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# Research on digital twin technology and its application in intelligent operation and maintenance of high-speed railway infrastructure

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## Abstract

**Purpose** – This paper analyzes the application of digital twin technology in the field of intelligent operation and maintenance of high-speed railway infrastructure from the perspective of top-level design.

**Design/methodology/approach** – This paper provides a comprehensive overview of the definition, connotations, characteristics and key technologies of digital twin technology. It also conducts a thorough analysis of the current state of digital twin applications, with a particular focus on the overall requirements for intelligent operation and maintenance of high-speed railway infrastructure. Using the Jinan Yellow River Bridge on the Beijing–Shanghai high-speed railway as a case study, the paper details the construction process of the twin system from the perspectives of system architecture, theoretical definition, model construction and platform design.

**Findings** – Digital twin technology can play an important role in the whole life cycle management, fault prediction and condition monitoring in the field of high-speed rail operation and maintenance. Digital twin technology is of great significance to improve the intelligent level of high-speed railway operation and management.

**Originality/value** – This paper systematically summarizes the main components of digital twin railway. The general framework of the digital twin bridge is given, and its application in the field of intelligent operation and maintenance is prospected.

**Keywords** System architecture, Digital twin, Intelligent railway, Beijing–shanghai high-speed railway, Intelligent maintenance

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## 1. Introduction

With the rapid development of simulation and digital technologies, Digital Twin technology has become a research hotspot across various industries (Nie, Zhou, & Xiao, 2022). The concept of the Digital Twin was first introduced by NASA in 2010. Subsequently, in 2011, the U.S. Air Force Research Laboratory explicitly proposed the use of Digital Twin technology to address maintenance issues of aircraft bodies and introduced a conceptual model for predicting the structural lifespan of aircraft. In 2012, NASA and the U.S. Air Force Research Laboratory collaborated to jointly propose a Digital Twin paradigm for future aircraft to extend the service life of high-load aircraft under extreme conditions. In 2014, Professor Michael Grieves of the United States published a white paper on Digital Twin technology, further elaborating on the basic conceptual model (Meng, Ye, & Yang, 2020). In 2017, Professor Tao Fei from China introduced the concept of the Digital Twin Workshop, discussing its characteristics and operational mechanisms. Building on these conceptual and framework studies, researchers have explored key technologies related to Digital Twin, such as the Bayesian network for wing monitoring proposed by Professor of Vanderbilt University, and the Five-Dimensional Digital Twin Model proposed by Professor Tao Fei from China. These advancements have significantly contributed to the further application of Digital Twin technology (Liu, Guo, & Wang, 2018; Tao, Liu, Zhang, & Hu, 2019; Tao, Ma, & Hu, 2019).

Since 2017, Digital Twin technology has rapidly developed in the field of industrial manufacturing. The globally renowned consulting firm Gartner has consecutively listed Digital Twins as one of the top ten strategic technology trends for three years. In 2019, led by the Digital Twin Research Group at Beihang University, China, and in collaboration with scholars from five countries, a comprehensive system of Digital Twin technologies and tools was established. Additionally, a Digital Twin standards system was created in partnership with 18 organizations. In 2020, the Industrial Internet Consortium in the United States released a white paper titled “Digital Twin in Industrial Applications,” providing operational guidance for the practical application of Digital Twins in industry (Lu, Zhang, & Zhao, 2021; Shen, Cao, & Jia, 2022). Furthermore, companies such as General Electric in the United States, Siemens in Germany, Dassault in France, as well as China’s State Grid Corporation, have all initiated Digital Twin projects and achieved positive results.

From a technical perspective, digital twin has seen rapid development in recent years. Wei Guofeng proposed a multi-sensing node convolutional neural network individual identity fusion recognition algorithm for radio frequency digital twin based on the demand for electromagnetic space (Wei, Ding, & Jiao, 2023). Su Dongyu uses fuzzy information clustering and rough set feature matching methods to implement resource scheduling and information invocation in the digital twin system, and combines data moving, backup, replication and other technologies to realize data management optimization of transmission lines (Su, Xie, & Jia, 2021). Ning Zhicheng used LSTM models to analyze test data and remote sensing data for spacecraft, correcting the bias between the physical model and the virtual model to obtain high-precision spacecraft models (Ning, Liu, & Wang, 2022). Luo Bin has effectively supported the construction and operation of the integrated dispatching and management system of the Three Gorges Intelligent watershed operation and management work platform by constructing the digital twin platform of water conservancy (Luo, Zhou, & Zhang, 2024).

As the backbone of China’s economy and an integral part of the comprehensive transportation system, the railway industry has made significant progress in business areas such as operations management, command and dispatch, and safety monitoring after years of information technology development (Li, Zhang, & Guo, 2020). These advancements have laid a technical foundation for the construction of Digital Twin Railways. Meanwhile, China’s railways are facing challenges in cost reduction, energy conservation, and innovation under the new circumstances, leading to a strong demand for intelligent and digital railway solutions (Wang, He, & Tian, 2020). Therefore, it is very necessary to realize the perception, analysis and interaction of the whole life cycle of railway business by constructing the Digital Twin system. This paper provides a detailed theoretical exploration of the definition, connotation, characteristics, and key technologies of Digital Twin technology, as well as its application status. Additionally, the paper uses the Jinan Yellow River Bridge on the Beijing-Shanghai High-Speed Railway as a case study to illustrate the process of constructing a Digital Twin system, offering effective theoretical support for the intelligent operation and maintenance of high-speed railway infrastructure.

## 2. Overview of digital twin

### *2.1 Definition*

The modern industrial system is evolving towards integration and intelligence, and industrial equipment is becoming increasingly complex. Traditional simulation models struggle to achieve real-time status assessment and anomaly detection for complex equipment in dynamic and ever-changing environments. Simultaneously, modern industrial management systems demand higher standards for the stability, controllability, and real-time performance of equipment. In response to these challenges, scholars have proposed the use of Digital Twin technology to simulate physical entities, processes, or systems in order to guide actual production.

Digital Twin refers to the construction of a digital model within an information platform, where the model dynamically operates and self-learns based on multiple feedback data sources. This allows for real-time representation of the physical entity’s actual changes within the digital world. Building on this foundation, technologies such as big data and artificial intelligence are comprehensively employed to monitor the system’s state, conduct simulation experiments, and perform predictive analyses. Additionally, commands can be issued to the physical entity, enabling the addition or extension of new capabilities. Consequently, Digital Twin emerges as a new generation of digital products capable of finely expressing physical entities, featuring virtual-physical interaction and bidirectional mapping capabilities.

