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Developments of digital twin technologies in industrial, smart city and healthcare sectors: a survey

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Abstract

Digitization and digitalization have already changed our world significantly. Further disruptions are imminent with the ongoing digital transformation, a major component of which is digital twins. As the big data techniques, Internet of Things, cloud computing, and artificial intelligence algorithms advance, the digital twin technology has entered a phase of rapid development. It has been stated to be one of the top ten most promising technologies. Although it is still in its early stages, digital twins are already being widely used in a variety of fields, especially in industry, smart cities, and smart health, which are points that attract most researchers to study. In the literature, there can be seen numerous articles and reviews on digital twins, published every year in these three fields. It is therefore timely, even necessary, to provide an analysis of the published work. This is the motivation behind this article, the focus of which is the major research and application areas of digital twins. The survey first analyzes the recent developments of digital twins, then summarizes the theoretical underpinnings of the technology, and finally concludes with specific developments in various application areas of digital twins. It also discusses the challenges that may be encountered in the future.

Keywords: Digital twin, digital twin applications, smart cities, healthcare, artificial intelligence

1. INTRODUCTION

Over the past several decades, one particular endeavor of artificial intelligence (AI) researchers has been to develop intelligent systems that would allow machines help human beings do, not only all the onerous and dangerous tasks, but also the detection, prognostics, and subsequent decisions[1]. Artificial intelligence systems are guided by processes that mimic human reasoning in order to provide assistance and better services. For this reason, the application software ("apps") that we have been using in our daily lives in recent years, such as in household appliances, electronic maps, *etc*., have taken a different dimension and slowly made their way into different fields with surprising benefits[2]. For example, in mechanical engineering fields, AI algorithms are developed to classify different types of faults of rotating machines and provide prognostics with excellent performance[3]. This progress has been possible with the progress of big data processing techniques, increased computing power, and a new generation of artificial intelligence algorithms. Hence, artificial intelligence techniques combined with big data techniques and powerful computing machine have been adopted into a variety of fields.

In addition to AI, the advent of the Internet of Things (IoT) over the past two decades is enabling data exchange between different sources[4,5]. In fact, the proliferation of technologies, including Internet-connected sensors[6] and actuators, has enabled continuous communication between big data. Hence, to make the most of IoT technology, it usually depends on big data analysis and processing capabilities. Big data does not mean large data volume alone. It has four key characteristics, namely volume, variety, velocity, and veracity, which present significant difficulties in its analysis to extract value. Fortunately, scientific advances in data fusion techniques[7], high-dimensional data processing[8,9], big data analytics[10-12], and cloud computing[13] have made it possible to apply IoT technology in various fields. From the discussion above, the IoT technology produces data, the cloud computing technology provides an information shared pool, and AI algorithms and big data analytics techniques are good tools to improve the performance of cloud computing and IoT.

On the other hand, as the data analysis algorithms, IoT, cloud computing, and AI techniques advance, the combined use of these technologies has enabled the emergence of digital twins that are AI-based virtual replicas of physical systems, as first presented by Grieves[14]. The digital twins (DT) paradigm is nowadays becoming the focus of attention of an increasing number of researchers in various fields, especially in industry[15], smart cities, and smart health[1,16,17], which are extremely developed by the rapid development of IoT. Industry is the cornerstone of our society; it not only strongly improves our life quality but also brings serious accidents. Hence, in industry, digital twin technologies are mainly applied in the field of product design, manufacturing, and prognostics and health management (PHM). Smart cities and smart health are the concepts of the future and are the focus of attention of many national organizations and researchers. Especially, the smart city concept has attracted the attention of numerous researchers and national institutes based on the development of IoT, cloud computing, and AI techniques. In the future, these techniques could keep monitoring the city processes and human health states, which will provide a strong support for the healthy development of humans and cities. Hence, this review focuses on providing approaches, challenges, and solutions for applying the digital twin to industry, smart cities, and smart health. Figure 1 shows the proportion of papers in the digital twin sunder these three themes, according to the data collected from Web of Science Core Collection Database with the search strings "digital twin and industry", "digital twin and healthcare", "digital twin and smart city", *etc*. The Web of Science Core Collection contains more than 10,000 authoritative, high-impact international academic journals, conferences, and books. The statistical results are representative of the focus of research by national researchers. Its statistical results indicate that the penetration of DTs in smart health and smart cities is yet in its infancy. However, this also means that industries, smart cities, and smart health will be the hottest application fields on DTs in the

