buildings

MDPI

Article

Digital Twin Model and Its Establishment Method for Steel Structure Construction Processes

Zhansheng Liu [1,2,*] and Sen Lin [1,2]

1 Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing 100124, China
2 Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China
* Correspondence: liuzhansheng@bjut.edu.cn

Abstract: At present, the informatization level in the construction process of steel structures is relatively low. Meanwhile, digital twin technology, with better interactive features, provides a new development direction for the intelligent construction of steel structures. Therefore, this paper introduces the concept of a digital twin into the steel structure construction process, analyzes the connotation and characteristics of the digital twin model, and proposes the digital twin model architecture for steel structure construction processes. Furthermore, a method for establishing a digital twin model for steel structure construction processes is presented, which includes three stages: the acquisition and transmission of physical space data, the construction of a digital twin virtual model, and information exchange in the digital twin model. Based on these concepts, this paper describes a digital twin system architecture for the steel structure construction process from the perspective of data flow in the digital twin model. Finally, with the application of information technology in the steel structure construction process of the university park library project in Xiongan New Area and the reconstruction and expansion project of the Nanchong Gaoping airport, the digital twin model and its establishment method methods are analyzed practically and demonstrated effectively in this study.

Keywords: digital twin; steel structure; construction process; intelligent construction

Citation: Liu, Z.; Lin, S. Digital Twin Model and Its Establishment Method for Steel Structure Construction Processes. *Buildings* **2024**, *14*, 1043. https://doi.org/10.3390/buildings14041043

Academic Editors: Francisco López-Almansa and Nerio Tullini

Received: 31 January 2024
Revised: 26 March 2024
Accepted: 3 April 2024
Published: 8 April 2024

1. Introduction

1.1. Background

The rapid development of information technology has had a profound impact on society and has greatly improved the informatization level of all industries. However, compared to other industries, the construction industry has one of the lowest levels of informatization [1,2]. In recent years, many countries have attached great importance to the application of information technology in the construction industry and have issued relevant policies for its promotion [3]. Under the current circumstances, in order to better improve the informatization and intelligence level of the construction process and meet the needs of modern society, intelligent construction has become a new trend in the development of the construction industry [4,5]. Digital twin technology provides a new method for the realization of intelligent construction [6].

Driven by social development and industrial demand, steel structure buildings progressively highlight the advantages of a high degree of industrialization, low-carbon environmental protection, and recyclable utilization, have become a pivotal building form for adapting to the industrialization and green development of buildings, which have developed speedily and are getting increasingly extensively used in various large public buildings. Therefore, it is imperative to integrate digital twins and information technology into the construction process of steel structures, leverage the advantages of new technologies, and change the traditional construction mode. This article focuses on the construction process of steel structures, proposes a digital twin model for the construction process of steel structures, and analyzes its establishment method, targeting the construction practice cases of large public buildings in China.

1.2. Literature Review

Many theoretical methods for the application of information technology in the construction process and the implementation of intelligent construction have been researched around the world. Fan et al. [7] proposed a definition of intelligent construction, discussed its main characteristics, and studied the characteristic representation method and reward mechanism of the closed-loop control state of intelligent construction. Mao et al. [8] proposed a theoretical framework and studied the kernel logic of data-driven models for intelligent construction. Based on the internet configuration and physical information systems, Niu et al. [9] proposed a theoretical framework for intelligent construction using means such as technical analysis and case studies. In recent years, many information technologies have been applied in the construction process of buildings, including BIM, the Internet of Things [10], artificial intelligence technology [11], and so on. BIM technology, as a key foundational technology for the development of architecture in the intelligent construction industry, has been deeply researched in the field of architectural applications. It is also widely used in many environments, such as visual display, collision detection [12], construction simulation [13], engineering quantity calculation [14], and normalization examination [15], among others. Yang et al. [16] proposed a BIM model for the entire informatization process of steel structure dismantling and used the moving wedge matrix method to formulate and optimize dismantling plans. For the assembly process during the steel structure construction stage, Wang et al. [17] proposed a steel structure virtual assembly framework based on BIM technology, established a virtual assembly program prototype of the steel structure, and achieved the two basic functions of geometric detection and assembly detection. The Internet of Things is considered the evolution of the internet. Multiple devices are associated with each other in real time through unique identifiers (UIDs) to better facilitate the interaction of data among them [18]. In building construction, the Internet of Things can realize the collection and transmission of massive data, such as the equipment and environment in the construction process, and achieve real-time control of the construction site. Artificial intelligence technology is an important aspect of the "intelligence" in intelligent construction. Based on intelligent algorithms, artificial intelligence technology analyzes the massive data generated in the construction process, then carries out intelligent analysis, prediction, and other functions of the construction process [19]. With the rapid development of various information technologies, the integration and application of information technology has become a new trend. At present, a variety of information technologies are applied in the field of engineering construction, such as BIM + 3D laser scanning [20], BIM + VR [21], BIM + GIS [22], AI + IoT [23], and so on.

With the proposal of the development of intelligent construction strategies in various countries, the proposal of intelligent construction theory, and the integrated application of BIM, the Internet of Things, and other information technologies in building construction, the integration of digital twin technology and the building construction process has been remarkably promoted [5]. Digital twin technology, with its high-fidelity simulation of the real world and realization of intelligent closed-loop control through virtual–real interactions, has received extensive attention and gradually become a research hotspot [24]. The concept of digital twin technology was first proposed by Professor Michael Grieves in 2002 [25], and it was initially applied in the aerospace field [26]. Subsequently, due to the high-fidelity dynamic simulation characteristics, the research and application of digital twin technology have gradually expanded to many industries, such as machinery, manufacturing [27], medical [28], agriculture [29], power generation [30], ecological environment [31], and so on. Tao et al. [32,33] proposed a five-dimensional digital twin structure model, studied the interaction theory and key technologies of digital twin models, and provided a new framework for the application of digital twin technology in other industries. Digital twin technology is a digital mapping of physical entities, providing a transformation of the foundation of traditional construction modes in the construction industry [34]. Liu et al. [35] introduced digital twin technology into the construction industry, established an application framework of digital twin technology in the field of intelligent construction, and applied digital twin technology for the intelligent monitoring of the stress state during the tensioning process of pre-stressed steel structures. Pan et al. [36] took project management in the process of intelligent construction as a research object and proposed a closed-loop digital twin framework integrating BIM, IoT, and data mining. Wang et al. [37] constructed a digital twin system architecture for pre-fabricated building products and elaborated on its related supporting technologies and implementation methods. Regarding building operation and maintenance, Zhao et al. [38] proposed the theory of an intelligent building operation and maintenance system construction combining digital twin technology with machine learning, explained the fusion mechanism for the digital twin technology and machine learning, and proposed a construction method for a building operation and maintenance system based on digital twin technology. Based on the concept of digital twins, Torzoni et al. [39] proposed a prediction method for the health monitoring and maintenance of civil engineering structures.

1.3. Research Gaps and Organizational Structures

As mentioned above, various information technologies have been widely used in construction processes, but most of them are single-point applications. Digital twin technology provides a new framework for the integration and application of various information technologies in the process of building construction and the realization of intelligent construction. At present, the study and application of digital twins is mainly focused on manufacturing, machinery, and other fields [40]. In the field of architecture, scholars in the field of civil engineering have carried out corresponding research and explorations and have proposed digital twin application frameworks for pre-fabricated buildings, building operation and maintenance, and so on. However, for the construction process of steel structures, establishing a digital twin model is still in the exploration stage. Digital twin models can combine and express the information of various elements of the steel structure construction process in a virtual space. Furthermore, according to the actual needs of the steel structure construction process, the construction process of the steel structure can be analyzed and simulated in the virtual space, providing a reference for the real steel structure construction process.

