory should not only meet the corresponding standard requirements, but also meet certain personalized needs (region, culture, customization), so that industrialization and differentiation coexist.

3 Architecture of Industrial Intelligent Construction Factory

3.1 Functional Zoning

The design of the prefabrication factory should meet the requirements as follows. Firstly, the relative positions of the material preparation area, precast area, maintenance area, and storage area should be arranged reasonably and the production capacity should be matched. Secondly, the layout of each area should meet the requirements for the connection between the front and rear construction processes, facilitating the timely transportation and storage of prefabricated products. Finally, the various areas within the prefabrication factory should be reasonably arranged while ensuring simultaneous and non-conflicting operations[38]. Based on the design requirements of prefabricated factories [39], and according to the people-oriented requirements and the function of the intelligent construction factory, its zoning is summarized in Fig 3. This zoning layout enables seamless coordination between different functions, reducing delays and improving overall productivity.

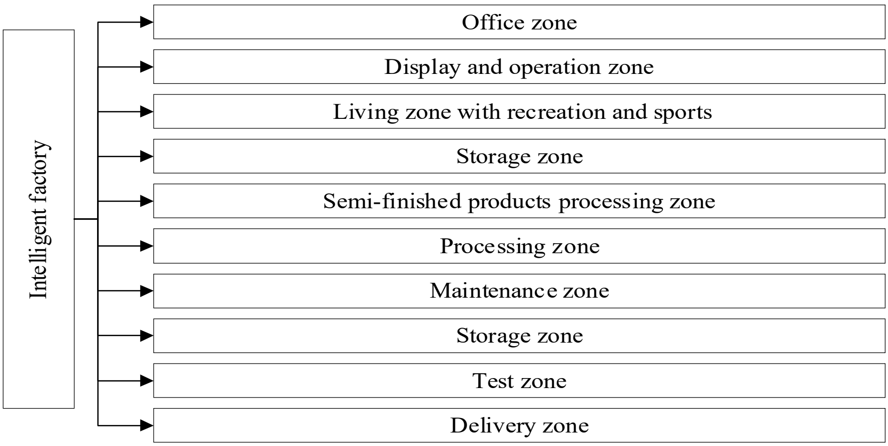

Fig. 3. Intelligent construction factory zoning

3.2 Organizational Structure

The organizational structure of smart factories in Industry 4.0 is one of major ongoing research projects in recent years. For instance, Wang et al. summarized the smart factory framework composed of four distinct layers: the physical resource layer, industrial network layer, cloud layer, and supervisory control terminal layer[40]. This scholar has continued to use this framework in future research and conducted further research on smart factories based on cloud computing[41, 42]. Wan et al. proposed a data-driven reconfigurable production mode of Smart Factory for pharmaceutical manufacturing, outlining an architecture composed of three main layers: perception layer, deployment layer, and executing layer[43]. However, the above studies are related to smart factories in the manufacturing industry, and there is currently no comprehensive research summarizing the organizational structure of intelligent construction factories in the construction industry. Therefore, considering the characteristics of prefabricated factories, the organizational structure of intelligent construction factories is defined in Fig 4 which includes perception layer, transmission layer, control layer, application layer, and terminal layer.

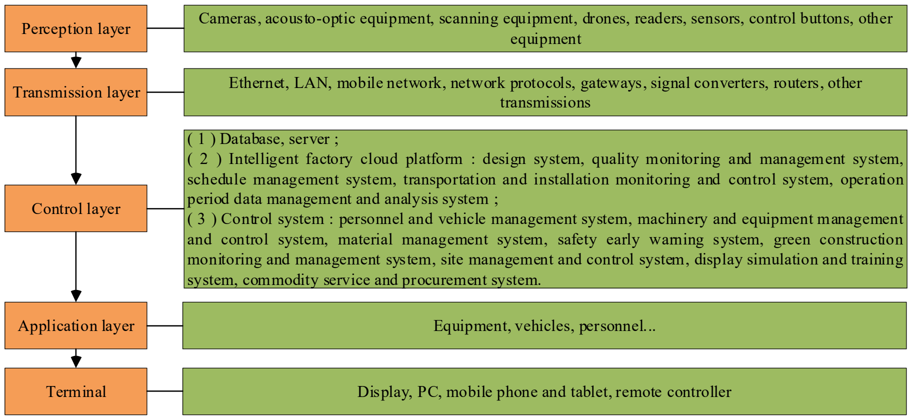

Fig. 4. Organizational structure of an intelligent construction factory

3.3 Intelligent Modules

The coverage of intelligent technologies related to Construction 4.0 is very wide. This paper systematically sorts out and visualizes the intelligent technologies related to Construction 4.0 through cluster analysis. First, a total of 1206 Construction 4.0-related articles in the past 10 years were extracted from the Web of Science database and imported into Cite Space for keyword co-occurrence analysis. Based on the generated knowledge graph, as shown in Fig 5, the summary of intelligent technologies related to Construction 4.0 is shown in Fig 6.

