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ORIGINAL ARTICLE

Digital twin and its applications: A survey

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Abstract
Digital twin is a technology that integrates multi-physical, multi-scale, and multi-disciplinary attributes. At the same time, it has the characteristics of real-time synchronization, faithful mapping, and high fidelity. It can realize the interaction and integration of physical world and information world. In recent years, digital twin technology has attracted the attention of academic and business circles, especially its application. Based on this background, this paper summarizes the concept and evolution of digital twin, studies the application tools and platforms of digital twin, and discusses the relationship between digital twin and related technologies. Then we focus on the application scenarios of digital twin, and summarize the new trends and requirements of digital twin application. The purpose of this paper is to provide reference for the practice of digital twin concept and technology in related fields in the future.

Keywords Digital twin · Application · Tools and platforms

1 Introduction

Recently, many countries around the world have issued their own advanced manufacturing development strategies in order to realize intelligent manufacturing, which integrates cloud computing, Internet of Things (IoT), and big data. Some examples include industrial Internet in the USA [1], and industrial 4.0 in Germany [2], as well as "made in China 2025" and "Internet + " in China [3]. To reach this goal, digital twin has been introduced as one of the most promising technologies, which is good at realizing interactive integration of the physical world and the information world of manufacturing [4]. Gartner, the most authoritative IT research and consulting company in the world, ranked digital twin as one of the top ten strategic development technologies in 2016 and 2017 [5]. Lockheed Martin, the world's largest arms manufacturer, also ranked digital twin as the no. 1 of the six top technologies in the future defense and aerospace industry in November 2017 [6]. On December 8, 2017, the Intelligent Manufacturing Alliance of CAST Member Societies listed digital twin as one of the top ten scientific and technological advances in intelligent manufacturing in the world [7].

Because of its great development potential, digital twin technology has attracted more and more attention from both industry and academia. In recent years, several works related to reviewing digital twin technology have been published in the literature, which summarized basic concepts, technical connotations, and development trends. All these works can be classified into three categories: the first is to review theoretical research progress of digital twin technology and its basic concepts, structures, and characteristics [8, 9, 10]; the second is to summarize the investigation of digital twin and its application fields, focusing on guiding the development and application of digital twin in today's academic and industrial environment [11, 12, 13]; and the third is to put forward a new concept of "digital twin workshop" and review the related applications of digital twin technology around this concept [14, 15].

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Different from all these existing works, in this paper, we (i) discuss the concept of digital twin and its evolution process, (ii) emphasize the advantages of digital twin compared with the existing technology, (iii) aim to investigate the specific implementation of digital twin application platform, and (iv) assess the realization possibility in the future so as to propose new trends and new needs. On this basis, this paper summarizes the applicability of digital twin in the main application scenarios, as well as the difficulties and challenges faced.

A set of general questions that this article raises for investigation include the following:

1 How was the digital twin proposed? How did it evolve? What are its applicable criteria? These topics will be presented and discussed in Section 2.
2 Are there any commercial tools and platforms to support the construction and application of digital twin? What problems need to be solved? These topics will be dealt with in Section 3.
3 What are the current technologies related to digital twin? What do they have to do with digital twin? The reader will find these topics in Section 4.
4 How is digital twin applied in real environment? What are the ways to use it? What are the important practical benefits of using digital twin's features? These matters are analyzed in Section 5.
5 Based on the practical application cases of digital twin, what are the new trends and requirements for the development and application of digital twin in the future? These themes are presented in Section 6.

2 The evolution and applicable criteria of the digital twin technology

Digital twin technology is also known as digital image and digital mapping. It uses data to simulate the behavior of physical entities in the real environment, so as to increase or expand the ability of physical entities through virtual real interaction feedback, data fusion analysis, decision iteration optimization, and other means. It can further describe the fusion state between physical world and information space, which is suitable for application optimization of practical engineering and can effectively deal with complex and changeable engineering construction problems [16]. Digital twin plays a role of bridge or link between the physical world and the information world in the whole life cycle of products, and provides more real-time, efficient, and intelligent services to the production process [17, 18, 19].

2.1 The evolution of the digital twin technology

A timeline on the development of digital twin technology is shown in Fig. 1. In 2002, Professor Michael Grieve proposed the concept of "virtual digital expression equivalent to physical products" in the course of "product life cycle management" at the University of Michigan, and gave the definition "one or a group of digital copies of a specific device can abstract the real device and can be tested under real or simulated conditions" [20]. This concept was further called "mirrored spaced model" in 2003–2005 and "information mirroring model" in 2006–2010. Although this concept in