Intelligent construction is a new development direction for steel structure construction processes, and the integration and application of various information technologies provide a basis for the development of intelligent construction. Thus, this paper introduces the concept of digital twin models in the construction process of steel structures. First, the connotation and characteristics of the digital twin model for steel structure construction processes are analyzed in Section 2. Then, in Section 3, a digital twin model architecture for the steel structure construction process is proposed. Based on this, in Section 4, through the integration of perception technology, the Internet of Things, and other technologies, an establishment method for a digital twin model of the steel structure construction process is proposed. Finally, the applications of information technology in the construction of steel structures for the university park library project in the Xiongan New Area and the reconstruction and expansion project of the Nanchong Gaoping airport are used as examples, in order to analyze the digital twin model of the steel structure construction process.

2. Connotation and Characteristics of a Digital Twin Model for Steel Structure Construction

The connotation of the digital twin model for steel structure construction processes is to integrate the digital twin and various building information technologies. Based on the elements used in an actual steel structure construction scenario, various information perception and transmission technologies are used to collect information about each element during the construction process, form the digital twin data, and establish a virtual digital model for each construction element and its related activities. Furthermore, under certain rule constraints, digital twin data is processed according to the real construction process in the virtual space. Finally, through the information platform, guidance, management, and control of the construction process of steel structures can be achieved in the real space. The digital twin model of the steel structure construction process integrates information technologies such as digital twin, intelligent algorithm, Internet of Things, and so on, and it conspicuously demonstrates multiple characteristics such as multiple dimensions, intelligence, high integration level, real-time performance, and interactivity.

(1) Multiple dimensions. Due to the complexity of the construction process of steel structures, which involve multiple elements and diverse demands, a digital twin model of steel structure construction is established in multiple dimensions. According to its spatial dimensions, the digital twin model of steel structure construction can be divided into the component level, unit level, and structural level. According to its application function dimension, it can also be divided into the cost dimension, schedule dimension, quality dimension, and so on.
(2) Intelligence. The digital twin model of the steel structure construction process integrates multiple information technologies and intelligent algorithms. Intelligence is the specific embodiment and an inherent requirement of the value of digital twin models. Intelligence refers to the intelligence of the physical entities of the mechanical equipment used during the construction process, such as the intelligent welding of steel components. Additionally, digital twin models have the general capabilities of self-perception, learning, analysis, and mutual control.
(3) High integration level. A construction digital twin model is a model that integrates various types of information, such as personnel information, mechanical information, steel component information, environmental information, and so on. This information comprises a large amount of data and a variety of data types. The digital twin model cannot meet various functional requirements for the construction process without transforming and integrating these various types and large amounts of data such that they can be better utilized.
(4) Real-time performance. The construction period of steel structures is short, and the information changes quickly. The digital twin virtual model is a mapping of the physical entities and, so, the information in the digital twin virtual space also changes rapidly in real time. The steel structure digital twin model obtains relevant information based on the actual construction needs, processes the information according to the corresponding mechanisms, and provides timely data analysis results for the construction process.
(5) Interactivity. Digital twin technology consists of a physical space, a virtual space, and information exchange between these two spaces. The essence of digital twin technology is to depict a physical space through a virtual space. Based on continuously generated real-time twin data, digital twin models construct and present physical entities in the real world through the use of information technology platforms, such as BIM and virtual reality, allowing information exchange between the physical space and virtual space to be achieved.

3. Digital Twin Model for Steel Structure Construction Processes

Based on the concept of digital twin technology and the characteristics of steel structure construction, the establishment of a digital twin model for steel structure construction processes must follow certain principles. First, a digital twin model should be established to meet the needs of the steel structure construction project. Before establishing a digital twin model, it is necessary to fully analyze the construction needs and establish digital twin models with different levels and functions according to different needs, in order to describe the characteristics of the different levels and dimensions in the steel structure construction process. Second, while meeting real construction needs, digital twin models should be as simple as possible to avoid unnecessary resource consumption.

Based on the characteristics and application requirements of the digital twin model in the construction process, and according to the concept of the five-dimensional digital twin model [32], digital twin technology is introduced into the construction process of steel structures. A digital twin model architecture for steel structure construction processes is proposed, which includes five parts: physical spatial entities, virtual twin models, data centers, functional applications, and information links, as shown in Equation (1). The architecture diagram is shown in Figure 1.

$$DT_{sc} = \{PE, VM, DC, FA, IL\} \tag{1}$$

where DT_{sc} is the digital twin model framework and physical spatial entity for the construction process of steel structures; PE is the physical spatial entity; VM is the virtual twin model; DC is the data center; FA is the functional application; and IL is the information link.

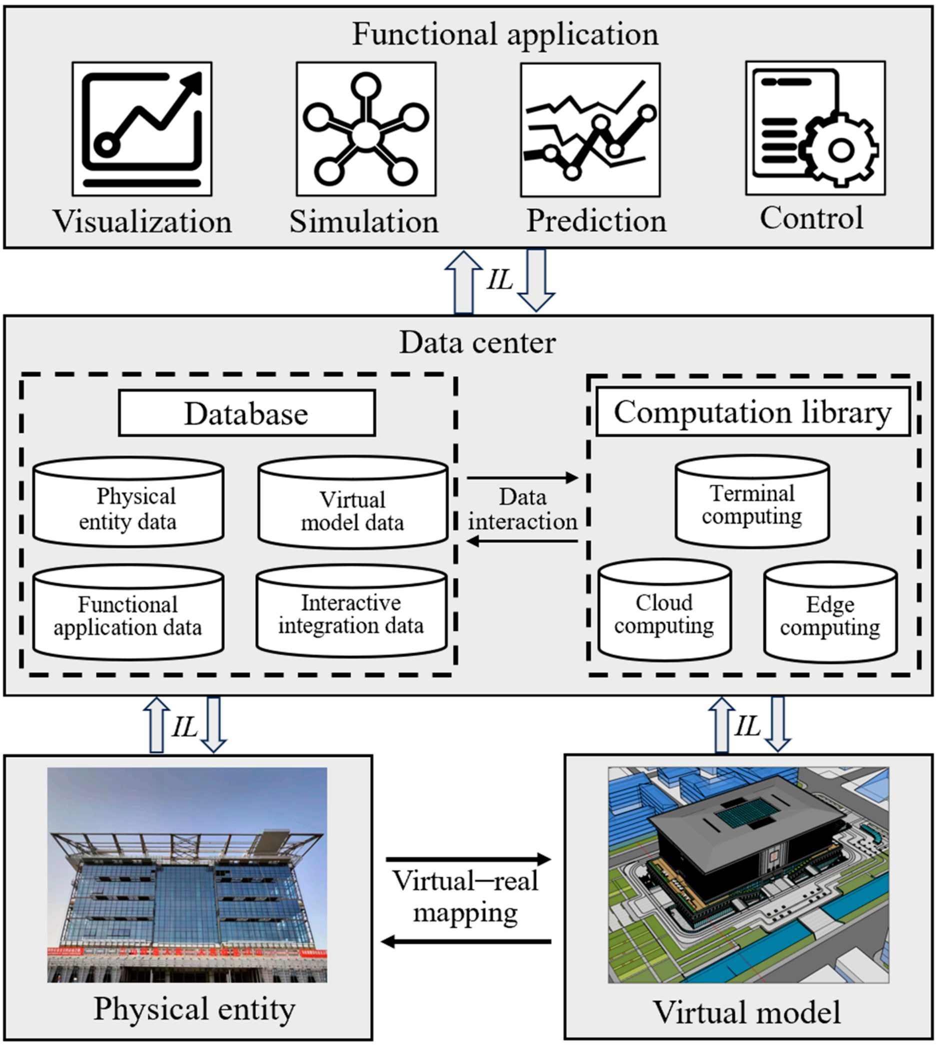

Figure 1. Digital twin model of the steel structure construction process.