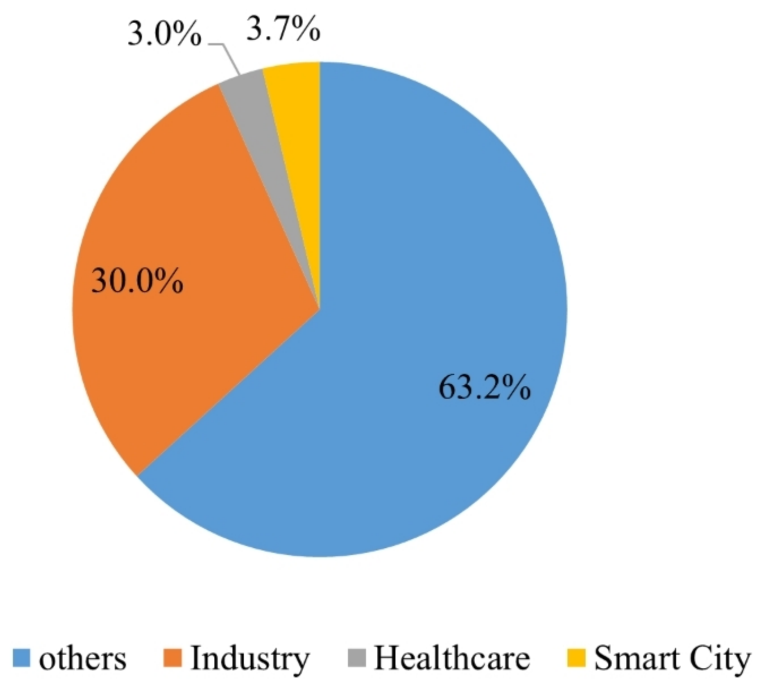

Figure 1. Distribution of digital twin publications in industry, smart cities, healthcare sectors, and others.

future. Despite the popularity of the digital twin technology, there is no comprehensive review of DTs in these three aspects.

In addition, there are some researchers who conducted comprehensive literature reviews about the concept, characteristics, and enabling technologies of DT[1,18-20].There are also several reviews of digital twin for each field.

For instance, in the industrial field, Teng *et al.*[21] summarized more than three hundred papers of data-driven models for energy saving in industry and provided a promising future of digital twin-based energy saving methods. Tao *et al.*[22-24] provided three reviews that depict digital twin applications and comparisons of digital twins and big data in industry. Minerva *et al.*[25] analyzed the advanced technologies used in manufacturing industry since the advent of the digital twin, which could inspire researchers in other fields. Ibrahim *et al.*[26] systematically summarized the effectiveness of machine learning algorithms in light-emitting diodes fault diagnosis and prognostics and presented the challenges and prospects of the digital twin in this field. In the healthcare sector, Subramanian described a liver digital twin on the basis of a mathematical framework of ordinary differential equations. These digital twin models were able to effectively reproduce normal liver function, disease evolution, and the effects of treatment. They can also be implemented in other organs and biosystems to develop medicines more productively and reliably[27]. In the smart cities, Boje *et al.*[28] summarized the strengths and weaknesses of the digital twin and the drawbacks of building information modeling (BIM) in urban construction. In addition, BIM lacks semantic completeness in some domains, for example the whole control systems, including sensor networks, social systems, and urban artifacts outside the building envelope, and therefore needs a whole, extensible semantic methodology that can incorporate different tiers of dynamic data. In addition, they provided a review of the various utilization of BIM in the building phase and emphasized its restrictions and demands, paving the way for the concept of digital twin construction[28]. After an in-depth analysis of these reviews, to apply digital twin technologies in these fields, the key components of the digital twin can be divided into three categories: data-related technologies (such as IoT), high-fidelity models (such as artificial intelligence model), and model-based simulation (such as finite element analysis). For instance, in the industrial field, IoT could be used to share the data, the data could be input into the artificial intelligence algorithm to get a perfect outcome, and then model-based simulation techniques could validate the results.