### *2.2 Conceptual framework*

Digital Twin technology provides comprehensive support and guidance throughout all stages of equipment development, from design and construction to implementation, operation, and subsequent management. Specifically, it encompasses:

(1) *Production and manufacturing stage:* By constructing twin models, pre-planning, designing, and simulating the construction process, the technology addresses issues that arise during the construction phase, reduces construction complexity, and enhances equipment reliability.

(2) *Operational monitoring stage:* Through virtual-real mapping, the internal, unmeasurable aspects of complex equipment are virtually constructed, enabling health monitoring of various parameters and equipment performance, status assessment, and simulation predictions.

(3) *Operation and maintenance management stage:* Supported by extensive model data and monitoring data throughout the entire lifecycle of complex equipment, a comprehensive lifecycle management mechanism can be established, facilitating later-stage operation and maintenance management as well as product optimization and upgrades.

### *2.3 Characteristics*

(1) *Data-driven:* The dual mapping and dynamic interaction between physical entities and virtual models are achieved through data, driving iterative updates of the twin models.

(2) *Model support:* Digital models enable the reproduction of complex system processes and provide three-dimensional visual representations. Various data types can be fully expressed through the twin models.

(3) *Precise mapping:* Information sensing technology allows for dynamic monitoring and comprehensive perception of physical entities, ensuring accurate mapping within the physical space.

(4) *Software-defined:* Twin models are displayed on a digital platform and simulate or monitor the state, behavior, and rules of physical entities dynamically in software form.

(5) *Intelligent decision-making:* By integrating technologies such as artificial intelligence, the twin models enable simulation, intelligent analysis, and predictive forecasting to assist in production decision-making.

## 3. Key technologies of digital twin

Digital Twin technology primarily encompasses information perception technology, data management technology, model construction technology, and integrated platform technology. The relationship among these technologies is illustrated in Figure 1.

### *3.1 Information perception technology*

Information perception technology is fundamental to the efficient and stable operation of a Digital Twin system (Yang, Sun, & Xiang, 2020). It functions by acquiring real-time data from physical devices and replicating the system's operational state, thereby enabling ubiquitous connectivity and bidirectional mapping between the physical entity and its twin. In this context, information perception technology serves as the foundation supporting the Digital Twin system (Tao, Cheng, & Cheng, 2017, 2019).

(1) *Spatiotemporal benchmarking:* Spatiotemporal benchmarking refers to the initial data and fundamental reference basis for measuring spatiotemporal data across temporal and spatial dimensions. This includes time benchmarks, geodetic benchmarks, and elevation benchmarks.

(2) *Data acquisition:* By establishing a multi-source, multi-modal, integrated information perception network, comprehensive and dynamic acquisition of the operational state of physical entities is achieved. This specifically includes:

- *Internet of things (IoT):* Utilizes intelligent sensors placed at specific spatial locations to capture and monitor dynamic changes in device data.
- *Remote sensing:* Provides large-scale data through remote sensing imagery, which offers substantial information and is a crucial component in constructing 3D models.
- *Navigation and positioning:* Through terminal devices, satellite navigation signals are received, enabling real-time dynamic reflection of the physical entity's movement trajectory.

(3) *Communication infrastructure:* High-speed, low-latency communication transmission is essential for real-time interaction within Digital Twin systems. Secure and reliable information transmission is critical to ensuring the system's stable operation. Therefore, Digital Twin systems impose higher demands on low-latency communication hardware and software, standardized communication protocols, and secure, reliable information transmission channels.

### *3.2 Data management technologies*

Data management technologies integrate various information resources to organize and manage complex temporal events. This integration ensures the orderly storage and efficient

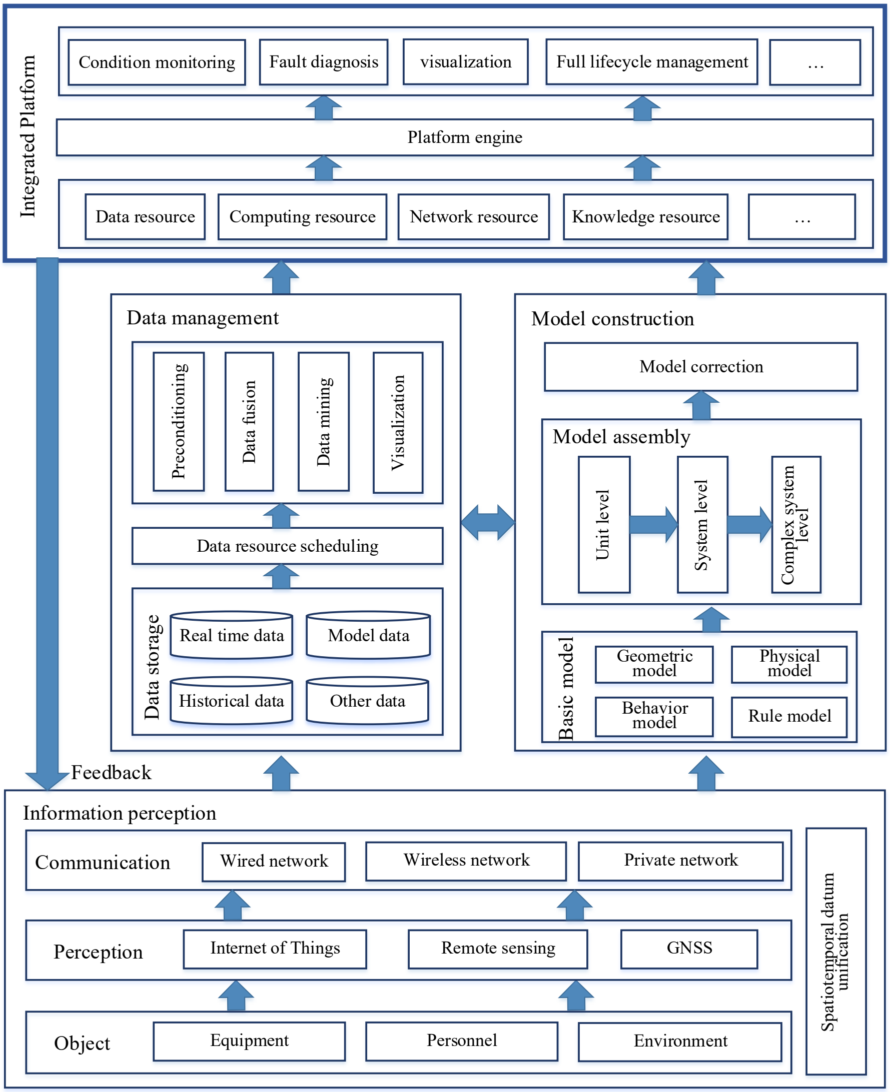

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**Figure 1.** Overall architecture of digital twin

distribution of massive spatiotemporal data. Therefore, data management technologies are critical for supporting the efficient and stable operation of Digital Twin systems.