Physical entities. The physical entities are the elements related to construction, such as personnel, machinery, components, environment, and so on. The physical entity is the cornerstone of the digital twin model and the object that the digital twin model serves.

Virtual model. The virtual model refers to the establishment of a digital model at the geometric, physical, behavioral, and rule levels, based on data from the construction process in a physical space. Through the interconnection and collaboration of various virtual models, a digital representation of the construction process of steel structures in a physical space can be achieved. With the accumulation of data, the accuracy of virtual models continues to improve and continuously approaches the real construction process in the physical space.

Data center. The data center consists of two parts: a database and a computation library. The function of the database is to provide storage for the operation data of the digital twin model. The computation library has a large number of algorithms and high computing power, providing support for the data processing of digital twin models. The data center controls the operation of the entire digital twin model through the storage and analysis of data. Due to the complexity of the construction process and the involvement of multiple elements, the data of the digital twin model are characterized by multiple data types and a large volume. The data of digital twin models can be divided into physical entity data, virtual model data, functional application data, and interactive integration data, according to their source [41], and can also be divided into static data and dynamic data from a temporal perspective.

Functional application. The functional application provides corresponding functions based on the specific construction needs. When a demand is initiated during the construction process, an in-depth analysis of the digital twin model in the construction process is carried out, relying on the data, computing power, and algorithm support of the data center. Functions such as the visual presentation, analysis, prediction, and control of the construction process are performed, and decisions are made that help the project personnel in the construction process.

Information link [31]. The information link refers to the interaction channel between the information and the resources of each module in the entire digital twin model [17]. The implementation of information links requires high-speed and stable communication networks (e.g., 5G, WiFi) to achieve the interconnection and exchange of information and resources among the various modules of the digital twin. The information link for the digital twin model of a steel structure construction process should also include a mapping method from the physical entities to the virtual entities, such as BIM models established through drawings and actual engineering situations.

4. Establishment Method for Digital Twin Model of the Steel Structure Construction Process

Based on the digital twin model architecture for steel structure construction processes, the establishment of a digital twin model includes three stages: the acquisition and transmission of physical space data, the construction of a digital twin virtual model, and information exchange in the digital twin model [42]. The acquisition and transmission of physical space data refers to the acquisition and transmission of relevant information about various elements of the construction process of steel structures in a physical space to a virtual space. Establishing virtual twin models involves creating digital models for the various construction elements of steel structures at the four levels of geometry, physics, behavior, and rules, and associating them with the physical space to form a multi-dimensional digital twin virtual model [43]. Based on digital twin theory, information exchange in the digital twin model allows for the combination of the various modules of the model, establishing closed-loop control of the digital twin model. The digital twin system provides technical support for the implementation of various processes in establishing the digital twin model, integrates specific functional modules, and provides a platform for project-related personnel to interact with the digital twin model. The establishment method for a digital twin model of a steel structure construction process is shown in Figure 2.

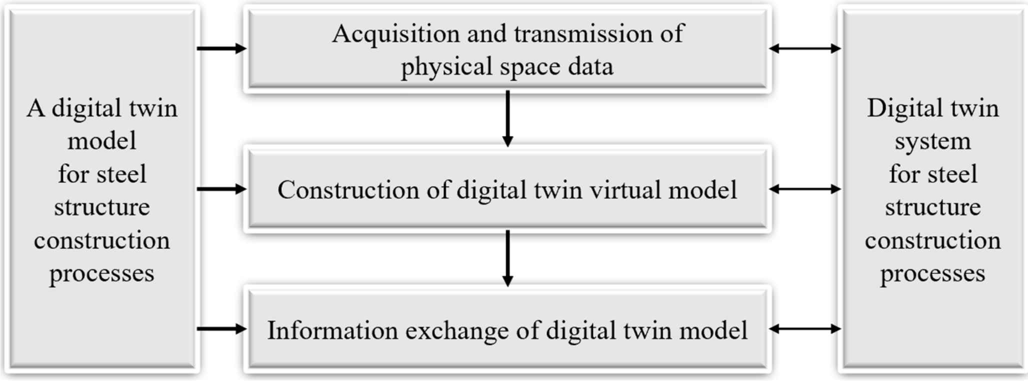

Figure 2. Operational flow of digital twin model.

4.1. Acquisition and Transmission of Physical Space Data

Data are the key to connecting the physical entity part with the digital twin virtual part. The acquisition of data for the various elements in the steel structure construction process is a primary issue in the application of digital twin technology. In the process of steel structure construction, the physical space data collection system is complex and dynamic, comprising the physical entity part and the data acquisition and transmission parts. Through comprehensively obtaining data on the various elements of the construction process, restoration of the physical space can be maximized in the virtual space. According to engineering practices [44], the physical space data of a steel structure construction process include the personnel, mechanical equipment, steel components, and environment (Equation (2)).

$$DT_{PS} = \{P_P, P_E, P_S, P_M\} \quad (2)$$

where DT_{PS} represents the set of physical space information, P_P represents the set of personnel information, P_E represents the set of mechanical equipment information, P_S represents the information set of the steel components, and P_M represents the set of environmental information.

The construction element information includes the number, size, shape, material, stress, and so on; the mechanical equipment information includes their function, location, status, and so on; the personnel information includes the personnel's numbers, positions, job types, and so on; and the environmental information includes the temperature, humidity, visibility, and so on.

Data acquisition modes include tag reading, sensor sensing, platform input, and other methods. For the acquisition of personnel information, their location information can be located in real time through smart helmets. Job types, numbers, and other personnel information can be entered into the digital twin system through platform input and matched with the other personnel information. Environmental information can be detected on the construction site through sensor devices and transmitted to the digital twin platform through the network. The information acquisition of the steel components is mainly achieved through reading RFID tags and information from sensors. During the construction process, the components will be used in different construction processes, such that the information on the components will change with the progress of the construction process. Regarding the change in information of the construction process components, the editable nature of their labels can be used to modify their information. Due to the complexity of the construction process, various types of construction machinery and equipment are required. To ensure that information is captured in real time during the construction process, an embedded information acquisition system is used to obtain real-time information on the current status of the machinery and equipment. According to a certain transmission protocol, the transmission of physical spatial information utilizes communication technology to transfer data from a data source to a database, mainly through network modules [6]. The processes for the acquisition and transmission of physical space data to the digital twin model during the steel structure construction process are depicted in Figure 3.