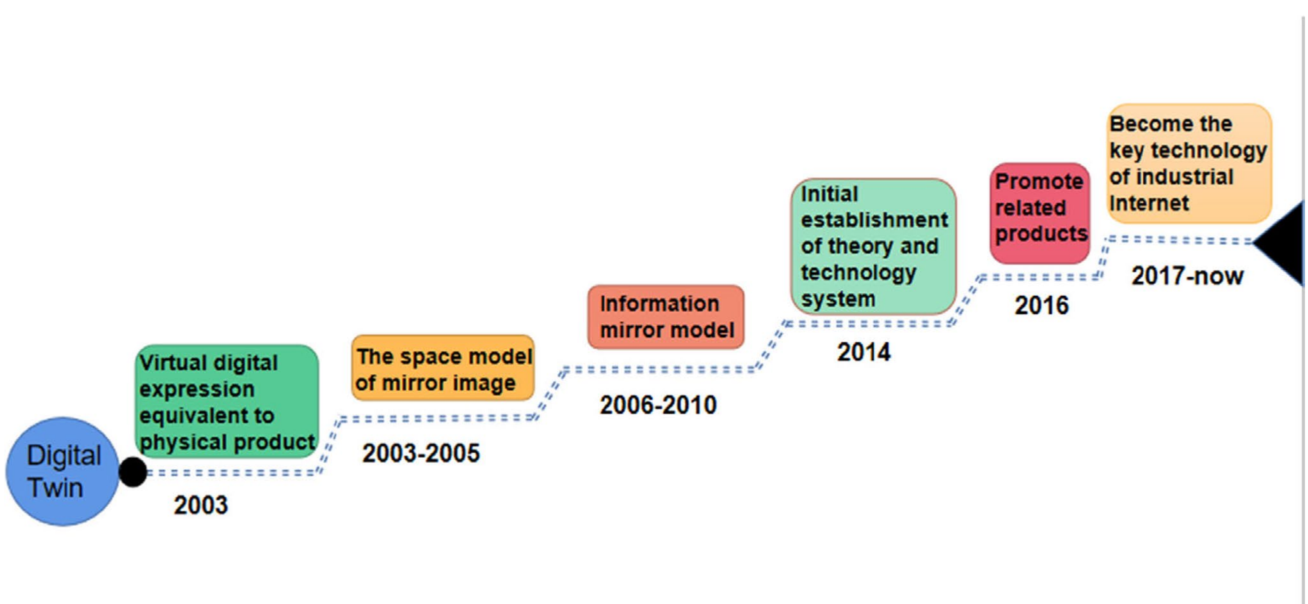

Fig. 1 Digital twin development process

fact is not "digital twin," both of them share some common constituent elements, such as virtual space, physical space, and interface between them. In 2011, Professor Michael Grieve said in his book "virtual perfect model of Intelligent Manufacturing: driving innovation and Lean products" that digital twin is composed of three parts: physical products in the physical world, virtual models in the virtual space, and data interface between physical world and virtual space [21]. In 2012, the National Aeronautics and Space Administration released the road map of "modeling, simulation, information technology and processing," and the concept of digital twin officially entered the public view. In 2013, the U.S. Air Force's science and technology planning document, Global Horizon, defined digital twins as a "game changing" technology. In 2014, Boeing, GE, and other companies launched a series of application research projects focusing on digital twin, and established theory and technology system for digital twin. Later, they turned this military technology into civilian use, and used "digital twin supply system" in asset management business and construction of industrial Internet. At the 2016 Siemens Industry Forum, Siemens expanded the concept of digital twin to consist of digital twin of products, digital twin of production process, and digital twin of equipment so that digital twin could reproduce the whole enterprise comprehensively and accurately. In [22], the authors gave the composition of digital twin from the perspective of product, which mainly included product design data, product process data, product manufacturing data, product service data, product retirement, and scrap data. Some other researchers proposed the composition of digital twin from the perspective of production, which included product design, process planning, production layout, process simulation, output optimization [23], to be more comprehensive and more in line with the requirements of intelligent factory. Besides, the composition of digital twin was also addressed from the perspective of workshop composition, which mainly included physical workshop, virtual workshop, workshop service system, and workshop twin data. The physical workshop is a real workshop, which mainly receives production tasks from the workshop service system and performs the tasks according to the execution strategy optimized by virtual workshop simulation. Virtual workshop is the equivalent mapping of logistics workshop, which is mainly responsible for simulation analysis and optimization of production activities, real-time monitoring, and prediction and adjustment of production activities in physical workshop. Workshop service system is the general name of all kinds of software systems in the workshop, which is mainly responsible for the operation of digital twin driving physical workshop and receiving production feedback from the physical workshop [24, 25]. Since 2017, digital twin has developed from a new management paradigm for industrial production process to a key technology of industrial Internet.

2.2 The applicable criteria of the digital twin technology

Not all objects and enterprises are suitable for the application of digital twin technology, which should be determined by integrating the product type, complexity, operating environment, performance, economic and social benefits, and other different dimensions of the enterprise. In order to assist enterprises to make correct decisions according to their own conditions, this section attempts to summarize the applicable principles of digital twin from different dimensions:

- Product

  Digital twin is applicable to the production of asset intensive and high-end products with high single value, such as wind turbines, nuclear power equipment in the energy field, CNC machine tools in the manufacturing field, and helicopters and automobiles in the transportation field. In the process of product production, digital twin is based on the multi-dimensional, multi-time, and multi-scale model that truly depicts physical products and the twin data of the whole life cycle, so as to carry out product design optimization, intelligent production, and reliable operation and maintenance.
- Complexity

  Digital twin is applicable to complex products, processes and demands. Complex processes such as discrete dynamic manufacturing processes and complex manufacturing processes, complex demands such as rapid personalized design requirements of complex production lines, complex systems such as ecosystems and satellite communication networks, and complex products such as 3D printers and aeroengines. Digital twin supports the reconstruction of complex products, processes, and demands in the time and space dimensions, and supports the reconstruction of key nodes. Simulation, analysis, verification, and performance prediction are carried out in this link.
- Operating environment

  Digital twin is applicable to extreme operating environment, extremely high or deep environment such as high-altitude flight environment, extremely hot or cold environment such as high-temperature cracking furnace environment, extremely large or extremely small scale such as ultra large steel ingot extreme manufacturing environment, micron and nano precision processing environment, and extremely dangerous environment such as nuclear radiation environment. Digital twin supports independent perception of operating environment, real-time visualization of operating state, multi-scale simulation of multi granularity and multi-scale, and real-time interaction between virtual and real.

- Performance
  Digital twin is applicable to instruments and systems with high precision, high stability, and high reliability, such as precision optical instruments and precision assembly process, high stability such as power grid system and oil and gas pipeline, and high reliability such as railway operation and industrial robots. Digital twin provides real-time performance evaluation, fault prediction, control and optimization decision-making for its installation, commissioning, and operation.
- Economic performance
  Digital twin is applicable to industries that need to reduce input–output ratio, automobile manufacturing in manufacturing industry, warehouse storage and logistics system in logistics and transportation industry, steel smelting in metallurgical industry, and crop health monitoring in agriculture and animal husbandry. Digital twin supports information sharing and enterprise collaboration in the industry, so as to realize the optimal allocation and lean management of industry resources and improve quality and efficiency.

3 Means and platform to realize digital twin

3.1 Technology

With the rapid development of digital twin technology, specific tools and platforms are needed for its applications. In general, these tools and platforms can be classified into four categories: modeling, simulation, operation, and interaction, as shown in Fig. 2. The modeling platforms include SolidWorks, 3D Studio MAX, and AutoCAD, which provide various graphics and image data exchange formats and corresponding commands [26]. The simulation platforms include Simulink of MATLAB, twin build of ANSYS, Azure of Microsoft, 3D experience of Dassault, and Teamcenter, which contain data and simulation model related to physical objects [27]. The operation platforms include plant simulation, Eclipse ditto, Watson IoT, IBM, etc. [28]. Plant simulation can verify the layout of workshop; Eclipse ditto can liberate IoT solutions from the requirements of implementing and operating custom back-end; both Watson IoT and IBM can combine various digital threads and data streams to create multiple views of the product. The interactive platforms include unity3D [29], which can create various types of interactive content, and predix [30], which can provide Physical model.

Note that although there exist many commercial tools and platforms that can facilitate the construction and application of digital twin, from the perspective of functionality, most of them focus on one or some specific dimensions, and are difficult in interaction, integration, and compatibility. In the future, how to realize the assembly and integration of different digital twins provided by different users for constructing complex products, systems, and processes will become a new challenge. In addition, different from product developers or providers who master the specific data, process, technology, and principle, it is very difficult for the third parties (such as product end users, product operation, and maintenance personnel) in the construction of digital twin. This requests the support from commercial tools and platforms to provide comprehensive functions and strong integration. The existing technologies in related fields are inextricably related to digital twin. In order to have tools and platforms for building digital twin with complex processes in the future, it is necessary to study the relationship between digital twin and related technologies.