Existing research has widely applied technologies such as IoT, big data, and cloud computing, demonstrating the significant potential of smart technologies in improving production quality and efficiency across different modules. For example, Zhao et al. proposed an innovative approach for the automated collection, analysis, and display of real-time data related to prefabricated elements[44], which combines Long Range (LoRa), Radio Frequency Identification (RFID), BIM, sensor networks, etc. Internet of Things (IoTs) enhances the traceability and transparency of industrial processes and facilitates [45, 46], which strongly supports the monitoring and data collection and analysis modules of intelligent construction factories. Kong et al. based on the IoTs technology, proposed the system design of intelligent building and the architecture model of intelligent manufacturing[47], providing a theoretical foundation for the collaborative control and decision-making module of intelligent construction factories. Ahn et al. focused on real-time positioning at construction sites, proposed a method for filtering and abstracting spatial and temporal data to estimate transportation costs using GPS information[48], which can be applied to the information transmission and sharing module to optimize resource allocation and logistics efficiency. Bae et al. proposed an off-site quality inspection method based on a projector-camera system for reconstructing 3D point clouds[49], providing technical support for the quality inspection module of intelligent construction factories.

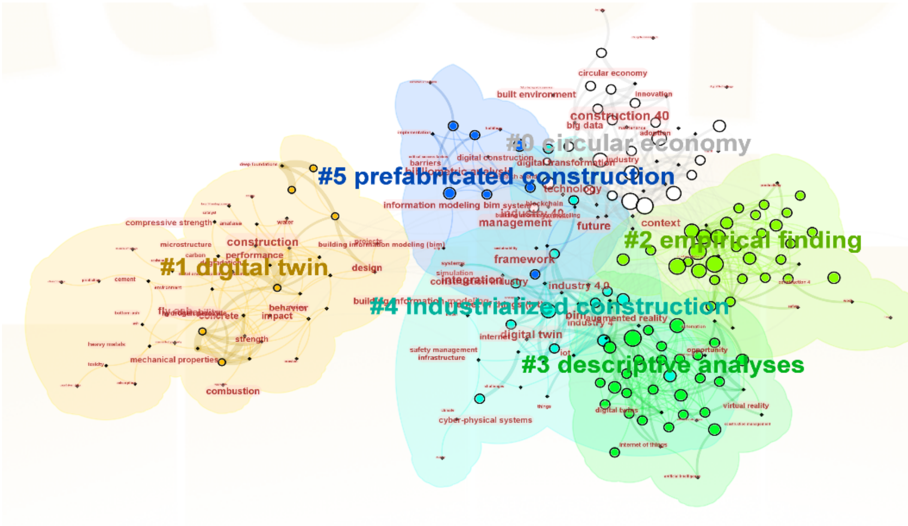

Fig. 5. Cluster analysis results of articles related to Construction 4.0

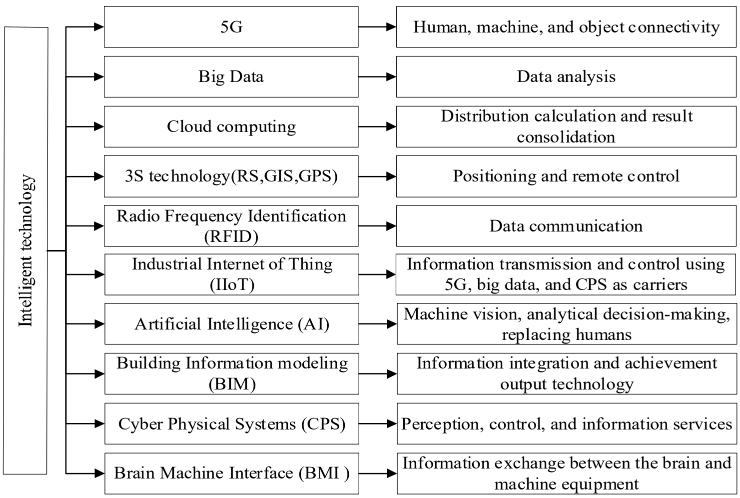

Fig. 6. Intelligent technology

Analyzing these studies shows that each intelligent module has already been explored and applied in different research. Based on these researches, this paper divides the intelligent modules of an intelligent construction factory into five key parts: monitoring, quality inspection, data collection and analysis, information transmission and sharing, collaborative control and decision-making.

3.2.1. Monitoring.

In terms of staff: identity recognition, entry and exit information, location monitoring, security monitoring, and epidemic prevention monitoring.

In terms of vehicles: identification of vehicle and license plate information, entry and exit information, vehicle load monitoring, position monitoring, and cleanliness monitoring.