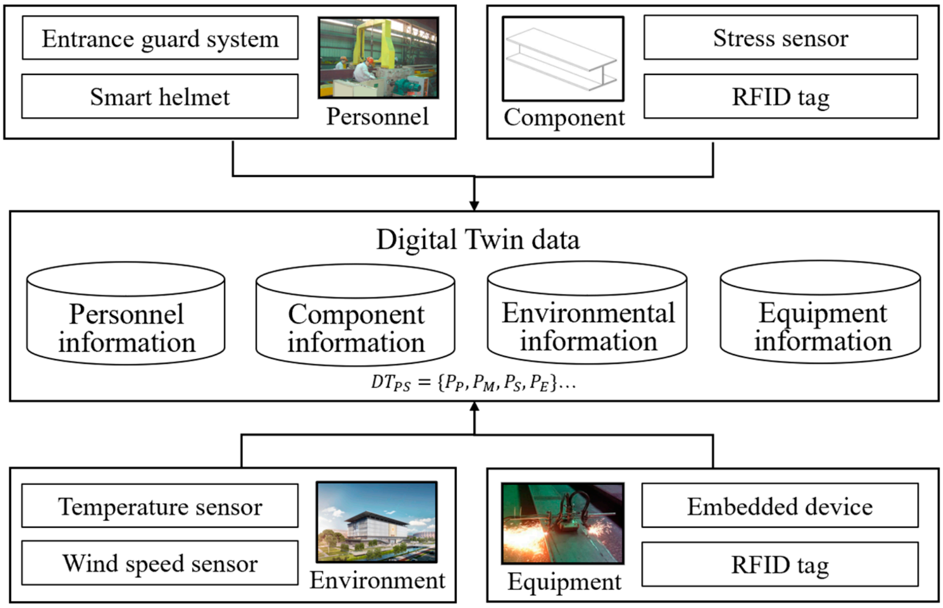

Figure 3. Acquisition and transmission of physical space data.

4.2. Construction of the Digital Twin Virtual Model

A digital twin virtual model is the concrete presentation of multi-source heterogeneous data in a virtual space. After the acquisition and transmission of the physical space data, it is necessary to analyze and process the acquired data to achieve high-fidelity simulation of the physical entities. According to the implementation logic of the digital twin virtual model, the virtual model carries out the establishment and association integration of the virtual model at the four levels of geometry, physics, behavior, and rules [41]. As a virtual digital mirror of the physical space, the digital twin virtual model reflects the real steel structure construction process of the physical space. After the acquisition and transmission of the physical space data, the data are processed, and a virtual model is established to realize the high-fidelity simulation of the physical space. Based on the implementation logic of the virtual model, the mathematical language expression of the virtual model is shown in Equation (3).

$$VM = \{V_G, V_P, V_B, V_R\} \tag{3}$$

where VM is the digital twin virtual model of the steel structure construction process, and V_G, V_P, V_B, V_R represent virtual models at the four levels of geometry, physics, behavior, and rules, respectively.

The geometry model is a virtual representation of the geometric attributes of a physical entity, such as its geometric size, shape, and position. In comparison, the physics model is a virtual expression of the information that reflects the physical properties of an entity collected by means of sensor perception and two-dimensional code reading. The rule model provides a constraint rule corresponding to the reality for the establishment and operation of the virtual model according to the current standards and construction schemes. The behavior model integrates geometric, physical, and rule models and makes a corresponding response to the actual situation of the construction process driven by the construction demand. The four models at different levels work together to construct a digital twin virtual model for steel structure construction processes. The construction of a digital twin virtual model is shown in Figure 4.

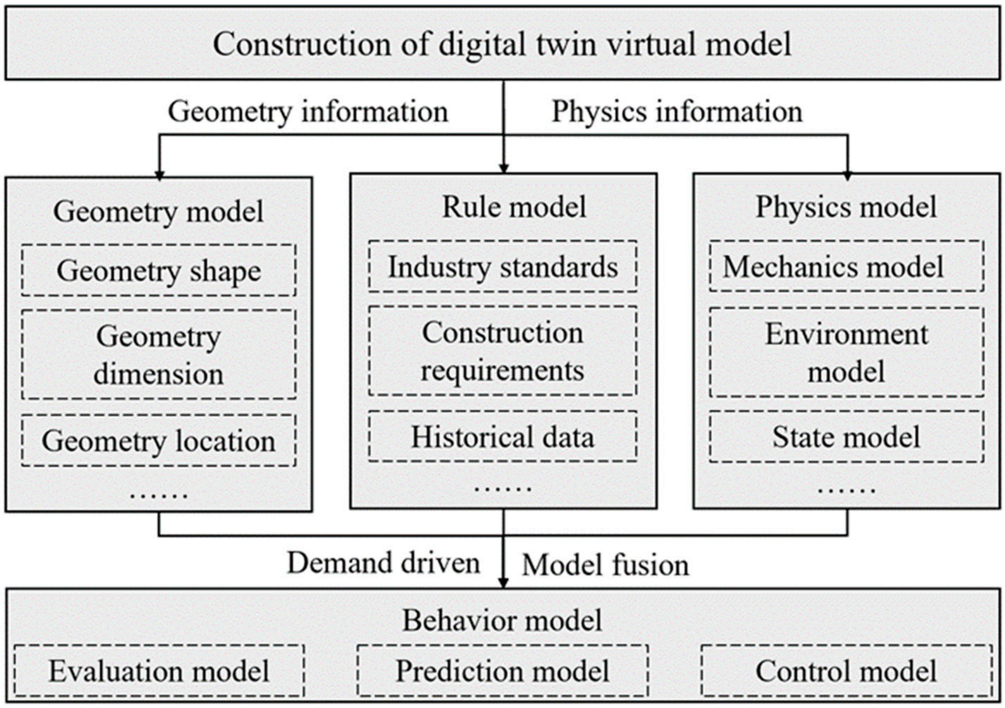

Figure 4. Construction of a digital twin virtual model.

4.3. Information Exchange of Digital Twin Model

The information exchange of the digital twin model in the steel structure construction process is achieved through data collection, transmission, analysis, and application [45]. According to the requirements of the construction process, the data from the physical space of the construction site are collected and transmitted to the virtual space through sensors and other methods, allowing for the operation of the digital twin model. Additionally, virtual spaces rely on the high computing power and algorithms of computing libraries to analyze and process data, and they provide corresponding functional support according to the actual construction needs of the physical space to support progress and decision making in steel structure construction processes.

Information exchange within the virtual space mainly occurs among the data center, virtual models, and functional modules. The data center provides data storage and algorithmic support for digital twin models, stores and processes multi-source heterogeneous data from the physical space, drives the modeling, updating, and simulation of virtual models, and supports the operation of the functional modules. The operation of its various modules is achieved through exchanging information within the digital twin model, thus forming closed-loop control of the digital twin, as shown in Figure 5. The various modules of the digital twin model are connected using Internet of Things technology, and based on a high-speed, stable, and low-latency data transmission protocol, a bidirectional data transmission channel is established between the physical space and the virtual space, completing the virtual–real interaction.

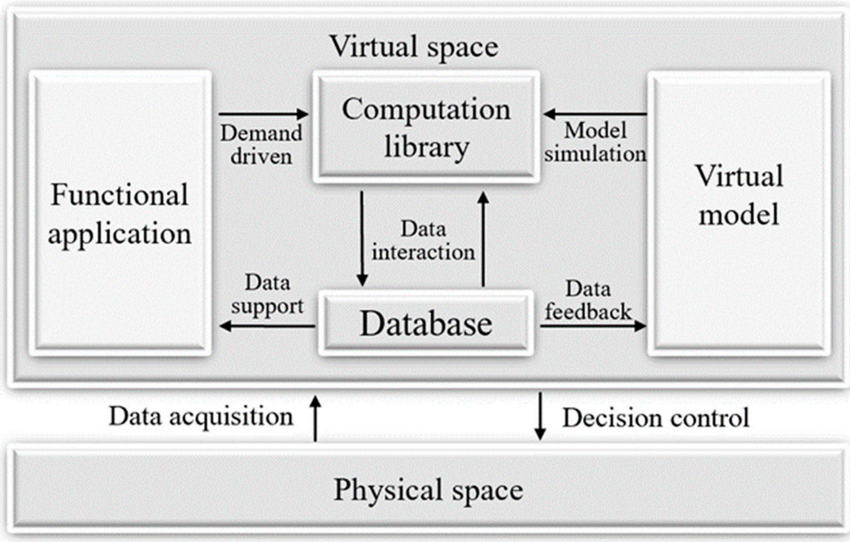

Figure 5. Information exchange of the digital twin model.