In summary, the digital twin has received plenty of attention in different fields because of its powerful potential. Nevertheless, the progress of digital twins is still in its early stages. There is no standardized definition, framework, or protocol for the digital twin. It can also be noticed that there is a lack of full and in-depth comprehension of the digital twin conception, advanced techniques, and applications in different application-oriented fields.

Thus, based on an overall survey of more than one hundred articles that are obtained from the world's largest technology publishers, databases, and academic search engines, including ScienceDirect, Scopus, Google Scholar, IEEE Xplore and Springer, this survey intends to address the following four goals: (1) provide a thorough summary for the conception of digital twins; (2) give a complete summary of the current status of the digital twin; (3) point out to some specific applications in industry, smart city, and healthcare sectors; and (4) discuss some challenges for further development of the digital twin framework.

The remainder of this paper is arranged as follows. Section 2 depicts the definition and history of digital twins. Section 3 summarizes the development of digital twins. Section 4 describes the digital twin applications in industry. Section 5 presents the digital twin applications in smart city. Section 6 shows the application of digital twins in healthcare. Section 7 summarizes the challenges in the development of digital twins. The work is concluded in Section 8.

2. DIGITAL TWINS - DEFINITION AND HISTORY

2.1 Definition of digital twins

The digital twin technology has recently attracted growing interest among researchers. The definition of digital twin was first proposed by Grieves[14], which is composed of three components: physical objects, virtual objects, and the links between them. The digital twin structure in[14] is illustrated in Figure 2.

In 2012, the National Aeronautical Space Administration (NASA) defined a digital twin as "an integrated multi-physics, multi-scale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, *etc*., to mirror the life of its corresponding flying twin"[29]. Since then, digital twins have become a hot research topic with intentions of application in various areas of industry, as well as smart cities and health. In the early stages of its use in industry, the digital twin was introduced in various areas with different expectations. In one case, for example[30,31], the argument was that the digital twin is a physical equipment model which contains all of the information of the device or system, which could interact with a living database and messages. Based on the statements of Gabor *et al.*[32], the digital twin is a specific form of simulation that is grounded in specialist expertise and actual data gathered from established systems to achieve more precise simulations at different temporal and spatial scales. According to Madni[33], the digital twin can be a virtual model based on a physical system, which could track the state, maintenance, and health management of the real-time physical system. The aforementioned discussions indicate that for some years there was no unique or specific definition for the digital twin paradigm in different application sectors. Neither academia nor industry helped distinguish digital twins from ordinary computing models and simulations. To disperse the cloud, it can be stated that the three particular pillars of digital twin are digital model, digital shadow, and digital thread[18].

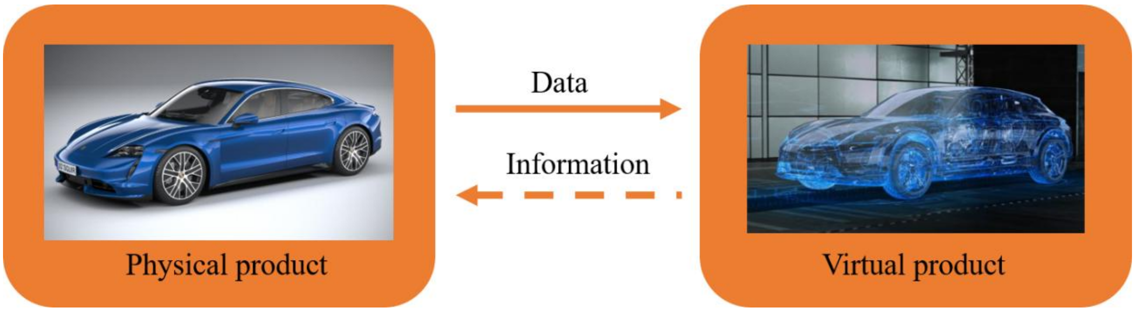

Figure 2. The structure of the digital twin model proposed in[14].