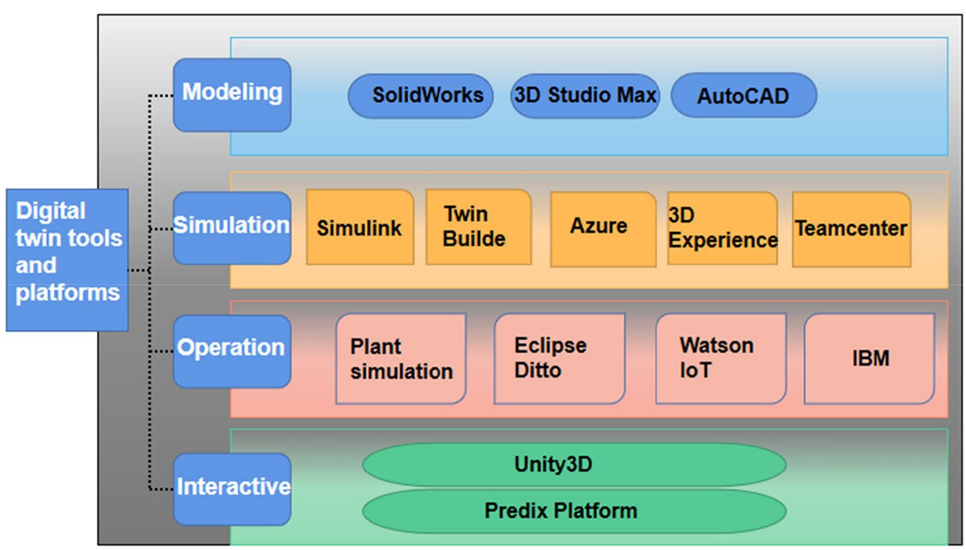

Fig. 2 Digital twin tools and platforms

4 The relationship between digital twin and CAD/PLM/industrial Internet/CPS

Digital twin is a technology that integrates sensing, networking, big data analytics, artificial intelligence, control, and modeling. In order to better understand this new concept, this section makes a brief comparison between the digital twin and other related technologies used in traditional industrial design, manufacturing, and service, such as CAD, product life cycle management (PLM), industrial Internet, cyber physical system (CPS), and industrial software/industrial APP. The relationship between digital twin and these related technologies is shown in Fig. 3:

- CAD is a static two-dimensional or three-dimensional mathematical modeling technology, while digital twin is a dynamic three-dimensional model based on high fidelity. A very important relationship between digital twin and CAD is data association. Moreover, digital twin is closely connected with physical entity, which is endowed with various attributes and functional definitions, including material, perception system, machine motion mechanism, etc. Because of this, digital twin can realize the association of assembly relationship data, manufacturing information data, functional performance data, health detection data, identity recognition data, and real-time detection data.
- PLM manages the design and manufacturing of a product, but the changes of engineering status in manufacturing cannot be fed back to the researchers and development designers. Related to PLM, digital twin can use PLM to manage the life cycle of products or devices and output files from PLM Software. When digital twin is used, the whole process of physical products (including loss and scrap) is presented digitally, which makes the concept of "whole life cycle" transparent, so that the automatic management of products becomes practical.
- Industrial Internet is a result of the integration of global industrial systems with advanced computing, analysis, sensing technology, and Internet connectivity. It has the ability of data acquisition and exchange for various physical entities, and can place data transmission and storage on the edge or cloud. Since the core of digital twin is model and data, and needs interconnection to realize the interaction of information instructions, industrial Internet provides a feasible solution, which makes digital twin become a dynamic model with vitality.
- CPS is a multi-dimensional complex system integrating computing, network, and physical environment. Digital twin shares some common features with CPS in the state monitoring and control of physical entities. However, CPS takes process as the core, while digital twin takes assets as the core.
- Industrial software is the substantiation of knowledge and experience in the process of product development, and is the source support of the service-oriented feature of industrial APP. Industrial app can analyze a large number of industrial data, and then form the evaluation result feedback and store it in the digital twin, so that the product and production mode can be optimized.

In short, digital twin is the rebirth of CAD model and the new substitute of physical prototype. Along with the digital twin, PLM can really become a reality. Digital twin is an important scene of industrial Internet, which has the characteristics of "virtual and real synchronization, integrating

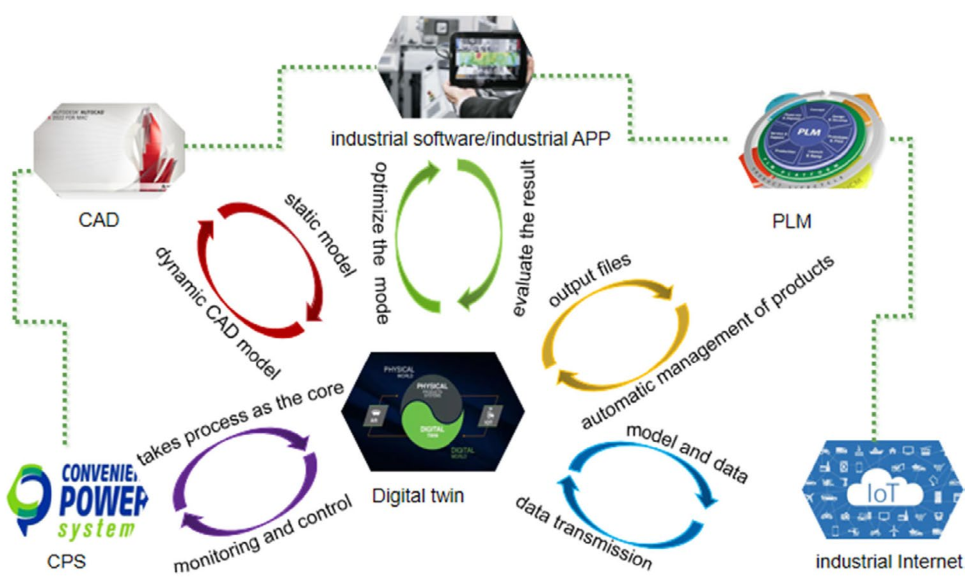

Fig. 3 The relationship between digital twin and related technology

virtual with real, controlling real with virtual," and it is an effective support for the industrial Internet platform to connect the soft and hard links. Digital twin is the foundation for building CPS and the necessary stage of CPS development. It realizes the feedback from the real physical system to the digital model, and can actually ensure the coordination between the digital and the physical world in the whole life cycle of products. Digital twin is an important embodiment of industrial software/industrial APP. The emergence of digital twin is a new technological breakthrough in the field of traditional industrial design, manufacturing, and service. It is expected to bring a new round of technological innovation in these fields.

5 Research on digital twin technology in intelligent manufacturing field and its application potential in other fields

Reconstructing the physical world through digital twin technology has been applied in many fields, from the early aerospace military industry to the broader civil field, from large-scale equipment manufacturing to consumer goods manufacturing. Digital twin technology has shown great application potential, especially in the field of intelligent manufacturing. Figure 4 summarizes some main application scenarios of digital twin technology. In this section, the theoretical research and practical application of digital twin technology in the field of intelligent manufacturing will be discussed in detail, and its application potential in the fields of electric power, medical treatment, urban management, and agriculture will be summarized.

5.1 The theoretical research of digital twin in intelligent manufacturing

Digital twin is a technology that makes full use of model, data, and intelligence and integrates multiple disciplines. It can provide more real-time and intelligent services in the application process of intelligent manufacturing. Therefore, it has become a hotspot of academic research. Among them, Boschert published the first paper on the application of digital twin technology in intelligent manufacturing industry, which opened the foundation of theoretical research by applying digital twin technology to intelligent manufacturing industry, and preliminarily gave the basic workflow of digital twin simulation modeling [31]. In order to develop a new mode of digital industrial manufacturing, Siemens designed and manufactured a small industrial control computer nanobox PC using digital twin technology [32]. Lu [33] analyzed the connotation, application scenarios, and research issues of digital twin–driven intelligent manufacturing under the background of industry 4.0. This paper summarized the definition of digital twins and the latest development results. Zhou [34] proposed the overall framework of digital twin manufacturing cell, providing a realistic perspective for the research of intelligent manufacturing paradigm. Tao [35, 36] summarized the concept of big data and digital twin in manufacturing industry and its application in product design, production planning, manufacturing, and predictive maintenance. On this basis, the similarities and