4.4. Operation of Digital Twin System in Steel Structure Construction Process

Operating the digital twin model in the steel structure construction process requires the collaboration of multiple information technologies. Using digital platform functions, such as data processing, parameter modeling, and intelligent analysis, digital twin models provide intelligent functional support for the construction process of steel structures, including visual presentation, construction simulation, intelligent welding, personnel management, environmental monitoring, and so on. In order to achieve the flow of information between various modules of the digital twin model in the steel structure construction process and to drive the operation of the digital twin model, support for the steel structure construction digital twin system is required, which includes a perception layer, transmission layer, data layer, terminal layer, and user layer, as shown in Figure 6.

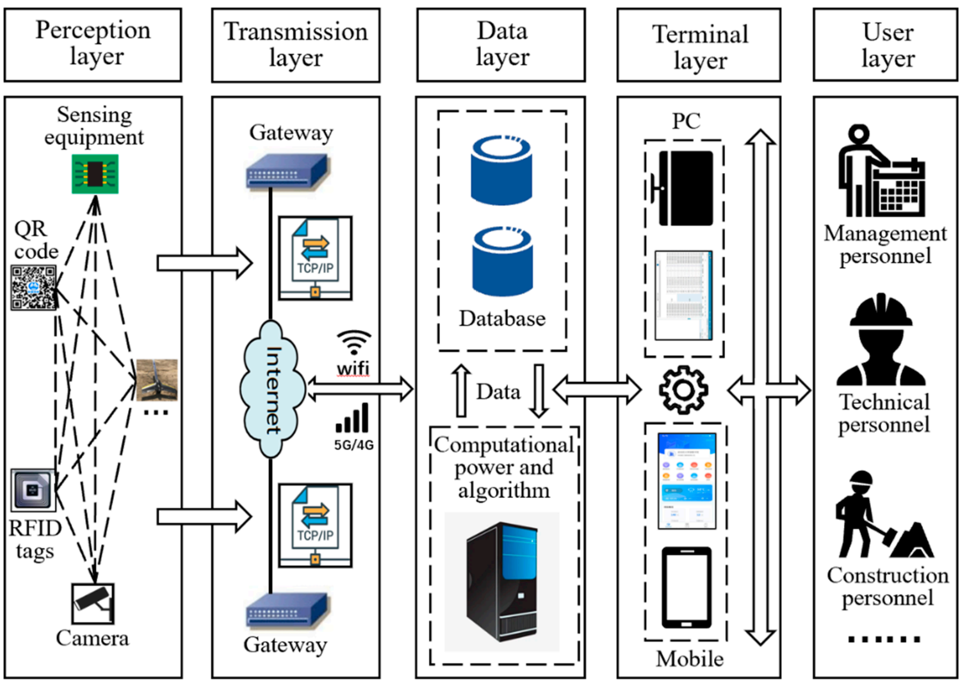

Figure 6. Digital twin system platform for the steel structure construction process.

Perception layer. The perception layer is the foundation for achieving information exchange between the physical and virtual spaces in digital twin models. As the construction process progresses, digital twin systems continuously generate multi-source heterogeneous data. Therefore, it is necessary to apply corresponding methods to perceive the data. Commonly used perception methods include QR code reading, sensor perception, and so on. For construction plans and other information, the corresponding data can be directly reflected in the data layer through platform input.

Transmission layer. The role of the transport layer is to transfer the data obtained by the perception layer to the database for management. The transport layer first processes the multi-source heterogeneous data obtained from sensors, videos, and so on, and relies on gateways to convert the data into a format that the server can receive. The data are then transmitted to the data layer through networks (e.g., wireless networks, mobile networks). Due to the characteristics of digital twin technology, the transmission network of the transport layer needs to have specific characteristics, such as fast speed and strong stability.

Data layer. The main function of the data layer is to store and analyze data, which is the key to ensuring the efficient operation of the digital twin model. Massive multi-source heterogeneous data from the physical entities and digital twin virtual models are transmitted to the data layer. The data layer improves the accuracy, completeness, and uniformity of the data through pre-processing them so they can be efficiently analyzed.

Terminal layer. The terminal layer relies on terminal devices and provides functional applications for the steel structure construction process based on the data analysis results of the data layer. The terminal layer is user-oriented and feeds back the operation process of the digital twin model to the user layer, providing support for the interaction between the users and the digital twin model.

User layer. The user layer is composed of the project-related personnel. The user layer is the feedback object of the digital twin system. The user layer is based on the terminal devices, and through its displayed digital twin system platform interface, it can obtain various information about the steel structure construction process in real time and control events that occur during the construction process in a timely manner.

5. Case Analysis

In order to further illustrate the characteristics of the digital twin model for steel structure construction and to present its specific implementation method more clearly, case studies were conducted from a macro perspective and a single-application perspective, using the steel structure construction processes of the university park library project in Xiongan New Area and the reconstruction and expansion project of the Nanchong Gaoping airport as examples.

5.1. University Park Library Project in Xiongan New Area

In the construction process of the university park library project in Xiongan New Area, various information technologies and platforms were used to obtain data on the construction elements and create virtual models. According to the virtual models and obtained data, intelligent construction technologies—such as steel structure construction process simulation, real-time personnel management, and real-time environmental monitoring—were applied, as shown in Figure 7.

To obtain and transmit the physical space data, information such as the personnel's numbers, job types, and work status was entered into the smart construction site platform as inputs. In addition, the locations and attendance information of the personnel were collected through intelligent safety helmets and access control systems, and the information was transmitted to the smart construction site personnel management module through the network to achieve efficient statistics on the personnel management process. Regarding the mechanical equipment, a perception module embedded in the tower crane was used to monitor the height, torque, and other working status information of the tower crane in real time, transmitting it to the smart construction site platform to manage the operating status of the tower crane. Regarding the materials, a logistics tracking platform was used to view the transportation trajectory of the steel structural components in real time and obtain the entry information of the materials. Regarding the environment, on-site sensors were used to detect the temperature, wind speed, noise, and other environmental factors, obtaining real-time environmental information on-site and providing a reference for the construction process.