(1) *Data storage and resource scheduling:* To ensure the simultaneous storage of spatial relationships and attribute relationships in spatiotemporal data, it is necessary to optimize the storage organization of existing databases or build spatiotemporal data indexes. This optimization is aimed at meeting the demands for high data access rates and concurrent storage queries. Additionally, a resource scheduling management system can be established based on stream data, batch data, model data, and historical

data, along with a multi-agent database cluster monitoring mechanism. These measures enhance the access efficiency of massive spatiotemporal data and the operational capabilities of database clusters, thereby meeting the Digital Twin system's needs for data integration, real-time processing, service orientation, and intelligence.

(2) *Data preprocessing and data fusion:* By preprocessing raw data, redundant, duplicate, and incomplete data are removed, while abnormal and noisy data are filtered out, thereby improving data quality and ensuring accuracy, completeness, and consistency. This process includes data cleaning, data integration, data reduction, and data transformation. Furthermore, by synthesizing, filtering, correlating, and integrating multi-source data, data fusion is achieved at the data level, feature level, and decision level. This approach effectively reduces data redundancy and enhances reliability, providing a robust data foundation for subsequent tasks such as data mining.

(3) *Data mining and visualization:* By applying statistical analysis, neural networks, and other methods to process data, deep data characteristics are mined, enabling situational awareness of physical entities. Furthermore, data visualization techniques are employed to present the results of data analysis in a direct, intuitive, clear, and effective manner.

### *3.3 Model construction techniques*

The construction of multidimensional and multi-granularity virtual models enables the digital representation of physical entities. By integrating perception information and enabling situational awareness, it becomes possible to describe, predict, optimize, and manage the entire lifecycle of physical entities or complex systems. Therefore, model construction techniques are considered the core support for the efficient and stable operation of Digital Twin systems (Tao, Zhang, & Qi, 2021).

(1) *Basic model construction:* This refers to the modeling of the fundamental units of physical entities, primarily described from four dimensions: "geometry-physics-behavior-rules." These dimensions cover the geometric characteristics, physical properties, coupling relationships, and dynamic changes of physical entities (Liu, Tao, & Cheng, 2020; Tao, Liu, & Liu, 2018).

- *Geometric dimension:* This involves the three-dimensional reconstruction of physical units through geometric and topological information. The main geometric modeling methods include manual modeling, BIM (Building Information Modeling), and large-scale modeling based on oblique photogrammetry combined with laser point cloud reification.
- *Physical dimension:* On the basis of the geometric model, physical properties such as materials and dimensions are added to express the physical characteristics of the equipment entities.
- *Behavioral dimension:* This involves the construction of dynamic models such as fluid dynamics or elastic system motion to describe the dynamic behavior of physical units. Additionally, the behavioral dimension includes the coupling relationships between various components.
- *Rules dimension:* This involves extracting operational patterns and evolution rules of physical entities from expert systems, state data, and historical data, enabling situational awareness and state prediction of the physical entities.

(2) *Model assembly and model fusion:* Through the assembly of basic physical entity models, the construction of twin models can be achieved at various levels, from the

unit level to the system level and eventually to the complex system level. First, the relationships between different levels of models are clarified, and spatial constraints between models are added during the assembly process. The assembly is then completed according to the order of model addition and spatial constraint conditions. Additionally, when spatial models cannot accurately characterize complex systems or processes, the coupling relationships between multiple models can be constructed to achieve model fusion across different disciplines and fields (Ma, Yin, & Li, 2021).

(3) *Model verification and model calibration:* After model assembly and fusion, the accuracy of the models needs to be verified to ensure their ability to accurately and comprehensively represent the physical entities. If the model accuracy is inadequate, the relevant parameters of the models need to be calibrated to ensure better adaptation to the requirements of different application scenarios.

### *3.4 Integrated platform technology*

Integrated platform technology enables the comprehensive integration of data resources, computational resources, knowledge resources, and network resources, converting them into shareable and exchangeable service resources. This integration allows for unified management of Digital Twin systems within the platform, making integrated platform technology a critical support for the efficient and stable operation of Digital Twin systems (Li, Tao, & Wang, 2019).

(1) *Platform architecture and business management:* By designing a well-structured twin system platform architecture, it is possible to effectively coordinate various resources such as data, computation, network, and knowledge. On this foundation, a thorough analysis of different business scenarios can be conducted to identify key logical elements. Application service programs can then be developed to support platform functions such as monitoring, evaluation, simulation, and management.

(2) *Platform interfaces and platform engine:* The design of a plug-and-play platform interface with a unified style allows for the on-demand dynamic scheduling of various functional modules within the twin system. This includes interfaces oriented towards physical devices, internal platform interfaces, and application service interfaces. Additionally, a platform engine can be constructed to abstract away certain technical details, thereby encapsulating core business functions into executable logic code. This approach enhances developer efficiency and simplifies the operational steps for system administrators.

### *3.5 Digital twin and emerging technologies*

(1) *Digital twin and artificial intelligence:* Artificial intelligence algorithms are employed to explore deep data characteristics and extract patterns of physical entity changes, providing intelligent services in accordance with business requirements.

(2) *Digital twin and 5G:* High-speed, low-latency 5G communication ensures real-time mapping and interaction between the physical and virtual aspects of the twin system, facilitating dynamic adjustments and timely corrections of the Digital Twin relative to the physical entity.

(3) *Digital twin and cloud-fog-edge computing:* The application of cloud computing, fog computing, and edge computing enables layered optimization of the computing and storage resources within the Digital Twin system, significantly enhancing data management capabilities (Gu, Chen, & Liu, 2021).

(4) *Digital twin and virtual reality:* By creating dynamic, three-dimensional immersive virtual environments, it is possible to transcend spatial and temporal constraints, allowing participants to simulate and experience the real physical world within a virtual space.

(5) *Digital twin and blockchain:* The decentralized, tamper-resistant, and traceable nature of blockchain technology ensures the security, reliability, and stable operation of the twin system.

(6) *Digital twin and the metaverse:* In the future, the continuous expansion of Digital Twin systems will facilitate value exchanges between the real world and the virtual world, thereby forming the prototype of the metaverse (Jing, Shen, & Yin, 2019; Wang, Gai, *et al.*, 2021; Wang, Dong, *et al.*, 2021; Wang, Hao, *et al.*, 2021).