Digital model (mirror): a digital model is a numerical version of an available or scheduled physical entity, the information flow between the physical entity and the model being only one way[34].

Digital shadow: the operating data of a physical system can automatically change the state of the virtual entity, but not vice versa[35,36]. The effectiveness of shadowing depends on the velocity and granularity (resolution) of monitoring.

Digital thread: it is a framework that elements in the system are linked together and provide a comprehensive observation of components throughout the operating cycle of the entity[37,38].

There is not only a different understanding of the definition of digital twins, but also a different understanding of their dimensions. For example, with the development of digital twins, some researchers[23,39,40] have argued that an entire digital twin is a five-dimensional model, including the physical section, digital section, linking, data, and service. Instead, in the early development of the digital twin, most researchers believed that the digital twin usually consisted of only three dimensions: physical, virtual, and connection parts[22,41,42]. Table 1 presents a short summary of how different dimensions of digital twins are understood based on four references[14,43-45]. Moreover, some researchers have the belief that the digital twin is focused on simulation[32,46], while other researchers argue that digital twins can be stretched from a numerical presentation of physical items to a numerical presentation of the entire organization[47].

2.2 History of digital twins

As indicated in Table 2, the digital twin paradigm has been around for less than 20 years. With the recent developments in IoT, data analysis methodology, AI (in the narrow sense) algorithms, and cloud computing, the digital twin is gradually being used in various areas. According to the Web of Science Core Database, the published articles per year from 2003 to November 2020 on DTs are shown in Figure 3. The figure indicates that there has been an incremental increase in the amount of literature published on digital twins after 2015.

Since NASA offered a specific concept of digital twins in 2012, DTs have entered a period of rapid development as a result of the advances made in communication techniques, IoT, cloud computing, big data analytics, and AI technologies, and many studies on this paradigm have been published, attracting the attention of scholars from all over the world. Figure 4 depicts the distribution of papers on digital twins among different countries as per Web of Science Core Collection Database. The ten countries that have published the most papers are the United States, Germany, China, England, Italy, France, South Korea, Spain, Russia, and India. In 2017, digital twins were considered as one of the top leading techniques of the future by the Gartner company[48,49]. After 2017, DT technology is already being applied in other areas,

Table 1. Comparing various dimensions of digital twin models[40]

	Publication			
Dimensions	[14]	[43]	[44]	[45]
<Physical part>	√		√	√
<Virtual part>	√	√	√	√
<Collaboration part>	√	√	√	√
<Data part>		√	√	√
<Circumstance>			√	√
<Customer>				√

Table 2. Comparing various dimensions of digital twin models[40]

Year	Important events of digital twins
2003	The first concept of digital twins was proposed
2005	Three subtypes of mirrored spaces model were differentiated
2010	The concept of digital twins was specifically defined
2012	Digital twins were listed as a key technology
2014	White paper of digital twins was published
2016	Digital twins were applied in Industry 4.0 by Siemens
2018	Digital twins were applied on a livestock farm
2020	Digital twins were applied in precision healthcare