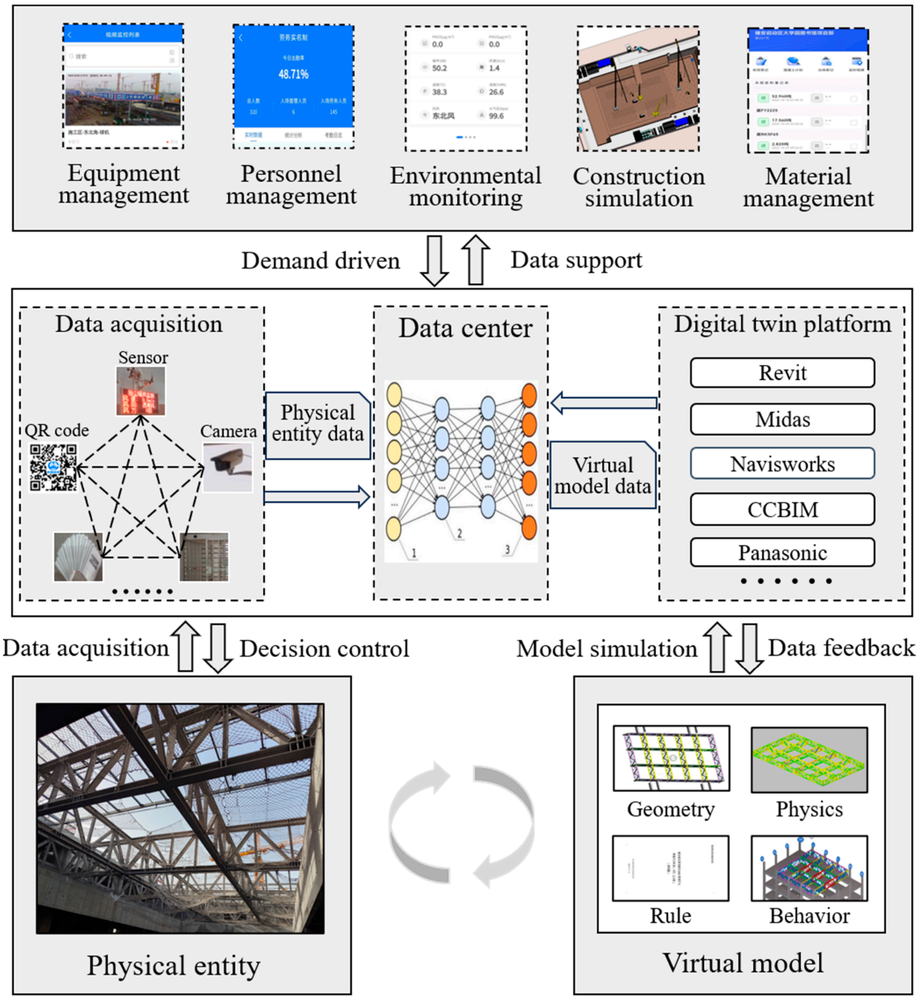

Figure 7. Application architecture of intelligent construction technology for steel structures based on digital twins.

With regard to the establishment of virtual models, in accordance with the information of architectural design drawings and the actual situation of the site, multiple software such as the BIM and finite element software were adopted to model the 3D virtual model of each professional design. The BIM model and finite element virtual model have the same geometric and physical properties as the physical entity. When modeling, the virtual model is constrained in line with the corresponding standards to form the rule model. Furthermore, the virtual model is integrated to drive the establishment of the behavior model through the needs of the construction process.

Through obtaining and transmitting physical entity data, constructing virtual models, and using networks and smart construction platforms to drive information exchange and the operation of a digital twin model, the establishment of digital twin models for steel structure construction processes can be achieved. Due to digital twin models, the construction and management process has become clearer and more direct, achieving information management of the personnel, machinery, and materials, and real-time monitoring of the environment during the construction process. In addition, quality and safety issues on-site can also be uploaded to virtual spaces through pictures and videos, enabling information-based management of the quality and safety aspects of the construction process. A digital twin model of the steel structure construction process can achieve the accurate, comprehensive, and rapid comprehension of various construction information, more effectively carry out collaborative management of the construction process, improve construction efficiency, reduce costs, and bring practical benefits to the process of construction projects.

5.2. Reconstruction and Expansion Project of the Nanchong Gaoping Airport

In the reconstruction and expansion project of the Nanchong Gaoping airport, the roof of Terminal T3 acquired a square pyramid grid structure with a maximum span of about 5 m and a maximum overhanging length of about 12 m. The digital twin model theory for steel structure construction processes was applied in the steel grid construction process of this project, as shown in Figure 8.

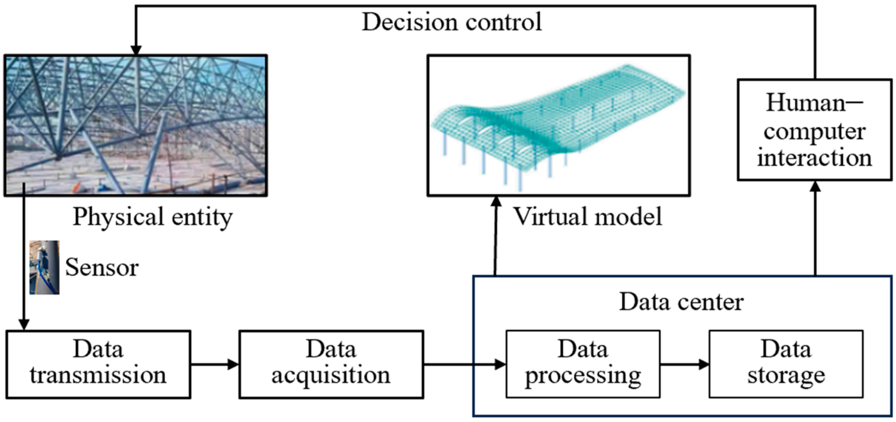

Figure 8. Example of application process.

Due to the long construction period of the steel grid structure in this project and the significant changes in the environmental temperature, the stress state of the steel structure was more significantly affected by temperature. Therefore, during the construction process, temperature and stress sensors were installed on the grid of the project to collect the stress and temperature data of the key steel components, which were transmitted to the platform. The virtual model was then modified based on the actual collected data. On the platform side, computers used the collected data to train and analyze machine learning algorithms. Through data training, the relationship between the temperature and stress of the key components of the steel grid structures was obtained, and then the impact of temperature changes on the stress of components could be predicted.

A BP neural network algorithm was adopted to process 600 sets of data to determine the relationship between temperature and stress. There were 480 sets of data in the training set and 120 sets of data in the testing set. A comparison between the predicted results on the neural network test set and the true monitoring values is shown in Figure 9, and some data are shown in Table 1. As shown in the figure, the predicted values (PVs) obtained from the BP neural network algorithm were highly consistent with the true values (TVs), indicating that the BP neural network established a reliable relationship between the temperature and stress during the steel structure construction and had high accuracy. By training machine learning algorithms on the temperature and stress data sets collected with sensors, it will be possible to accurately predict the impact of temperature changes on the stress of steel structural components in the future. Furthermore, the predicted results can be presented to relevant personnel to better guide the next construction step of the project, thereby forming closed-loop control of the steel structure construction process and ensuring safety during the construction process.

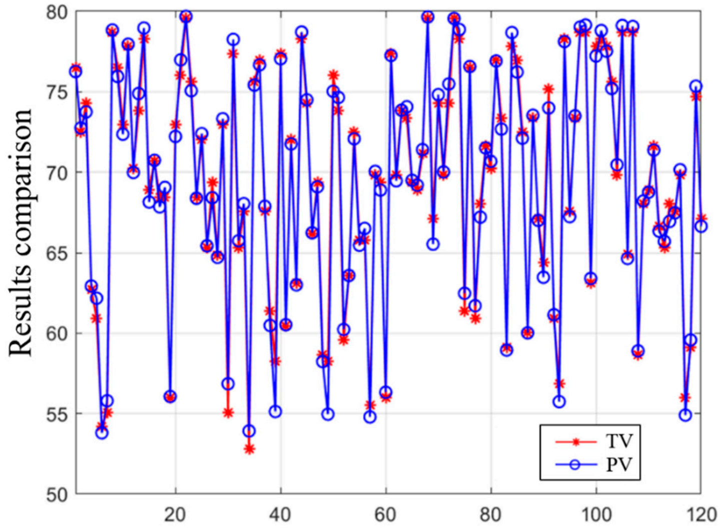

Figure 9. Comparison of prediction results.