## 4. Current status of digital twin applications

### *4.1 Digital twin in international applications*

With the rapid development of advanced technologies such as artificial intelligence, the Internet of Things, and cloud computing, the capabilities of Digital Twins have become increasingly prominent. Countries around the world are seizing this opportunity to accelerate the implementation of Digital Twin initiatives. Nations such as the United States, the United Kingdom, and Germany have elevated Digital Twin technology from localized exploration to national strategy, planning the long-term development of Digital Twins at the national level and establishing corresponding standards, principles, and development roadmaps. Countries like France, Russia, Japan, Singapore, South Korea, and Australia have also embarked on Digital Twin city construction, creating urban models across temporal and spatial dimensions to simulate extreme and anomalous events, thereby significantly enhancing urban infrastructure construction and operational management capabilities.

Many well-known enterprises are also leveraging Digital Twin technology to drive industrial optimization and upgrades, spawning new business models and injecting fresh vitality into their future development. For instance, Germany’s Siemens has developed industrial software such as NX and COMOS, which provides an integrated solution from product design and development to industrial manufacturing and operations management, embedding Digital Twins throughout the entire production process in the factory. The United States’ General Electric (GE) has constructed high-fidelity twin models of aircraft engines and, by utilizing foundational platform software and vast amounts of asset and equipment data, effectively predicts engine failure points and times. France’s Dassault Systemes, through its 3D EXPERIENCE strategy, has created a unified platform that integrates various applications such as design, simulation, analysis, data management, and community collaboration, and is actively expanding in areas like Digital Twin humans and medical devices. Additionally, companies like PTC, Microsoft, and ANSYS in the United States are also advancing Digital Twin development and have achieved significant economic benefits.

### *4.2 Digital twin in China applications*

China was one of the earliest countries to propose the concept of Digital Twin as an industry, recognizing it as a crucial driver of the new economy. In 2020, the National Development and Reform Commission (NDRC) and the Central Cyberspace Administration issued the Implementation Plan for Promoting the Action of “Cloud Adoption, Data Utilization, and Intelligence Empowerment” to Foster New Economic Development, which specifically introduced the “Digital Twin Innovation Plan” as part of China’s national strategy. Additionally, various relevant policies have been intensively issued by the NDRC, the Ministry of Industry and Information Technology, and the Ministry of Science and Technology, which have significantly promoted the rapid development of Digital Twin technology. Digital Twin technology also plays a vital role in the construction of smart cities and intelligent governments in pilot areas or key cities such as Beijing's sub-center, Xiong'an New Area, Guangzhou, and Shenzhen, introducing new concepts, models, and mechanisms for urban governance in the new era (Wang, Gai, *et al.*, 2021; Wang, Dong, *et al.*, 2021; Wang, Hao, *et al.*, 2021; Chen, Li, & Ma, 2022). Moreover, Digital Twin technology has been widely applied in several typical domestic industries, including:

(1) *Aviation industry:* The Digital Twin was first applied in this field, enabling the structural design of complex equipment such as aircraft. It also facilitates fault prediction and health management based on equipment status data and historical data, thereby improving equipment reliability and resource utilization (Fu, Cao, & Gao, 2021).

(2) *Power industry:* Currently, Digital Twin technology is mainly used for intelligent control and monitoring of power plants to ensure production safety and enhance power generation efficiency. Specific applications include real-time intelligent monitoring of power plants, analysis of equipment operation trends, precise diagnosis of power generation equipment faults, and lifecycle management of equipment (Liu, Chen, & Cong, 2021).

(3) *Petrochemical industry:* By constructing Digital Twin factories, it is possible to achieve dynamic production scheduling in workshops, multi-dimensional analysis of workshop energy consumption, health management of workshops, real-time control of industrial production processes, and visualization management of underground pipelines (Chen & Xiao, 2021; Sun, Liu, & Shen, 2022).

(4) *Automotive industry:* The main application scenarios include the refined design of automotive parts, vehicle damage assessment based on finite element analysis, vehicle fault diagnosis, and collaborative scheduling for autonomous driving (Jiang, Shen, & Lv, 2022).

In summary, Digital Twin technology is currently applied in various areas such as planning and design of equipment and facilities, status monitoring, intelligent control, and collaborative scheduling in factories and workshops, as well as visualization and lifecycle management in unmanned driving scenarios. Through the interaction and integration of the physical and digital realms, Digital Twins enable the shared intelligence and collaborative development of physical entities and digital models. This provides reliable technological support for high-quality enterprise development and effectively promotes the digital transformation of related industries.

## 5. The current state and demand analysis of digital twin railways

### *5.1 The current application of digital twin railways*

The world is entering an era dominated by the information industry, and as a fundamental sector within China's economic structure, the railway industry exhibits a strong demand for intelligent development. Digital Twin technology, as a significant tool for enhancing efficiency, demonstrates clear value in areas such as digital modeling, simulation, and predictive analysis. By constructing a Digital Twin Railway, it becomes possible to achieve comprehensive lifecycle perception, analysis, and interaction of railway operations, thereby providing reliable technical support for the intelligent development of railways.

At present, China has begun exploring the field of Digital Twin Railways and has achieved preliminary results. During the construction phase, integrating BIM models with monitoring and inspection data collected during construction can form an information system aimed at completion and delivery. In the construction of bridges and tunnels, high-definition images, design drawings, geological descriptions, and other information are collected and integrated into an information application system at the construction process level to assist in project management. In the operation and management phase, the effective information of railway facilities is integrated into a unified BIM model, breaking down business barriers between various specialties and achieving intelligent operation and maintenance of equipment and facilities, such as railway communications. Alternatively, the concept and methods of Digital Twins are used to establish emergency response models for passenger stations and design related simulation software, or to visualize key railway facilities or typical scenarios (Wang, Gai, *et al.*, 2021; Wang, Dong, *et al.*, 2021; Wang, Hao *et al.*, 2021).

Overall, Digital Twin technology has currently undergone preliminary exploratory applications in the rail transit industry and has achieved initial success in both railway construction and operation management, playing a positive role in guiding railway production. However, existing Digital Twin Railways often focus more on the construction of geometric models with insufficient integration with system mechanisms. Furthermore, due to the lack of unified standards, it is challenging to describe the precision, maturity, and intelligence levels of twin models. Therefore, it is highly necessary to integrate key elements across various professional and business domains in the railway industry and to construct a Digital Twin Railway with unified connotations and standards.