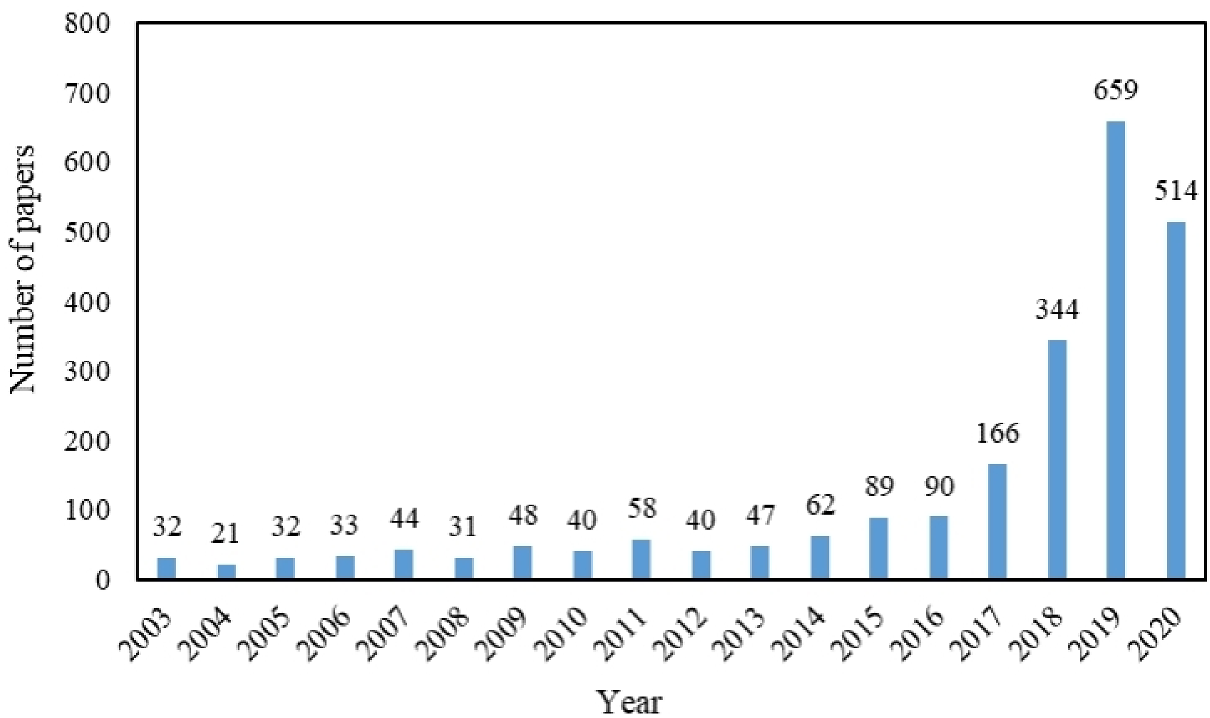

Figure 3. Number of papers published per year.

including smart cities and healthcare. In 2020, some researchers proposed a standardized framework of digital twins for health and well-being[50].