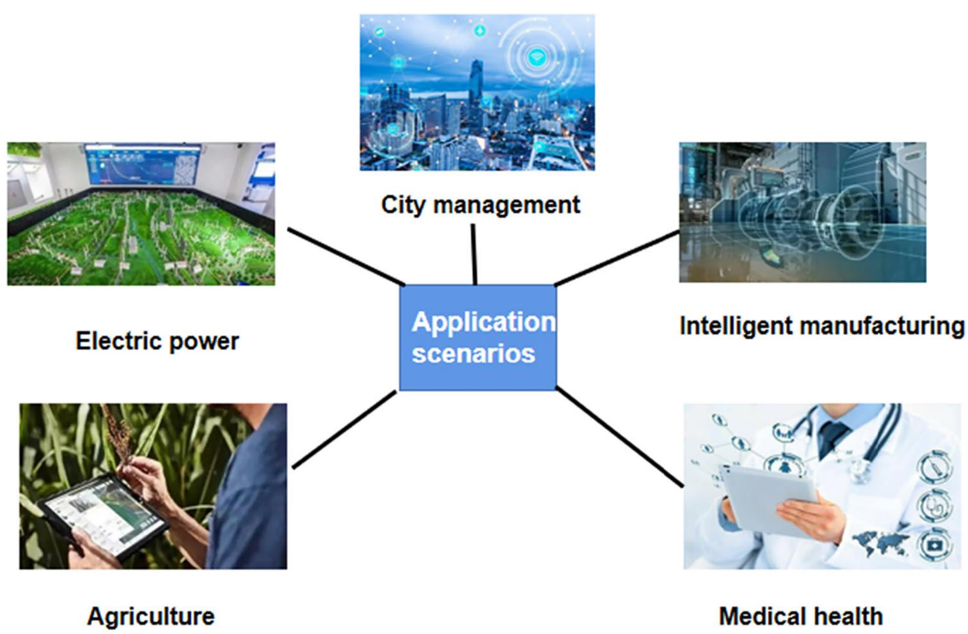

Fig. 4 Digital twin main application scenario

differences between big data and digital twin are compared from the overall and data perspectives, and the composition and operation mechanism of DTS are designed. The four characteristics and five major key technologies of realizing DTS are expounded, which provides basic theoretical support and reference for the implementation and application of digital twin in production and manufacturing.

5.2 The practical application research of digital twin in intelligent

5.2.1 Manufacturing

The advantages of digital twin in the manufacturing industry are remarkable. There is a saying in the industrial circles that "1% revolution in the industrial field, the global industrial production efficiency is increased by 1% and the cost is reduced by 30 billion." Digital twin can greatly improve the understanding, control, and prediction of mechanical equipment and processes through the real-time understanding of target perception data and the prediction and analysis of empirical models. Intelligent manufacturing generally includes three aspects: (i) intelligence of products and equipment, (ii) intelligence of production process, and (iii) intelligence of service. Therefore, intelligent manufacturing is commonly referred to as the general name of advanced manufacturing processes, systems, and modes based on the new generation of information technology, which run through all links of manufacturing activities such as design, production, management, and service, and have the functions of deep self-perception of information, intelligent optimization, self-decision-making, accurate control, and self-execution.

Although intelligent manufacturing equipment industry has made some development in recent ten years, it is still relatively weak, and there are challenges in key basic intelligent technology, design, and integration ability. It is mainly reflected in the weak digital foundation, which is in the transition stage from mechanical automation to digital automation; the enterprise system integration ability is relatively weak, the quality and level are not high, and there is a lack of personalized customization, intelligent manufacturing, productive services, etc. The use of digital twin technology can improve the efficiency of design, operation, control, and management in the field of Intelligent Manufacturing in three aspects: product life cycle optimization, control of whole production process management, control and product/production line/logistics simulation.

Product life cycle optimization The product life cycle consists of seven parts: product strategy, product market, product demand, product planning, product development, product listing, and product market. Optimizing the product life cycle will help to improve the production efficiency of the manufacturing industry. Through design tools, simulation tools, Internet of things, and other means, digital twin maps various attributes of physical equipment into virtual space to form a detachable, reproducible, modifiable, and erasable digital image, which improves the operator's understanding of physical entities. This will make production more convenient and shorten the production cycle. From the perspective of digital design and related technologies, the digital twin technology can be introduced into the existing intelligent product design framework [25, 37]. By using the digital twin intelligent task planning method, the required work can be completed while meeting the production requirements. By building a digital twin model with scalability, interoperability, and fidelity attributes, the reference model is transformed, combined, decomposed, and evaluated in the product life cycle [38, 39], which can reduce the workload of using simulation technology in the whole life cycle of complex technology system.

Control of workshop production process The control of workshop production process aims to avoid all possible waste during this process in order to achieve the goal of zero switching waste, zero inventory, and zero defect. In reality, it has to face challenges, such as serious waste of materials in the production process, widespread invalid labor, and poor production site environment. To address these challenges, the researchers applied the digital twin technology to the whole production process management and control, and realized the workshop management and control by combining the digital twin, enterprise information system, and existing information technology [40]. In addition, by synchronizing the digital model with the virtual and real of physical equipment, a digital twin system workshop can be formed [41, 42]. The modeling results are combined with the measurement data to build an iterative evolutionary model structure [43, 44] for the performance evaluation and adjustment of the workshop, so as to realize the control of the production process.

Simulation of product/production line/logistics Simulation is an indispensable tool in the process of product design and manufacturing. It plays a great role in reducing losses, saving funds, shortening development cycle, and improving product quality. Complex product/production line/logistics system faces corresponding challenges in simulation modeling, simulation operation, evaluation analysis, and decision support. Digital twin supports system manufacturing, understanding, prediction, and optimization through intelligent perception and simulation. Digital twin technology is used to create digital copies of components, equipment, and systems. Through virtual verification and optimization in virtual space, the operation efficiency of real scenes can be improved [32, 45]. In addition, building a digital twin network model through blockchain technology can simulate and realize product data management [38, 39].

In summary, in the field of intelligent manufacturing, the use of digital twin technology will greatly promote the reform of product design, production, maintenance, and repair. At present, the main problem is that the functional units of evaluation objects in the process of product boundary definition and target determination cannot be accurately confirmed. In addition, it is very difficult to solve the multi-objective optimization problem of product life cycle. At present, the major difficulty in applying digital twin technology to the whole production process management and control of workshop is that the actual workshop managers lack comprehensive, full-scale, and unified decision support technology and tools. Moreover, traditional workshop data integration and product data integration lack relevant fusion technology, which cannot provide data governance services combining digital twin technology. For applying digital twin to product/production line/logistics simulation, the simulation experiment needs technicians to have a more in-depth and clear understanding of the theoretical mechanism, and at the same time, it cannot be too idealistic to put aside the actual situation. Therefore, in the application process of digital twin, it is difficult to start the work when the simulated data is difficult to be measured. These problems will be the research hotspots of digital twin applied in intelligent manufacturing field in the future. Table 1 lists the current application cases of digital twins in the field of intelligent manufacturing.

5.3 The application potential of digital twin in other fields

With the gradual appearance of the application value of digital twin, in addition to being widely concerned in the field of intelligent manufacturing, digital twin technology has also received attention and application practice from the electric power, medical and health, urban management, and agricultural industries.