In terms of site: video monitoring of entrances and exits, site perimeter, abnormal behavior monitoring, and panoramic perception of the venue.

Green construction: dust monitoring, noise monitoring, meteorological monitoring, water quality monitoring, harmful gas monitoring, pollution discharge monitoring, and electricity consumption monitoring.

3.2.2. Quality Inspection.

Materials and equipment: manufacturer, place of origin, indicators, factory inspection, incoming inspection, and coding information.

Semi-finished products: design information, material information, processing personnel information, coding information, etc.

Finished products: design, materials, appearance inspection, testing, installation information and coding information, etc. Mainly for goods that can be directly supplied or products with targeted processing.

3.2.3. Data Collection and Analysis.

Basic information collection and coding: personnel and ID information, construction qualification information, site and usage information, geographic location information, equipment information, vehicle information, product design information, coding information.

Real time information collection during the implementation process: personnel access information, vehicle access and load information, material consumption and inventory information, equipment usage and working status information, site usage and occupation information, material inspection information, inspection information (including labor and equipment), environmental meteorological information, product quality inspection information, monitoring information and warning information.

Critical information input: personnel, machinery, materials, processes, environment, safety, etc.

Data analysis: Comparing basic information, instant information, and critical information, forming comparisons in terms of input, output, progress, quality, etc.

3.2.4. Information Transmission and Sharing.

It mainly involves the transmission, comparison, and real-time feedback among design information, production information, transportation and installation information, completion information, and daily operation information.

3.2.5. Collaborative Control and Decision-Making.

Collaborative control: mainly involves the instrument device end, the main control module end, the network PC end, and the personal mobile phone end, which can always send relevant instructions to the instrument device for control. The example of collaborative control is shown in Fig 7. By utilizing technologies such as Unity 3D, AR/VR, BIM, GIS, and oblique photogrammetry modeling, the site, equipment, and personnel can be modeled for operational and process simulations. It can also serve as a training platform for visitors or participants to gain an understanding of the entire site and operating methods.

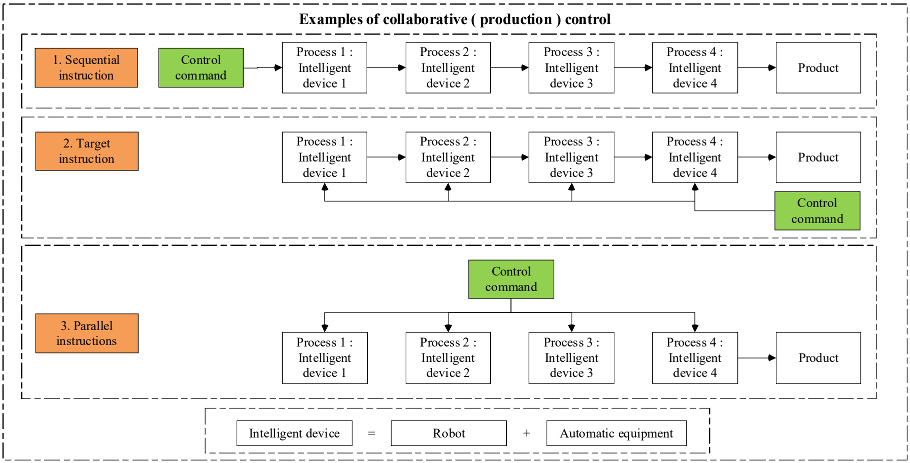

Fig. 7. Collaborative production example

4 Conclusions

This study provides a comprehensive overview of intelligent construction factories, focusing on their concepts, characteristics, and structures. By systematically defining the elements of an intelligent construction factory, including functional zoning, organizational structure, and intelligent modules, this research contributes to a deeper understanding of how intelligent technologies can be integrated into the construction industry. The intelligent construction factory, under the framework of Construction 4.0, plays a pivotal role in revolutionizing the transportation infrastructure sector. By integrating advanced technologies such as BIM, IoT, AI, and robotics, these factories enhance productivity, ensure high-quality output, and promote sustainable practices. The seamless connection between digital design, automated production, and intelligent logistics enables a more efficient and precise construction process, ultimately reducing costs and environmental impact. The practical impact of this study on the construction industry is significant, providing valuable references for the future design of intelligent construction factories.

Looking forward, the future development of intelligent construction factories will likely involve further advancements in automation, data-driven decision-making, and the integration of more sophisticated AI algorithms. Further research is also needed on how to address challenges in the implementation of intelligent construction factories, such as high initial costs and the complexity of technology integration, and explore how to promote the widespread application of intelligent technologies in the construction industry. In summary, intelligent construction factories represent the future of the construction industry, particularly in the field of transportation infrastructure, offering a path towards smarter, more efficient, and sustainable construction practices.

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