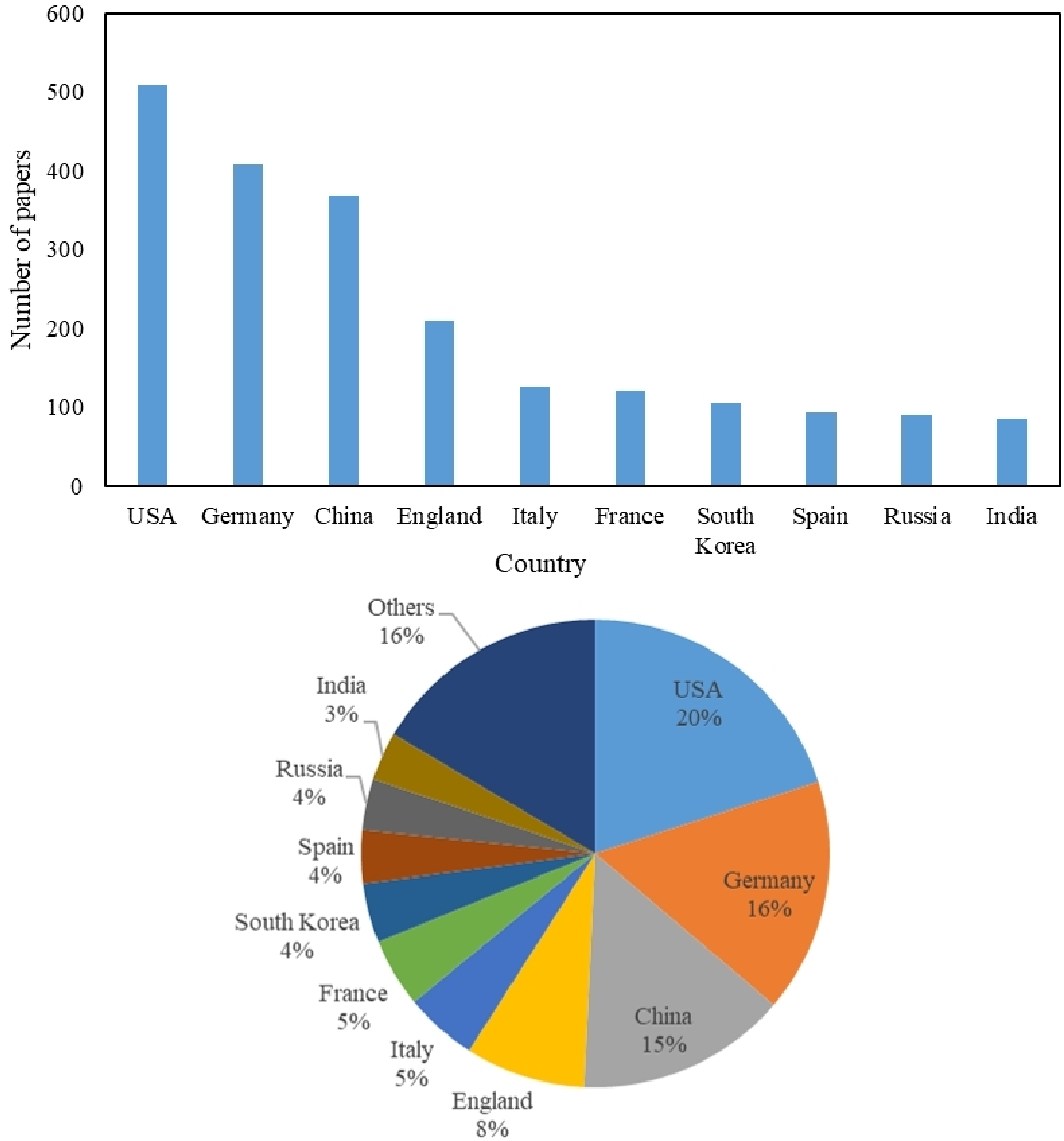

Figure 4. Distribution of articles on digital twins among different countries.

3. THE DEVELOPMENT OF DIGITAL TWINS

The developmental components of DTs are usually separated into four parts: digital twin modeling and simulation[51], data fusion, interaction, and service.

3.1 Digital twin modeling and simulation

Modeling and simulation are fundamental for the realization of DTs. The literature is full of research articles on modeling frameworks, methods, and technologies in industry, smart cities, and healthcare, some of which are highlighted below.

In the industrial sector, Yu *et al*.[52] used DTs for health management based on a hybrid model of Bayesian network, Gaussian particle filter, and Dirichlet process mixture model. Gao *et al*.[53] realized a deep digital twin integration model of the production line between the physical production line and the digital production line based on the real-time models and simulation methods. In the smart city sector, Du *et al*.[54] used the virtual reality to simulate complicated missions in a virtual city to develop personal digital twins with information-driven cognition, aiming to build a personalized information system in the future. Dembski *et al*.[55] developed a DT, integrating a street grid model based on space syntax, an urban mobility simulation, a wind flow simulation, and some volunteered geographic information. In the healthcare sector, Jimenez *et al*.[56] developed a DT by integrating IoT and cloud computing systems, which could improve the rehabilitation process for patients.

3.2 Data fusion

As is well known, digital twin models contain a large amount of data, and therefore it should have a strong ability for data fusion. According to Xie *et al*.[57], there exist many data from many sensors; hence, it is necessary to use techniques of data processing and data fusion. Data fusion can thus be stated to be one of the core techniques for the realization of a digital twin model. Although there are numerous publications on data fusion or digital twins, there are only a few publications on data fusion for digital twins. In smart cities, there is a wealth of live camera data and location data. It is therefore important in the digital twin city framework to adopt the appropriate data fusion techniques to deal with these data[58]. Some researchers assert that data fusion technologies can be classified into three groups: data-level fusion, feature-level fusion, and decision-level fusion[59].

3.3 Interaction

Although there is currently only a few research works reporting on the interaction for DTs, it is important that the different modules of DTs cross-collaborate with each other for the digital model to work properly. For example, it is necessary to check the interconnection situation between the physically based manufacturing model and its DTs that it achieves exclusive control of the digital twin[60].