In the application of electric power, digital twin is the most promising enabling technology to realize smart grid. Digital twin technology can be combined with deep learning technology to realize real-time maintenance and feedback closed-loop operation after analyzing and processing the characteristic data based on the operation data and equipment status of power equipment [40]. The digital twin of power system is a new product under the joint action of multiple backgrounds of data science. It can build the data model of power system and has good applicability to meet the needs of the development of the times [41]. Table 2 lists the current application cases of digital twins in the field of power system.

Table 1 Application of digital twin in intelligent manufacturing

Product life cycle optimization based on digital twin	(1) A new DT-driven intelligent product design (DTPD) framework [25]
	(2) A new PLM paradigm for multi-life cycle remanufacturing process [37]
	(3) An intelligent task planning method based on digital twin method [38]
	(4) A new type of "testable digital twin" was produced by combining virtual test bench and digital twin [39]
Whole process management and control of workshop-oriented production driven by digital twin	(1) A workshop management and control system by combining digital twin, enterprise information system and existing information technology [40]
	(2) A digital twin method to measure and reduce the residual strain in the manufacturing process [41]
	(3) An architecture based on digital twins for the workshop of flow intelligent manufacturing system in the Industrial 4.0 environment [42]
	(4) A new digital twin workshop driving method for rapid reconfiguration of automated manufacturing system [43]
	(5) An assembly workshop as the research object based on digital twin method [44]
Simulation of product/production line/logistics based on digital twin	(1) PickMaster Twin to test the robot configuration on the virtual production line [32]
	(2) A "digital twin" program to encourage small and medium-sized contractors [45]
	(3) A digital twin peer-to-peer network realized product data management through simulation [38]
	(4) A digital twin simulation method of naval ships [39]

Table 2 Application of digital twin in power field

Intelligent inspection	An accurate digital model of an electrical network for modeling, optimization, and control [40]
Load forecasting and user behavior analysis	A framework of power grid digital twin for computing the output of the network [41]

In the field of medical and health, digital twin technology provides a conceptual framework to analyze emerging data-driven healthcare practices and is helpful to solve the current problems in the development of medical field in terms of hospital navigation and equipment management, hospital operation simulation, and health treatment. Digital twin has broken through the limitations on the development of the medical field at both technology and mechanism levels. In the medical field, digital twin will become a new platform and experimental means for personal health management and health medical services. Table 3 lists the current application cases of digital twins in the medical field.

Smart city is a new direction developed on the basis of information port and digital city. The rapid development and change of information technology make the "smart city" face severe challenges in technology and platform selection. In the field of smart city, digital twin technology can accelerate the integration and application of information resources through data collection, and timely find and solve the problems of uneven data quality, data redundancy, data lack of value, and so on through quality management, and improve the government's public service level through accurate analysis. Digital twin will promote the construction of smart city in terms of comprehensive urban safety management, smart community construction, and smart traffic management. Digital twin city is the typical application of digital twin technology at the urban level, which can promote people-centered urban design and realize collaborative innovation in smart city construction. Table 4 lists the current application cases of digital twins in the field of smart city.

In the field of agriculture and animal husbandry, how to use big data, great wisdom, and big algorithm to establish a digital agriculture and animal husbandry system and how to transform the data into economic benefits, into a huge driving force for enterprise development, and into a benchmark and banner for industry development are the challenges faced by the development of agriculture and animal husbandry industry. As a multi-disciplinary technology that makes full use of model, data, intelligence, and integration, the application of digital twin in the field of agriculture and animal husbandry is divided into two aspects: agricultural management and animal husbandry management. In the field of agriculture and animal husbandry, digital twin is expected to become the core means of management, which may completely change agriculture. Table 5 lists the current application cases of digital twins in the field of agriculture and animal husbandry.

Table 3 Application of digital twin in medical and health field

Hospital navigation and equipment management based on digital twin	(1) A 3D model of the hospital can be built by digital twin technology [46]
	(2) A navigation route and itinerary planning can be customized in the digital world [47]
	(3) The emergency rescue flow line, infection control flow line, and barrier-free flow line can be planned by digital twin technology [48]
	(4) A BIM information model was built by digital twin [49]
Hospital operation simulation based on digital twin	(1) Digital twin technology combined with big data and VR system [50]
	(2) A new framework of hospital twin [51]
	(3) A digital hospital model established by digital twin [52]
	(4) A "continuous life cycle integration" method based on the concept of digital twin [53]
Health treatment based on digital twin	(1) Experts carry out visual consultation to various data and models [54]
	(2) Digital twin can build the operation procedure plan before operation [55]
	(3) Digital twin allows virtual experiment and clinical experiment of drugs on molecular cell level [56]
	(4) A method and algorithm to optimize the treatment of individual patients by extensive digital twin simulation [57]
	(5) A software framework called Smart Fit to monitor and manage athletes' fitness activities and results [58]
	(6) An artificial intelligence model to predict the response to treatment in early stages of critical illness [59]

Table 4 Application of digital twin in smart city

Comprehensive management of urban security based on digital twin	(1) A digital twin model of urban building [60]
	(2) A vision for a Disaster City Digital Twin paradigm [61]
	(3) The fire drill program can be developed based on the digital twin [62]
Smart community construction based on digital twin	(1) A digital twin information system to innovate and develop the service mode of education, employment, social security, pension, medical care, etc. [63]
	(2) A public and open digital twin of the Docklands are in Dublin, Ireland [64]
	(3) The methods and tools for a cognition-driven, personalized information system [65]
	(4) A digital twin city (DTC) model that integrates multimodal data (physiological sensing, visual sensing) on environmental demands in urban communities [66]
Intelligent traffic management based on digital twin	(1) The digital twin technology can identify and optimize the regional road conditions and plan the optimal navigation path for the ambulance [67]
	(2) A new network architecture, IDT-SDVN, by maximizing the advantages of SDVNs [68]

Table 5 Application of digital twin in the field of agriculture and animal husbandry

Agricultural management based on digital twin	(1) A method combining agent technology with machine learning to develop network physical system with digital twin plants [69]
	(2) A model to realize digital twin in sustainable agriculture to monitoring and optimization of agricultural food life cycle [70]
	(3) The virtual model for agriculture can digitally copy the real farm [71]
Animal husbandry management based on digital twin	(1) A management platform to put forward the digital twin in the field of animal husbandry [72]
	(2) A pig model to simulate the best breeding period of pigs by identifying shared data and simulating average feed consumption and weight gain [73]
	(3) A design concept of intelligent pig farm using digital twin technology to improve animal welfare [74]
	(4) A solution based on digital twin to remotely monitor the silo storage of livestock farms and optimize the supply route [75]

6 Future trends of digital twin

The application of digital twin technology in various fields is still a developing subject, and there are still many challenges waiting for solutions. With the continuous development of corresponding theories and technologies, the development and application of digital twin show new trends and new demands.

To meet the needs of intelligent interconnection The application foundation of digital twin is intelligent interconnection. Intelligent interconnection refers to two-way communication and closed-loop control between physical entities, virtual model data, and services. This is the cornerstone to realize the interaction and integration of virtual and real digital twins. At present, there are deficiencies in the application scope and accuracy of industrial interconnection methods. These deficiencies mainly including unstructured data generally do not have explicit attribute names, its entity attributes do not necessarily appear in structured data, and entity attributes in structured data do not necessarily find corresponding new entities in unstructured data. The key is that there is no effective solution to determine the similarity judgment threshold. Secondly, big data fusion is oriented towards cross language fusion, and there are few research results in this field. In view of the existing problems, some scholars began to study the real-time interconnection method for digital twin technology, such as interconnection between physical entities and virtual entities based on middleware [76], real-time communication and data exchange of information system based on Automation ML [77], industrial Internet for real-time collection and integration of multi-source heterogeneous data in intelligent manufacturing Hub [78] and remote interaction between field physical devices and models and users based on MT Connect [79], so as to meet the needs of industrial interconnection.