Table 1. Temperatures and stress values.

No.	Temperature /°C	Stress (TV) /MPa	PV /MPa	No.	Temperature/°C	Stress (TV) /MPa	PV /MPa
1	17.105	79.584	79.590	13	29.246	65.117	65.052
2	18.373	77.823	77.935	14	30.217	64.469	64.097
3	19.043	77.823	77.040	15	31.867	62.252	62.468
4	20.106	76.941	75.609	16	32.415	60.916	61.919
5	21.229	74.282	74.110	17	33.495	60.470	60.822
6	22.359	72.947	72.644	18	34.066	61.362	60.231
7	23.556	71.608	71.157	19	35.342	59.577	58.882
8	24.368	69.817	70.194	20	36.040	58.682	58.126
9	25.229	69.817	69.214	21	37.223	59.577	56.816
10	26.113	69.368	68.247	22	38.647	56.887	55.195
11	27.426	67.117	66.874	23	39.336	54.634	54.395
12	28.305	66.665	65.986	24	40.714	54.182	52.774

6. Summary and Future Works

At present, practical problems, such as a low level of informatization and excessive reliance on experience, affect the construction process of steel structures. Traditional construction methods are not able to adapt to modern production methods. Therefore, there is an urgent need to achieve real-time, efficient, and accurate statistics, simulation, analysis, and prediction of construction processes to make the management of the construction of steel structures more efficient and decision making more scientific. In this context, the emergence and application of a large number of information technologies have provided new ideas for solving these problems.

Based on rapidly developing digital and information technology, this article proposed a digital twin model for the steel structure construction process, analyzing its connotations and characteristics. Furthermore, an operation method for the digital twin modeling of steel structure construction processes was proposed, including three stages: the acquisition and transmission of physical space data, the construction of virtual models, and information exchange in the digital twin model. Digital twin modeling of steel structure construction processes provides an intelligent method for steel structure construction, contributes different functions according to the different needs of the construction process, and reduces the influence of human factors in the construction process. Therefore, digital twin modeling could improve the accuracy of construction process decision making and achieve intelligent construction and management methods.

Using the proposed steel structure digital twin model and its operating method, the authors of this article took the steel structure of the university park library project in Xiongan New Area as an example and conducted a case analysis from a macro perspective. A construction system based on a digital twin model was built for this project, utilizing technologies such as BIM, the Internet of Things, and smart construction platforms and achieving good results in its construction and management efficiency, energy consumption control, and other aspects. Furthermore, taking the reconstruction and expansion project of the Nanchong Gaoping airport as an example, a case study was conducted from the perspective of a single-point application to illustrate the details of data collection and data processing in the digital twin model of a steel structure construction process.

Digital twin technology plays a pivotal role in achieving intelligent construction and management during the construction process. This paper came up with a digital twin model architecture for steel structure construction processes and delved into its establishment method. But for the time being, the application of digital twin technology in steel structure construction still confronts a multitude of challenges. For this reason, the next step should be guided by the specific requirements of the steel structure construction process, starting from the bottom technology and standard level, so as to explore how to collect, fuse, and process physical entity data in an all-round and real-time manner, further develop corresponding digital twin platform systems, integrate specific functional modules, and provide guidance for on-site construction. With further technological development, the application of digital twin technology in steel structure construction is expected to become increasingly comprehensive, thereby promoting the better development of steel structures.

Author Contributions: Conceptualization, Z.L.; methodology, S.L.; software, Z.L. and S.L.; validation, Z.L. and S.L.; writing—original draft preparation, S.L.; writing—review and editing, Z.L.; project administration, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to confidentiality.

Acknowledgments: The authors would like to thank the Beijing University of Technology for its support throughout the research project.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the study's design; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Opoku, D.-G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M. Digital twin application in the construction industry: A literature review. *J. Build. Eng.* **2021**, *40*, 102726. [CrossRef]
2. Liu, Z.; Sun, X.; Shi, G. Summary of application of intelligent construction in civil engineering construction. *Constr. Technol.* **2021**, *50*, 40–53.
3. Zhang, J.; Chen, M.; Ballesteros-Pérez, P.; Ke, Y.; Gong, Z.; Ni, Q. A new framework to evaluate and optimize digital transformation policies in the construction industry: A China case study. *J. Build. Eng.* **2023**, *70*, 106388. [CrossRef]
4. Baduge, S.K.; Thilakarathna, S.; Perera, J.S.; Arashpour, M.; Sharafi, P.; Teodosio, B.; Shringi, A.; Mendis, P. Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications. *Autom. Constr.* **2022**, *141*, 104440. [CrossRef]
5. Sepasgozar, S.M.E.; Khan, A.A.; Smith, K.; Romero, J.G.; Shen, X.; Shirowzhan, S.; Li, H.; Tahmasebinia, F. BIM and Digital Twin for Developing Convergence Technologies as Future of Digital Construction. *Buildings* **2023**, *13*, 441. [CrossRef]
6. Tuhaise, V.V.; Tah, J.H.M.; Abanda, F.H. Technologies for digital twin applications in construction. *Autom. Constr.* **2023**, *152*, 104931. [CrossRef]
7. Fan, Q.; Lin, P.; Wei, P.; Ning, Z.; Li, G. Closed-loop control theory of intelligence construction. *J. Tsinghua Univ. (Sci. Technol.)* **2021**, *61*, 660–670.
8. Mao, C.; Peng, Y. The Theoretical Framework and Core Logic of Intelligent Construction. *J. Eng. Manag.* **2020**, *34*, 1–6.
9. Niu, Y.; Anumba, C.; Lu, W. Taxonomy and deployment framework for emerging pervasive technologies in construction projects. *J. Constr. Eng. Manag.* **2019**, *145*, 04019028. [CrossRef]