### *5.2 Analysis of the intelligent operation and maintenance requirements for high-speed railway infrastructure*

In recent years, China's high-speed railways have achieved remarkable success on a global scale. However, due to the extensive scale and wide distribution of the railway network, the operation and maintenance of the infrastructure face various complex challenges, including geological, environmental, and climatic conditions. These factors impose higher demands on the safety, efficiency, and reliability of the high-speed railway system. The specific challenges include:

(1) *High standards for modeling:* China's high-speed railways cover vast areas and involve complex scenarios, necessitating the development of an efficient enabling model to guide railway operation and maintenance.

(2) *High requirements for production coordination:* The management of railway operations involves multiple railway bureaus and various specialties, creating an urgent need for a management system that covers the entire lifecycle of the railway infrastructure.

(3) *High safety requirements:* The high speeds and complex operational environments of high-speed railways intensify the need for fault prediction of infrastructure and real-time monitoring and intelligent analysis of train conditions.

Digital Twin technology, as a tool for enhancing efficiency, can play a crucial role in model design, simulation, analysis, and prediction, thereby enabling intelligent operation and maintenance management of high-speed railway infrastructure in China. The overall demand for intelligent operation and maintenance of high-speed railway infrastructure is to integrate key elements from various disciplines and scenarios of high-speed railways to construct a Digital Twin Railway model. This model should highly integrate data from multiple disciplines, driving the dynamic operation of the twin model through data integration. By leveraging big data, cloud computing, virtual reality, and other technologies, it aims to achieve real-time visualization of railway equipment and facilities, operational simulation, intelligent decision-making, and lifecycle management, ultimately establishing a Digital Twin Railway that covers all aspects of operation and maintenance management. The specific requirements are as follows:

(1) There is an urgent need to define and design the Digital Twin Railway from a top-level design perspective, ensuring uniformity in the model's content, form, standards, and representation.

(2) A mechanism model suitable for railway scenarios needs to be developed to depict the true evolutionary rules of high-speed railway equipment and facilities, enabling situation awareness and other capabilities.

(3) It is essential to integrate key elements from various business areas of high-speed railways and highly incorporate them into the twin model to facilitate comprehensive data analysis.

(4) The real-time performance of the Digital Twin system needs to be enhanced to enable intelligent decision-making and rapid response for monitoring and detecting high-speed railway equipment and facilities, as well as for addressing critical disasters.

## 6. Design of the digital twin bridge system for the Beijing-Shanghai high-speed railway

### *6.1 System architecture*

The Beijing-Shanghai High-Speed Railway is the largest investment project in the history of China's high-speed railways. Since its inauguration, the railway has continuously advanced its level of informatization. However, existing inspection and monitoring methods still lack the capacity for timely dynamic responses to infrastructure conditions, particularly in the comprehensive maintenance of bridges, where there is a strong demand for intelligent solutions. Therefore, this chapter takes the Jinan Yellow River Bridge on the Beijing-Shanghai High-Speed Railway as a case study to detail the construction process of the Digital Twin system. The overall architecture is illustrated in Figure 2.

(1) *Facility layer:* The sensing equipment includes existing information systems, on-site monitoring sensors, and drawings and documentation. Communication equipment comprises wireless networks, wired networks, and the dedicated railway network. The cloud environment and edge computing environment provide fundamental computational and storage resources.

(2) *Data layer:* The data layer forms the foundation of the Digital Twin Bridge system. It includes data sources such as bridge data, operational data, and external data; data processing, which encompasses data cleaning, data integration, data standardization, and data transformation; and data management, including catalog management, data tagging, and data updating.

(3) *Service layer:* Building on existing informatization achievements, this layer utilizes an integrated platform to provide technical and business services. These services are combined and made available through interfaces according to business needs, specifically including twin model services, basic platform services, and business support services.

(4) *Application layer:* This layer applies the Digital Twin Bridge system platform to achieve the integration display of bridge facilities, fault diagnosis, condition monitoring, and full lifecycle management, thereby supporting the enhancement of intelligent infrastructure operation and maintenance management for the Beijing-Shanghai High-Speed Railway.

### *6.2 Definition and connotation*

A Digital Twin Bridge system is composed of three key components: the physical bridge entity, the digital bridge model, and the interconnected mapping between the virtual and real

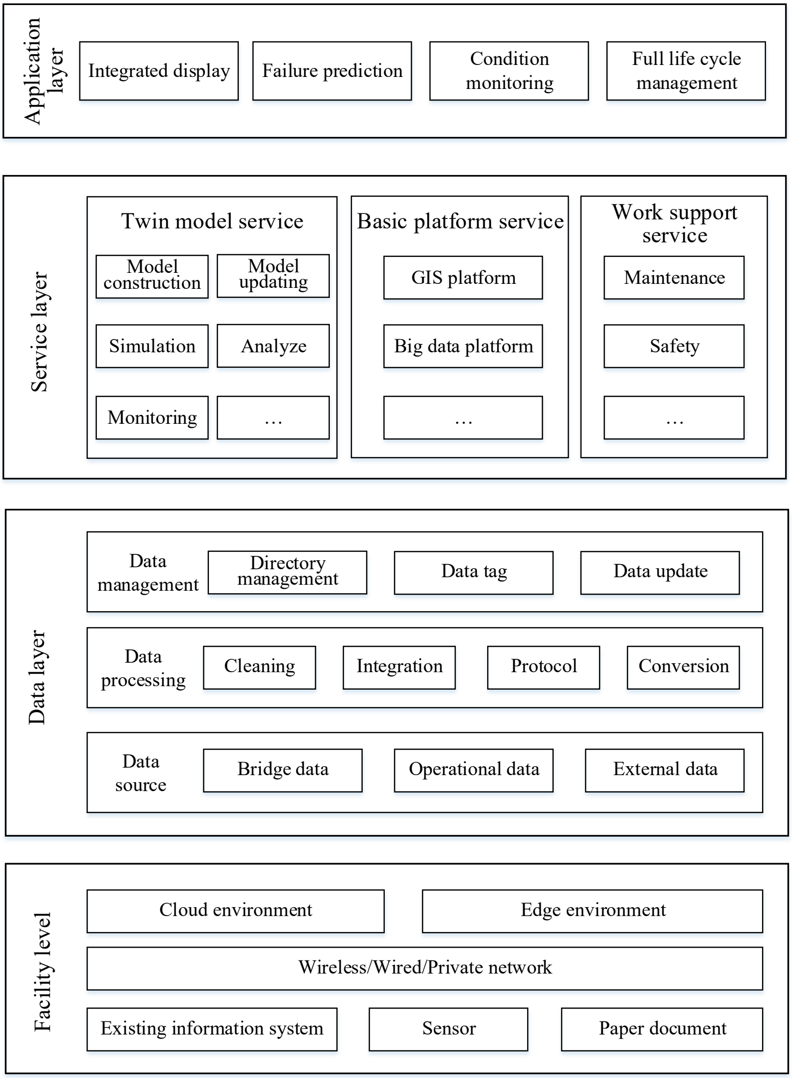

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**Figure 2.** Overall architecture of digital twin bridge system

worlds. The physical bridge entity encompasses all information related to the bridge in the real world, including geometric information, physical properties, and attribute data. The digital bridge model in the virtual world consists of the representation model, the mechanism model, and the constraints between these two, which together construct the Digital Twin Bridge model. This allows for the digital representation of features, constraints, and other elements of the bridge in the virtual space. The physical bridge entity and the digital bridge model are interconnected through virtual-real mapping, which includes sensing devices, communication equipment, computational resources, and network infrastructure.