To meet the data requirements of physical information fusion Data is the core driving force of digital twin. Compared with traditional digital technology, digital twin emphasizes the fusion of information and physical data [80, 81]. At present, digital twin mainly relies on the data of information space for processing, simulation analysis, virtual verification, and operation decision-making. It lacks the consideration and support of sudden disturbance data and transient abnormal data, which may lead to the problem of "imitation but not truth." Although part of the current system has used information data and physical data at the same time, in the real implementation process, these two kinds of data are often isolated, and the consistency and synchronization of information physics are poor. This results in problems such as difficult interaction and deep fusion, poor real-time and accuracy of the results. How to realize digital twin physical information fusion is the trend of digital twin development in the future. Recent development in this field includes data-driven intelligent manufacturing [82], design system [83], operation and maintenance [84], simulation, and optimization [85], etc.

To meet the needs of deep integration with the latest technologies The deep integration of digital twin and the latest technology can realize the integration of information physical system, and then realize the integration of information physical data. The application of digital twin is inseparable from the support of virtual real interconnection technology, data storage and sharing technology, big data technology, and data fusion technology. The difficulty in realizing the integration with new technologies lies in the fact that the transmission interface and standard of the data network cannot be unified. Different buses themselves bring obstacles to the integration. Secondly, it is also faced with the problem that the definition of the connection port standard and format between the edge controller and the cloud cannot be unified. To solve these problems, the deep integration of digital twins and the latest technology can realize the integration of information physical systems, and then realize the integration of information physical data. At present, there are researches on the integration of digital twin and the latest technology, such as digital twin reference model based on information physical system [86], virtual reality fusion and interaction of digital twin driven by VR/AR [87], intelligent manufacturing mode driven by digital twin and big data fusion [88], and three-tier architecture of digital twin based on cloud, fog, and edge [89].

To meet the needs of dynamic multi-dimensional and multi-scale models Traditional digital modeling mainly focuses on the construction of geometric and physical dimensional models, but with the improvement of system functional complexity, the construction of models needs to be integrated from different dimensions, different spatial scales, and different time scales. Traditional technology cannot meet the needs of dynamic multi-dimensional multi-temporal and spatial scale model. To solve this problem, the digital twin technology research team of Beihang put forward the digital twin five-dimensional model, and studied the composition architecture [90] and application criteria of the digital twin five-dimensional model. These studies will provide a reference for the application of digital twin technology to build dynamic, multi-dimensional, and multi-temporal scale models.

To meet the needs of application expansion Digital twin was first applied in military industry and aerospace field, and gradually expanded to civil field in recent years, including intelligent manufacturing, electric power, automobile, medical, smart city, etc. It is expected that in the future, the application field of digital twin could be further expanded.

7 Conclusion

As an enabling technology and method to practice the advanced concepts of intelligent manufacturing, industry 4.0, industrial Internet, CPS, and smart city, digital twin is widely concerned by enterprises, research institutions, and researchers. At present, digital twin has been introduced into China for only a few years, and it is in the preliminary exploration and practice stage. There is still a long way to go before it is widely used. At present, there are still many problems in the application of digital twin technology: (i) digital twin needs high fidelity simulation modeling technology in the aspect of model construction. Digital twin is the hyper realistic dynamic model of physical entity in digital space. High precision of product virtual model, multi physical field modeling, and high fidelity response simulation are the primary technical problems to be solved. (ii) In the aspect of information physical data fusion, digital twin needs to be based on massive data of all elements and whole life cycle, and the technical problems related to advanced sensor technology, adaptive sensing, precise control, and execution need to be solved. (iii) Digital twin need analysis and decision-making to control physical products in terms of interaction and collaboration, and this process requires corresponding technical capabilities such as high real-time data interaction, high confidence simulation and prediction, and super computing power. This paper reviewed the concept and evolution of digital twin, and introduced the tools and platforms of digital twin. Moreover, this paper discussed the relationship between digital twin and related technologies, and introduced the application scenarios of digital twin. Starting from the application needs, we summarized the new needs and new trends of the future development of digital twin. The purpose is to constantly stimulate human innovative thinking and constantly pursue optimization and progress. We hope that the related work can provide inspiration and reference for further research on digital twin theory, technology, and engineering application.

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Data availability This paper is a theoretical study without relevant data.

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Declarations

Ethics approval There is no moral problem in this paper.

Consent to participate All the authors agree to participate.