10. Ghosh, A.; Edwards, D.J.; Hosseini, M.R. Patterns and trends in Internet of Things (IoT) research: Future applications in the construction industry. *Eng. Constr. Archit. Manag.* **2021**, *28*, 457–481. [CrossRef]
11. Chen, H.P.; Ying, K.C. Artificial Intelligence in the Construction Industry: Main Development Trajectories and Future Outlook. *Appl. Sci.* **2022**, *12*, 5832. [CrossRef]
12. Zabin, A.; González, V.A.; Zou, Y.; Amor, R. Applications of machine learning to BIM: A systematic literature review. *Adv. Eng. Inform.* **2022**, *51*, 101474. [CrossRef]
13. Tak, A.N.; Taghaddos, H.; Mousaei, A.; Bolourani, A.; Hermann, U. BIM-based 4D mobile crane simulation and onsite operation management. *Autom. Constr.* **2021**, *128*, 103766. [CrossRef]
14. Liu, H.; Cheng, J.C.; Gan, V.J.L.; Zhou, S. A knowledge model-based BIM framework for automatic code-compliant quantity take-off. *Autom. Constr.* **2022**, *133*, 104024. [CrossRef]
15. Lin, J.; Guo, J. BIM-based automatic compliance checking. *J. Tsinghua Univ. (Sci. Technol.)* **2020**, *60*, 873–879.
16. Yang, B.; Liu, B.; Xiao, J. Disassembly analysis and realization of steel frame structure based on BIM. *J. Build. Struct.* **2022**, *43*, 305–314.
17. Wang, Y.-G.; He, X.-J.; He, J.; Fan, C. Virtual trial assembly of steel structure based on BIM platform. *Autom. Constr.* **2022**, *141*, 104395. [CrossRef]
18. Wu, L.; Lu, W.; Xue, F.; Li, X.; Zhao, R.; Tang, M. Linking permissioned blockchain to Internet of Things (IoT)-BIM platform for off-site production management in modular construction. *Comput. Ind.* **2022**, *135*, 103573. [CrossRef]
19. Abioye, S.O.; Oyedele, L.O.; Akanbi, L.; Ajayi, A.; Delgado, J.M.D.; Bilal, M.; Akinade, O.O.; Ahmed, A. Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *J. Build. Eng.* **2021**, *44*, 103299. [CrossRef]
20. Liu, J.; Cui, N.; Cheng, G.; Li, D.; Ma, X.; Liao, Y. Towards the automated virtual trial assembly of large and complex steel members using terrestrial laser scanning and BIM. *Eng. Struct.* **2023**, *291*, 116448. [CrossRef]
21. Schiavi, B.; Havard, V.; Beddiar, K.; Baudry, D. BIM data flow architecture with AR/VR technologies: Use cases in architecture, engineering and construction. *Autom. Constr.* **2022**, *134*, 104054. [CrossRef]
22. Ma, Z.; Ren, Y. Integrated application of BIM and GIS: An overview. *Procedia Eng.* **2017**, *196*, 1072–1079. [CrossRef]
23. Zhong, R.Y.; Peng, Y.; Xue, F.; Fang, J.; Zou, W.; Luo, H.; Ng, S.T.; Lu, W.; Shen, G.Q.P.; Huang, G.Q. Prefabricated construction enabled by the Internet-of-Things. *Autom. Constr.* **2017**, *76*, 59–70. [CrossRef]
24. Su, S.; Zhong, R.Y.; Jiang, Y.; Song, J.; Fu, Y.; Cao, H. Digital twin and its potential applications in construction industry: State-of-art review and a conceptual framework. *Adv. Eng. Inform.* **2023**, *57*, 102030. [CrossRef]
25. Sheng, J.; Zhang, Q.; Li, H.; Shen, S.; Ming, R.; Jiang, J.; Li, Q.; Su, G.; Sun, B.; Huang, C.; et al. Digital twin driven intelligent manufacturing for FPCB etching production line. *Comput. Ind. Eng.* **2023**, *186*, 109763. [CrossRef]
26. Dong, L.; Zhou, X.; Zhao, F.; He, S.; Lu, Z.; Feng, J. Key technologies for modeling and simulation of airframe digital twin. *Acta Aeronaut. Astronaut. Sin.* **2021**, *42*, 113–141.
27. Leng, J.; Wang, D.; Shen, W.; Li, X.; Liu, Q.; Chen, X. Digital twins-based smart manufacturing system design in Industry 4.0: A review. *J. Manuf. Syst.* **2021**, *60*, 119–137. [CrossRef]
28. Haleem, A.; Javaid, M.; Singh, R.P.; Suman, R. Exploring the revolution in healthcare systems through the applications of digital twin technology. *Biomed. Technol.* **2023**, *4*, 28–38. [CrossRef]
29. Cho, J.; Kim, C.; Lim, K.J.; Kim, J.; Ji, B.; Yeon, J. Web-based agricultural infrastructure digital twin system integrated with GIS and BIM concepts. *Comput. Electron. Agric.* **2023**, *215*, 108441. [CrossRef]
30. Bai, H.; Wang, Y. Digital power grid based on digital twin: Definition, structure and key technologies. *Energy Rep.* **2022**, *8*, 390–397. [CrossRef]
31. Li, Q.; Liu, J.; Li, J.; Zhang, C.; Guo, J.; Wang, X.; Ran, W. Digital twin of mine ecological environment: Connotation, framework and key technologies. *J. China Coal Soc.* **2023**, *48*, 3859–3873.
32. Tao, F.; Liu, W.; Zhang, M.; Hu, T.; Qi, Q.; Zhang, H.; Sui, F.; Wang, T.; Xu, H.; Huang, Z.; et al. Five dimension digital twin model and its ten applications. *Comput. Integr. Manuf. Syst.* **2019**, *25*, 1–18.
33. Tao, F.; Xiao, B.; Qi, Q.; Cheng, J.; Ji, P. Digital twin modeling. *J. Manuf. Syst.* **2022**, *64*, 372–389. [CrossRef]
34. Zhang, D.; Wang, Y.; Liao, S.; Lu, Y. Review of Digital Twin Construction Technology for Civil Engineering. *Constr. Technol.* **2023**, *52*, 1–12.
35. Liu, Z.; Liu, Z.S.; Sun, J.; Du, X. Intelligent construction methods and model experiments based on digital twins. *J. Build. Struct.* **2021**, *42*, 26–36.
36. Pan, Y.; Zhang, L. A BIM-data mining integrated digital twin framework for advanced project management. *Autom. Constr.* **2021**, *124*, 103564. [CrossRef]
37. Wang, X.; Wang, S.; Song, X.; Han, Y. IoT-based intelligent construction system for prefabricated buildings: Study of operating mechanism and implementation in China. *Appl. Sci.* **2020**, *10*, 6311. [CrossRef]
38. Zhao, Y.; Wang, N.; Liu, Z.; Mu, E. Construction theory for a building intelligent operation and maintenance system based on digital twins and machine learning. *Buildings* **2022**, *12*, 87. [CrossRef]
39. Torzoni, M.; Tezzele, M.; Mariani, S.; Manzoni, A.; Willcox, K.E. A digital twin framework for civil engineering structures. *Comput. Methods Appl. Mech. Eng.* **2024**, *418*, 116584. [CrossRef]

40. Yevu, S.K.; Owusu, E.K.; Chan, A.P.C.; Sepasgozar, S.M.E.; Kamat, V.R. Digital twin-enabled prefabrication supply chain for smart construction and carbon emissions evaluation in building projects. *J. Build. Eng.* **2023**, *78*, 107598. [CrossRef]
41. Wu, X.; Liu, J.; Chen, H.; Xu, W.; Liu, X. Digital Twin Frame System of Shield Tunneling System. *J. Inf. Technol. Civ. Eng. Archit.* **2023**, *15*, 105–110.
42. Qian, W.; Guo, Y.; Zhang, L.; Huang, S.; Genget, S. Towards discrete manufacturing workshop-oriented digital twin model: Modeling, verification and evolution. *J. Manuf. Syst.* **2023**, *71*, 188–205. [CrossRef]
43. Tao, F.; Zhang, H.; Qi, Q.; Xu, J.; Sun, Z.; Hu, T.; Liu, X.; Liu, T.; Guan, J.; Chen, C. Theory of digital twin modeling and its application. *J. Manuf. Syst.* **2021**, *27*, 1–15. [CrossRef]
44. Jiang, W.; Ding, L.; Zhou, C. Cyber physical system for safety management in smart construction site. *Eng. Constr. Archit. Manag.* **2021**, *3*, 788–808. [CrossRef]
45. Dihan, M.S.; Akash, A.I.; Tasneem, Z.; Das, P.; Das, S.K.; Islam, M.R.; Islam, M.M.; Badal, F.R.; Ali, M.F.; Ahamed, M.H. Digital Twin: Data Exploration, Architecture, Implementation and Future. *Heliyon* **2024**, *5*, e26503. [CrossRef] [PubMed]