### 6.3 Twin model design

The Digital Twin Bridge model is composed of three parts: the decomposition of bridge elements, the construction of the twin model, and the model verification and correction, as illustrated in Figure 3.

Firstly, the geometric elements of the bridge are decomposed, and the spatial logical relationships between components are determined to facilitate subsequent assembly or integration in the virtual space. Secondly, based on the physical characteristics of the bridge, it is decomposed into material properties, mechanical properties, dynamic properties, and so forth, which serve as the basic components of the digital bridge mechanism model. Then, bridge data is organized, archived, and associated with the twin model, allowing various types of data to be fully expressed. This significantly enhances data sharing and linkage, providing a foundational data basis for the intelligent operation and maintenance of the bridge.

Based on the decomposition results of the bridge's key elements, the Digital Twin Bridge model is constructed, comprising both the representation model and the mechanism model. The representation model is used to characterize the static properties of the bridge and is a collection of basic information, including geometric models, physical models, behavioral models, and rule models. The mechanism model, on the other hand, characterizes the dynamic properties of the bridge, simulating the bridge's behavior under special conditions, including

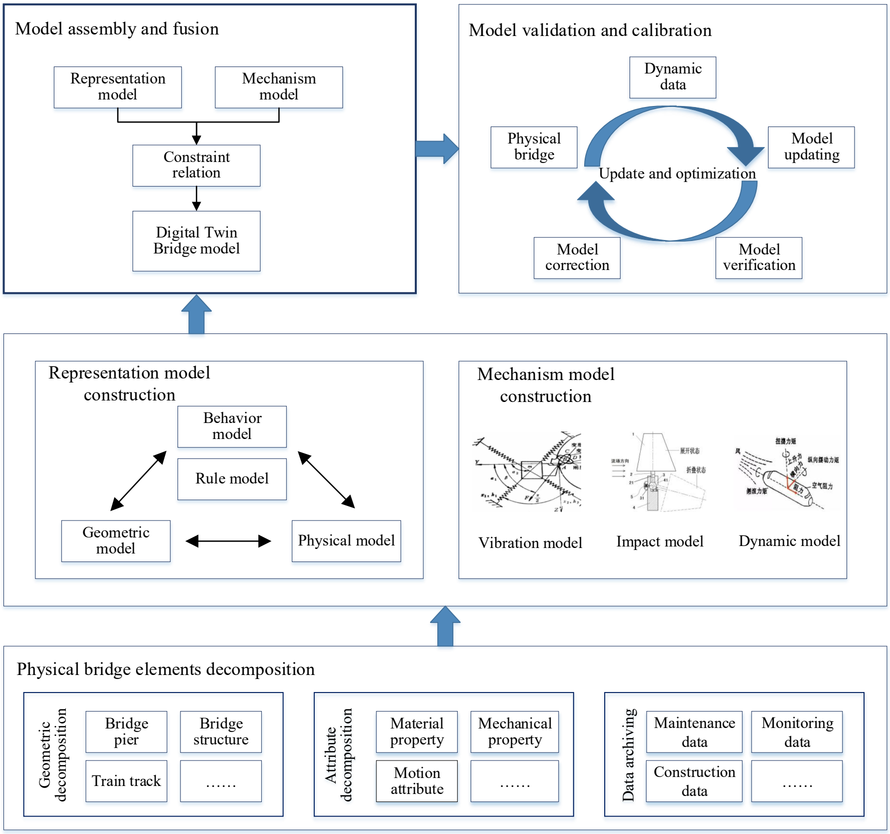

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**Figure 3.** Construction of digital twin bridge model

vibration models, impact models, and dynamic models. Furthermore, the representation model and the mechanism model are integrated according to spatial constraints and are associated with external environmental information, achieving the construction of a multi-domain, all-element Digital Twin Bridge model.

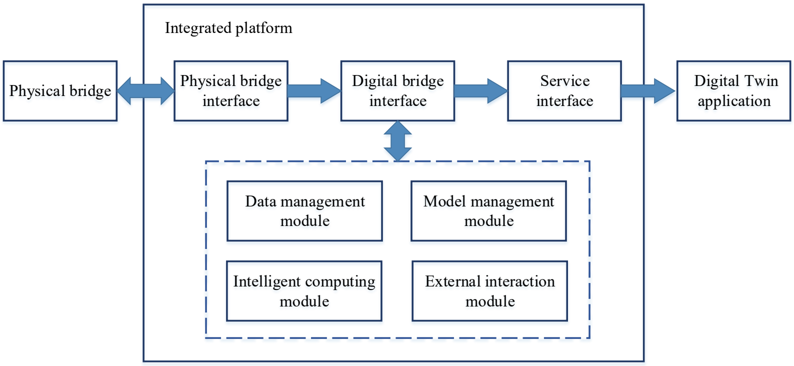
The Digital Twin Bridge model is data-driven. It perceives bridge information through IoT devices and transmits it in real-time to an integrated platform, driving the dynamic updating of the twin model. This model is then compared with the physical bridge to comprehensively assess its accuracy and authenticity, and continuously correct errors until it fully aligns with the actual operating state of the physical bridge. Through iterative refinement, the dynamic updating and optimization of the twin model are realized.

### *6.4 Integrated platform design*

The design of an integrated platform allows for the connection of various functional modules within the Digital Twin Bridge system, enabling the encapsulation of Digital Twin components into services for user management and utilization. The design of the integrated platform comprises two main parts: platform interface design and functional module design, as illustrated in Figure 4.