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References

1. Saadaoui S, Tabaa M, Monteiro F, Chehaitly M, Dandache A (2019) Discrete wavelet packet transform-based industrial digital wireless communication systems[J]. Information (Switzerland) 10(3):104
2. Kapanen A (2019) The impact of Industry 4.0 on postgraduate industrial management education in Germany[C]. INTED2019 Proceedings, pp 7165–7172
3. Wang F, Huang X (2018) Research on application- oriented electromechanical talents' training mode under background of "internet+ made in china 2025" promotion plan. Matter: Int J Sci Technol 4(2):172–181
4. Tao F, Anwer N, Liu A, Wang L, Nee AY, Li L, Zhang M (2021) Digital twin towards smart manufacturing and industry 4.0[J]. J Manuf Syst 58:1–2
5. Wang XV, Wang L (2019) Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0[J]. Int J Prod Res 57(11–12):3892 3902
6. Mendi AF, Erol T, Doğan D (2021) Digital twin in the military field[J]. IEEE Internet Comput 26(5):33–40
7. Wang Z, Feng W, Ye J, Yang J, Liu C (2021) A study on intelligent manufacturing industrial internet for injection molding industry based on digital twin[J]. Complexity p 16. https://doi.org/10.1155/2021/8838914
8. Liu Datong, Guo Kai, Wang benkuan, et al (2018) Overview and prospect of digital twin technology [J]. J Instrum 39(11):1–10
9. Madslien J (2018) Digital twins[J]. Prof Eng 31(5):28–29
10. Tao F, Liu W, Liu J, Liu X, Liu Q, Qu T, Hu T, Zhang Z, Xiang F, Xu W, Wang J, Zhang Y, Liu Z, Li H, Cheng J, Qi Q, Zhang M, Zhang H, Sui F, He L, Yi W, Cheng H (2018) Digital twinning and its application exploration [J]. Comput Integr Manuf Syst 24(01):4–21
11. Barricelli BR, Casiraghi E, Fogli D (2019) A survey on digital twin: definitions, characteristics, applications, and design implications[J]. IEEE Access 7:167653–167671
12. Yang linyao, Chen Siyuan, Wang Xiao, et al (2019) Digital twins and parallel systems: development status, comparison and prospect [J]. J Autom 45(11)
13. Zhang Tianying, Ji Hang Overview of digital twins [C] 2019 China high level Forum on system simulation and virtual reality technology
14. Minerva R, Lee GM, Crespi N (2020) Digital twin in the IoT context: a survey on technical features, scenarios, and architectural models[J]. Proc IEEE (99):1–40
15. Tao F, Zhang H, Qi Q, Zhang M, Liu W, Cheng J, Ma X, Zhang L, Xue R (2020) Digital twin ten questions: analysis and thinking[J]. Comput Integr Manuf Syst 26(01):1–17
16. Tao F, Zhang H, Liu A, Nee AYC (2019) Digital twin in industry: state-of-the-art[J]. IEEE Trans Industr Inf 15(4):2405–2415
17. Zhou G, Zhang C, Li Z, Ding K, Wang C (2020) Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing[J]. Int J Prod Res 58
18. Zhang C, Xu W, Liu J, Liu Z, Zhou Z, Pham DT (2019) A reconfigurable modeling approach for digital twin-based manufacturing system[J]. Procedia Cirp 83:118–125
19. Tao F, Cheng Y, Cheng J, Zhang M, Xu W, Qi Q (2017) Theory and technologies for cyber-physical fusion in digital twin shop-floor[J]. Comput Integr Manuf Syst 23(8):1603–1611
20. Grieves M (2014) Digital twin: manufacturing excellence through virtual factory replication[J]. White paper 1(2014):1–7
21. Grieves MW (2011) Product lifecycle management: the new paradigm for enterprises[J]. Int J Prod Dev 2(1):1–8
22. Zhuang BC, Liu JH (2017) H Xiong Connotation, architecture and trends of product digital twin[J]. Comput Integr Manuf Syst 23(4):753–768
23. Tang T, Teng L (2018) J Wu Digitalization is the only way to intelligent manufacturing[J]. China Mech Eng 29(3):366–377
24. Tao F, Cheng Y, Cheng J, Zhang M, Xu W, Qi Q (2017) Theory and technologies for cyber-physical fusion in digital twin shop-floor[J]. Comput Integr Manuf Syst 23(8):1603–1611
25. Tao F, Zhang M, Cheng JF (2017) Digital twin workshop:a new paradigm for future workshop[J]. Comput Integr Manuf Syst 23(1):1–9
26. Li M (2013) The design of desk lamp on 3D modeling based on Solidworks[J]. Int J Technol Manag 1:43–45
27. Gao J, Sun B, Huo W (2021) Sensorless control of switched reluctance motor based on Matlab/Simulink Simulation[J]. J Phys Conf Ser 1813(01):012021. IOP Publishing
28. (2018) Cloud-based cognitive premise security system using IBM Watson and IBM Internet of Things (IoT). Advances in Electronics, Communication and Computing
29. González JD, Escobar JH, Sánchez H, De la Hoz J, Beltrán JR (2017) 2D and 3D virtual interactive laboratories of physics on Unity platform[J]. J Phys Conf 935:012069
30. Paiva P, Freitas B, Carvalho LK, et al (2021) Online fault diagnosis for smart machines embedded in Industry 4.0 manufacturing systems: a labeled Petri net-based approach[J]. IFAC J Syst Control (3):100146
31. Boschert S, Rosen R (2016) Digital twin-the simulation aspect[M]. Springer Verlag, Berlin, Germany
32. Zhang M, Sui F, Liu A, Tao F, Nee A (2020) Digital twin driven smart product design framework[M]// Digital Twin Driven Smart Design
33. Schleich B, Anwer N, Mathieu L (2017) Shaping the digital twin for design and production engineering[J]. CIRP Ann Manuf Technol 66(1):33–35
34. Lu Y, Liu C, Wang IK, et al (2020) Digital Twin-driven smart manufacturing: connotation, reference model, applications and research issues[J]. Robot Comput Integr Manuf 61(Feb.):101837.1–101837.14

35. Zhou G, Zhang C, Li Z, Ding K, Wang C (2020) Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing[J]. Int J Prod Res 58(4):1034–1051
36. Tao F, Cheng Y, Cheng J et al (2017) Theory and technologies for cyber-physical fusion in digital twin shop-floor [J]. Comput Integr Manuf Syst 23(8):1603–1611
37. Sethy SP, Sameena T, Patil P, Shailaja K. Product life cycle management in pharmaceuticals: a review[J]. PHARMACEUTICALS: A REVIEW. Pharma tutor
38. Ferguson S, Bennett E (2017) Digital twin tackles design challenges[J]. World Pumps 17(4):26–28
39. Akhlaghi YG, Badiei A, Zhao X, Aslansefat K, Xiao X, Shittu S, Ma X (2020) A constraint multi-objective evolutionary optimization of a state-of-the-art dew point cooler using digital twins[J]. Energy Convers Manag pp 211–226
40. Zhang X (2018) Design and implementation of workshop management and control system based on digital twins [D]. Zhengzhou University, Zhengzhou
41. Zou R, Liang X, Chen Q, Chen Q, Wang M, Zaghloul MAS, Lan H, Buric MP, Ohodnicki PR, Chorpening B, To AC, Chen KP (2020) A digital twin approach to study additive manufacturing processing using embedded optical fiber sensors and numerical modeling[J]. J Lightwave Technol 99:1–1
42. Lu Y, Liu C, Kevin I, Wang K, Huang H, Xu X (2020) Digital twin-driven smart manufacturing: connotation, reference model, applications and research issues. Robot Comput Integr Manuf 61:101837
43. Qi Q, Tao F (2018) Digital twin and big data towards smart manufacturing and Industry 4.0: 360 Degree Comparison[J]. IEEE Access 3585–3593
44. Qi Q, Zhao D, Liao TW, Tao F (2018) Modeling of cyber-physical systems and digital twin based on edge computing, fog computing and cloud computing towards smart manufacturing. In: International Manufacturing Science and Engineering Conference 51357:V001T05A018. American Society of Mechanical Engineers
45. Sameena T, Patil P, Shailaja K Product life cycle management in pharmaceuticals: a review[J]. Pharmatutor
46. Liu Q, Leng J, Yan D, Zhang D, Chen X (2020) Digital twin-based designing of the configuration, motion, control, and optimization model of a flow-type smart manufacturing system[J]. J Manuf Syst 58:52–64
47. Leng J, Liu Q, Ye S, Jing J, Wang Y, Zhang C, Zhang D, Chen X (2020) Digital twin-driven rapid reconfiguration of the automated manufacturing system via an open architecture model[J]. 63
48. Wang S, Kang X, Yu H, Wang Z (2020) Production line design and iterative evolution based on digital twin technology[J]. Mech Eng 8:28–30
49. Guerrero LV, López VV, Mejía JE (2014) Virtual commissioning with process simulation (Tecnomatix): computer-aided design and applications: Vol 11, No sup1[J]. Comput-Aided Des Applic.
50. Aheleroff S, Zhong R, Xu X, Feng Z, Goyal P (2021) Digital twin enabled mass personalization: a case study of a smart wetland maintenance system[J]. International Manufacturing Science and Engineering Conference 84263:V002T07A025. American Society of Mechanical Engineers
51. Huang S, Wang G, Yan Y, Fang X (2020) Blockchain-based data management for digital twin of product[J]. J Manuf Syst 54:361–371
52. Dufour C, Soghomonian Z, Li W (2018) Hardware-in-the-loop testing of modern on-board power systems using digital twins[C]. 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) pp 118–123. IEEE
53. Brosinsky C, Westermann D, Krebs R (2018) Recent and prospective developments in power system control centers: adapting the digital twin technology for application in power system control centers[C]. 2018 IEEE International Energy Conference (ENERGYCON) pp 1–6. IEEE
54. Xie X, Parlikad AK, Puri RS (2019) A neural ordinary differential equations based approach for demand forecasting within power grid digital twins[C]. 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm) pp 1–6. IEEE
55. Yan J, Zlatanova S, Aleksandrov M, Diakite AA, Pettit C (2019) Integration of 3D objects and terrain for 3d modelling supporting the digital twin[J].
56. Zorich D (2010) Digital debates. WebWise Conference on Libraries and Museums in the Digital World Proceedings (10th, Capitol Hill, Washington, DC, February 25-27, 2009)[J]. Institute of Museum and Library Services
57. Gerogiorgis DI, Castro-Rodriguez D (2021) A digital twin for process optimisation in Pharmaceutical Manufacturing[M]. Computer Aided Chemical Engineering 50:253–258. Elsevier
58. Heaton J, Parlikad AK (2020) Asset information model to support the adoption of a digital twin: West Cambridge case study[J]. IFAC-PapersOnLine 53(3):366–371
59. Bezborodova OE, Bodin ON, Gerasimov AI, Kramm MN, Rahmatullov RF, Ubiennykh AG (2020) Digital twin technology in medical information systems[J]. Journal of Physics: Conference Series 1515(5):052022. IOP Publishing
60. Karakra A, Fontanili F, Lamine E, Lamothe J (2019) HospiT'Win: a predictive simulation-based digital twin for patients pathways in hospital[C]. 2019 IEEE EMBS international conference on biomedical & health informatics (BHI) pp 1–4. IEEE
61. Oppermann S, Wirtz S, Schallhorn J, Moecke H (2003) The hospital as the scene of an emergency: evacuation procedures for in-hospital emergencies[J]. NOTFALL UND RETTUNGSMEDIZIN 6(8):591–595
62. Peng Y, Zhang M, Yu F (2020) Digital twin hospital buildings: an exemplary case study through continuous lifecycle integration[J]. Advances in Civil Engineering pp 1–13
63. Organization WH (2003) Background document: the diagnosis treatment and prevention of typhoid fever[J]. The Department of Vaccines and Biologicals: Geneva. 15(6):460–463
64. Izzo Angelo AA (2018) PTR virtual issue on the experimental and clinical pharmacology of the nutraceutical curcumin[J]. Phytotherapy research: PTR 32(11):2107–2108
65. Sinisi S, Alimguzhin V, Mancini T, Tronci E, Mari F, Leeners B (2020) Optimal personalised treatment computation through in silico clinical trials on patient digital twins [J]. Fund Inform 174(3–4):229
66. Barricelli BR, Casiraghi E, Gliozzo J, Petrini A, Valtolina S (2020) Human digital twin for fitness management[J]. Ieee Access 8:26637–26664
67. Lal A, Li G, Cubro E, Chalmers S, Gajic O (2020) Development and verification of a digital twin patient model to predict specific treatment response during the first 24 hours of sepsis[J]. Critical care explorations 2(11):e0249
68. Angjeliu G, Coronelli D, Cardani G (2020) Development of the simulation model for digital twin applications in historical masonry buildings: the integration between numerical and experimental reality[J]. Comput Struct 238:106282
69. Chao F A, Cheng Z A, Ay B, Am A (2019) Disaster city digital twin: a vision for integrating artificial and human intelligence for disaster management[J]. Int J Inf Manag 56
70. Nochta T, Wan L, Schooling JM, Parlikad AK (2020). A Sociotechnical perspective on urban analytics: the case of city-scale digital twins[J]. J Urban Technol (4)
71. Bao J, Guo D, Jie L, Zhang J (2018) The modelling and operations for the digital twin in the context of manufacturing[J]. Enterprise Information Systems 13(4):534–556