Platform Interface Design includes the design of physical entity interaction interfaces, twin model interaction interfaces, and service interfaces oriented toward twin system applications. The physical entity interaction interface refers to the interface for real-time state data acquisition from the physical bridge and the interface for transmitting commands to the physical entity. This serves as the pivotal link enabling mutual mapping and interaction between the digital model and the physical entity. The twin model interaction interface is one of the most critical interfaces within the integrated platform, connecting with the main functional modules of the twin system. It empowers the digital bridge through the software and hardware support provided by various modules, ensuring the stable and efficient operation of the twin system. The service interface corresponds to various twin applications, which are facilitated by summarizing and organizing key elements of core business operations and using the platform engine to obscure certain technical details, thereby enabling the flexible application of the twin system.

Functional Module Design represents the core component of the integrated platform, consisting of the data management module, model management module, intelligent computing module, and external interaction module. The data management module handles data storage, scheduling, and intelligent monitoring of databases, ensuring the stable and



**Source(s):** Authors' own work

**Figure 4.** Design of digital twin bridge integration platform

efficient operation of the Digital Twin Bridge system. The model management module abstracts the information model of the actual physical bridge, including the management and control logic of the physical entity's operational processes, and is the most critical element within the Digital Twin system. The intelligent computing module drives the Digital Twin, providing computational power support through cloud, fog, and edge computing for Digital Twin applications. The external interaction module refers to external software and hardware, including finite element analysis, which adds or extends new capabilities to the twin system.

## 7. Prospects for the application of the digital twin bridge system in the Beijing-Shanghai high-speed railway

### *7.1 Full life cycle management*

The Digital Twin Bridge system enables comprehensive lifecycle management of bridge facilities. This includes:

(1) *System management:* covering aspects such as authority management, personnel management, and event management;

(2) *Equipment management:* involving status monitoring, fault early warning, and equipment maintenance;

(3) *Model management:* including data collection, model visualization, and condition assessment.

See Figure 5.

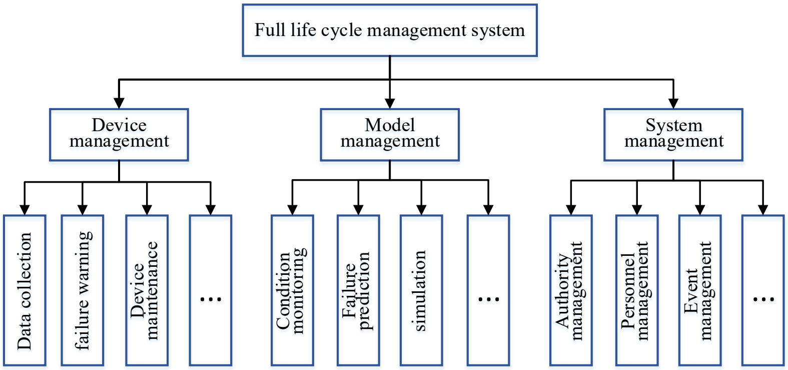
### *7.2 Fault prediction*

The Digital Twin Bridge system facilitates fault prediction for real-world bridge facilities. This encompasses:

(1) Bridge Lifespan and Condition Assessment;

(2) *Gradual fault prediction:* addressing issues such as surface cracks, bearing displacements, and bridge body settlement;

(3) *Sudden fault warning:* including warnings for structural damage and bridge deck subsidence.



**Source(s):** Authors' own work

**Figure 5.** Full life cycle management system

Initially, various bridge monitoring data are uploaded to the central platform and linked to the twin model. Based on historical data and typical analysis algorithms, models for bridge condition assessment and fault feature extraction are trained. To ensure the realism of scenarios and the reliability of predictive results, environmental variables and control variables are incorporated. This process enables the evaluation of bridge lifespan and the prediction of gradual or sudden faults, with the results being promptly fed back to inform necessary measures, ensuring the safety and stability of bridge facilities. In addition, the maintenance plan can be automatically given according to the fault type of the bridge. In the future, automatic equipment can be used to automatically repair the fault point of the bridge, and the bridge status can be feedback based on real-time data, so as to realize the interactive feedback between the twin model and the physical entity. See Figure 6.

### *7.3 Status monitoring*

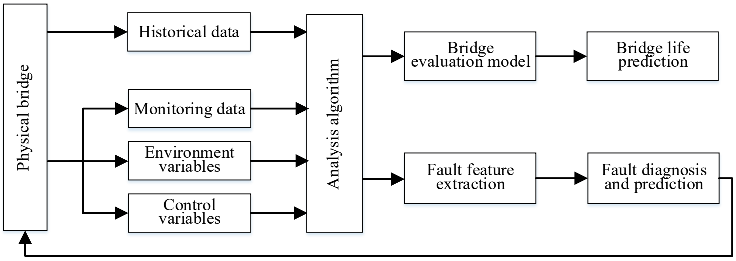
The Digital Twin Bridge system allows for real-time status monitoring of bridge facilities, including:

1. *Bridge facility monitoring:* such as rotation, deflection, and displacement;
2. *Track facility monitoring:* involving components like fasteners, track gauge, and catenary;
3. *Train facility monitoring:* covering aspects such as pressure, speed, and position;
4. *Environmental monitoring:* including meteorological, hydrological, and geological conditions.

Initially, various monitoring data from the bridge and track are uploaded to the central platform and linked to the twin model. Based on evaluation models and historical data, the system assesses the safety status of the bridge. Combined with real-time data on train operations and environmental conditions, the system comprehensively evaluates the impact of train passage on the bridge, including effects on vibration and impact levels. It then calculates parameters such as the optimal train speed range and bridge safety coefficients, which are promptly fed back to ensure the safety and stability of the bridge facilities during train operations. This entire process is simulated within the twin system. To ensure timely responses, edge computing nodes can be established in station segments with the necessary conditions, providing low-latency, fast-response Digital Twin services. See Figure 7.

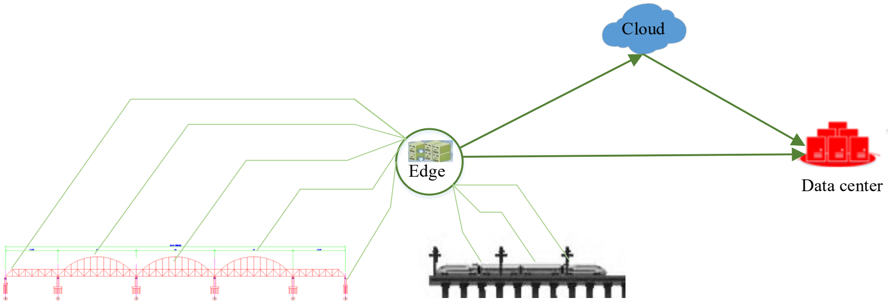
## 8. Conclusion

Digital Twin technology maps the attributes, conditions, structure, and behavior of the physical world to a virtual environment. By integrating with various railway business domains, it offers new technological methods for accurate understanding, prediction, control,



**Source(s):** Authors' own work

**Figure 6.** Digital twin bridge failure prediction



**Source(s):** Authors' own work

**Figure 7.** Full life cycle management system

and guidance of railway operations. Particularly in the intelligent operation and maintenance of high-speed railways, Digital Twins enable detailed simulation analysis and predictive calculations of infrastructure, facilitating comprehensive data analysis and decision-making support. This significantly enhances the intelligence level of high-speed railway operation management, contributing to cost reduction, efficiency improvement, and quality enhancement. The construction plan for the Digital Twin Bridge system outlined in this paper requires further optimization of the model algorithms and system construction processes. Moreover, systematic validation should be conducted to bridge the gap between the theoretical framework and engineering practice.

## References

Chen, Y., & Xiao, Z. (2021). Digital twin technology and its application in petrochemical industry. *Natural Gas Chemical Industry*, *46*(2), 25–30.

Chen, R., Li, J., & Ma, Y. (2022). Practice of mingzhu Bay smart city information platform construction based on digital twin technology. *Land and Resources Information Technology*, 2, 63–68.

Fu, Y., Cao, H., & Gao, W. (2021). Digital twin driven remaining useful life prediction for aero-engine turbine discs. *Chinese Journal of Mechanical Engineering*, *57*(22), 106–113.

Gu, M., Chen, X., & Liu, G. (2021). Research and application of enterprise digital twin system based on Cloud+Side+End. *China Instrument*, *9*, 19–25.

Jiang, Y., Shen, X., & Lv, H. (2022). Construction and simulation of operation digital twin model for alkaline water electrolyzer. *Journal of Electrotechnolo*, *37*(11), 2897–2908.

Jing, Q., Shen, H., & Yin, Y. (2019). A ship digital twin framework based on virtual reality system. *Journal of Beijing Jiaotong University*, *44*(5), 117–124.

Li, H., Tao, F., & Wang, H. (2019). Integration framework and key technologies of complex product design-manufacturing based on digital twin. *Computer Integrated Manufacturing Systems*, *25* (6), 1320–1336.

Li, P., Zhang, X., & Guo, Y. (2020). Blockchain technology and its typical application in railway industry. *Railway Computer Applications*, *29*(1), 9–15.

Liu, D., Guo, K., & Wang, B. (2018). Summary and perspective survey on digital twin technology. *Journal of Instrumentation*, *39*(11), 1–10.

Liu, W., Tao, F., & Cheng, J. (2020). Digital twin satellite: Concept, key technologies and applications. *Computer Integrated Manufacturing Systems*, *26*(3), 565–588.

Liu, Y., Chen, S., & Cong, Z. (2021). Key technology and application prospect of digital twin in power equipment industry. *High Voltage Technology*, *47*(5), 1539–1554.

Lu, J., Zhang, H., & Zhao, R. (2021). *Concepts, Practice and application of digital twin technology in water conservancy engineering*. Machinery Industry Press.

Luo, B., Zhou, C., & Zhang, Z. (2024). Key technology and application of digital twin platform of water conservancy business models. *Yangtze River*, *55*(6), 227–233.

Ma, R., Yin, T., & Li, H. (2021). Basic structure and characteristics of dam mechanism-data-driven fusion models. *Journal of Hydro Electric Power*, *41*(5), 59–74.

Meng, S., Ye, Y., & Yang, Q. (2020). Digital twin and its aerospace applications. *Acta Aeronautica et Astronautica Sinica*, *41*(9), 1–12.

Nie, R., Zhou, X., & Xiao, J. (2022). Analysis and perspective on digital twin technology. *Aerospace General Technology*, *6*(01), 1–6.

Ning, Z., Liu, X., & Wang, S. (2022). A digital twin modeling approach for aerospace control systems with mechanism and data fusion. *Aerospace Control and Application*, *48*(2), 1–7.

Shen, C., Cao, Q., & Jia, M. (2022). Concepts, characteristics and prospects of application of digital twin in power system. *Proceedings of the Chinese Society for Electrical Engineering*, *42*(2), 487–498.

Su, D., Xie, J., & Jia, W. (2021). Research on data management method of transmission line based on digital twin. *Modern Scientific Instruments*, *38*(5), 199–203.

Sun, X., Liu, S., & Shen, X. (2022). Digital twin-driven intelligent assembly method for high precision products. *Computer Integrated Manufacturing Systems*, *6*, 1704–1716.

Tao, F., Cheng, Y., & Cheng, J. (2017). Theories and technologies for cyber-physical fusion in digital twin shop-floor. *Computer Integrated Manufacturing Systems*, *23*(8), 1603–1611.

Tao, F., Liu, W., & Liu, J. (2018). Digital twin and its potential application exploration. *Computer Integrated Manufacturing Systems*, *24*(1), 1–18.

Tao, F., Liu, W., Zhang, M., & Hu, T. (2019). Five-dimension digital twin model and its ten applications. *Journal of Computer Integrated Manufacturing Systems*, *25*(01), 1–18.

Tao, F., Ma, X., & Hu, T. (2019). Research on digital twin standard system. *Computer Integrated Manufacturing Systems*, *25*(10), 2405–2418.

Tao, F., Zhang, H., & Qi, Q. (2021). Theory of digital twin modeling and its application. *Computer Integrated Manufacturing Systems*, *27*(1), 1–15.

Wang, T., He, H., & Tian, H. (2020). *Intelligent high-speed railway strategy research*. China Railway Publishing House.

Wang, C., Dong, B., & Yu, H. (2021). Digital twin technology and its application in the integrated energy system of smart city. *Proceedings of the CSEE*, *41*(5), 1597–1607.

Wang, Z., Gai, S., & Cui, Y. (2021). Research of smart agriculture system based on digital twin and block-chain. *Journal of the Hebei Academy of Sciences*, *38*(1), 66–73.

Wang, K., Hao, R., & Lu, W. (2021). Research status and perspective of BIM-based digital twin railway engineering. *Railway Technology Innovation*, *4*, 45–51.

Wei, G., Ding, G., & Jiao, Y. (2023). Multi-sensing node convolution fusion identity recognition algorithm for radio digital twin. *Journal of Communications*, *44*(11), 13–24.

Yang, S., Sun, Y., & Xiang, X. (2020). Ship digital twin and A review of life-cycle service. *Ship Science and Technology*, *42*(11), 1–8.

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