72. White G, Zink A, Lara Codecà, Clarke S (2021) A digital twin smart city for citizen feedback[J]. Cities 110
73. Du J, Zhu Q, Shi Y, Wang Q, Lin Y, Zhao D (2019) Cognition digital twins for personalized information systems of smart cities: proof of concept[J]. J Manag Eng 36(2)
74. Ahn C, Ham Y, Kim J, Kim J (2020) A digital twin city model for age-friendly communities: capturing environmental distress from multimodal sensory data[C]// Hawaii International Conference on System Sciences.
75. Agnusdei GP, Elia V, Gnoni MG (2021) A classification proposal of digital twin applications in the safety domain[J]. Comput Ind Eng 154(5):107137
76. Zhao L, Han G, Li Z, Shu L (2020) Intelligent digital twin-based software-defined vehicular networks[J]. IEEE Network 34(5):178–184
77. Laryukhin V, Skobelev P, Lakhin O, Grachev S, Yalovenko O (2019) Towards developing a cyber-physical multi-agent system for managing precise farms with digital twins of plants[J]. Cybernetics and Physics 8(4):257–261
78. Monteiro J, Barata J, Veloso M, Veloso L, Nunes J (2019) Towards sustainable digital twins for vertical farming[J]. Thirteenth International Conference on Digital Information Management (ICDIM) pp 234–239. IEEE
79. Yun S, Park JH, Kim WT (2017) Data-centric middleware based digital twin platform for dependable cyber-physical systems[C]. 2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN) pp 922–926. IEEE
80. Alves RG, Souza G, Maia RF, Tran ALH, Kamienski C, Soininen J, Aquino PT, Lima F (2019) A digital twin for smart farming[C]. 2019 IEEE Global Humanitarian Technology Conference (GHTC) pp 1–4. IEEE
81. Erdélyi V, Jánosi L (2019) Digital twin and shadow in smart pork fetteners[J]. International Journal of Engineering and Management Sciences 4(1):515–520
82. Schroeder GN, Steinmetz C, Pereira CE, Espindola DB (2016) Digital twin data modeling with AutomationML and a communication methodology for data exchange[J]. IFAC-Pap Line 49(30):12–17
83. Tao F, Cheng J, Qi Q (2017) IIHub: an industrial Internet-of-Things hub towards smart manufacturing based on cyber-physical system[J]. IEEE Trans Ind Inf 1–1
84. Coronado PDU, Lynn R, Louhichi W, Parto M, Wescoat E, Kurfess T (2018) Part data integration in the Shop Floor Digital Twin: Mobile and cloud technologies to enable a manufacturing execution system[J]. J Manuf Syst 48:25–33
85. Tao F, Zhang M (2017) Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing[J]. Ieee Access 5:20418–20427
86. Tao F, Zhang M, Liu Y et al (2018) Digital twin driven prognostics and health management for complex equipment[J]. Cirp Annals 67(1):169–172
87. Tao F, Qi Q, Liu A, Kusiak A (2018) Data-driven smart manufacturing[J]. J Manuf Syst 48:157–169
88. Romelfanger M, Kolich M (2019) Comfortable automotive seat design and big data analytics: a study in thigh support[J]. Appl Ergon 75:257–262
89. Yan J, Meng Y, Lu L, Guo C (2017) Big-data-driven based intelligent prognostics scheme in industry 4.0 environment[C] Prognostics and System Health Management Conference (PHM-Harbin).
90. Rado O, Lupia B, Leung JMY, Kuo YH, Graham CA (2014) Using simulation to analyze patient flows in a hospital emergency department in Hong Kong[C]. Proceedings of the International Conference on Health Care Systems Engineering. Springer, Cham, pp 289–301