3.4 Service

Service in digital twins includes several functions, such as health management, status monitoring, prognostics, decision-making, *etc*. For example, in a manufacturing process, it can be designed to provide some advice for customers to choose the appropriate tools. In actual working conditions, it should monitor the health status of the system continually to be aware of a malfunction[57]. In robotics, the ontology that describes the robotic control services is commonly utilized. Since, at present, numerical models for process simulation, path simulation, *etc*. are packaged as cloud services, they should be easy for the robotic system to call[61]. In addition, the design for service should contain several features, including smart implementation, precise forecasting, and reliable control. The service is a set of mathematical algorithms that combine tracking, evaluation, optimization, and estimation[62]. The integration between digital twin and service is a hot research spot, which could help enhance the reliability of the digital twin framework.

4. INDUSTRIAL APPLICATIONS OF DIGITAL TWINS

This section provides a summary of the industry implementations of digital twins that are discussed via a series of published papers. They are concentrated in the fields of product design, manufacturing, and PHM. Figure 5 shows several applications of digital twins in industry.

4.1 Product design

Digital twins can prove to be very valuable in product design and are commonly used to design a new product, redesign a product, and analyze the latent client requirements and the product flaws[63].

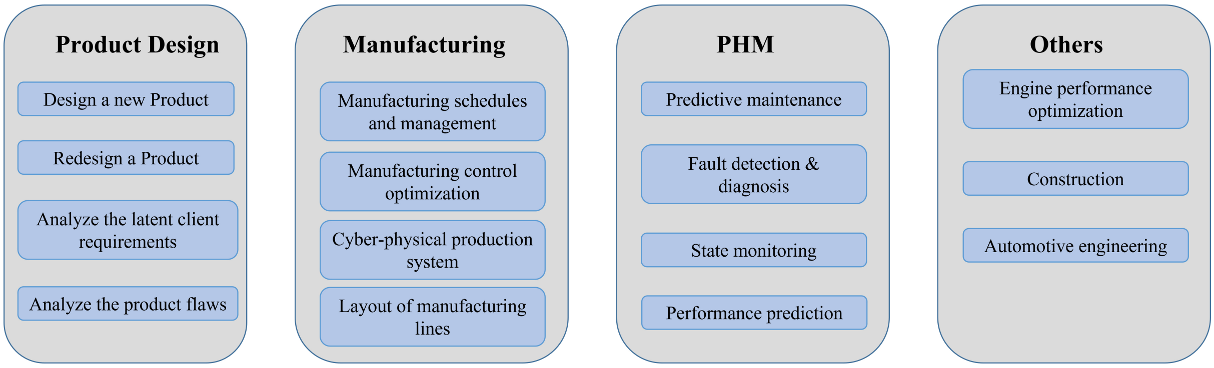

Figure 5. Applications of digital twins in industry.

4.1.1 Design a new product

Zheng *et al.*[64] described a DT model that used different mechanisms in conjunction with the design of a family of products and defining the usage phases of the product. In the product family stage, it was used for benchmarking and interacting methods. It was also used in the redesign and their configuration strategies in the usage phase.

4.1.2 Redesign a product

Tao *et al.*[39] developed a DT model which could be helpful for the iterative redesign of a current product through linking the physical model and virtual model, rather than redesigning a completely new product.

4.1.3 Analyze the product flaws

At the product design phase, the DT data incorporates at least six kinds of data to help designers analyze prospective user demands and product flaws[65].

4.2 Manufacturing

The digital twin technology allows for a more stable, elastic, and predictable production process, on the basis of cyber-physical systems (CPS). The relevant applications are summarized as follows.

4.2.1 Manufacturing schedules and management

Based on the CPS, Biesinger *et al.*[66] developed a DT concept for the automated notion of a body-in-white production system based on the resources, products, and process information from the cyber-physical system. Based on the real-time data available from the cyber-physical system, Agostino *et al.*[67] described a DT methodology for manufacturing schedules and management. This framework could improve the capability of the production system for three diverse core indices of achievement, which was assessed through a factual situation involving a manufacturer that provides mechanical components to the motor industry[67].

4.2.2 Manufacturing control optimization

Min *et al.*[68] proposed a DT framework and methodology on the basis of IoT and AI in the petrochemical industry and developed a practical cycle of data communication between the physical factory and the virtual DT model for manufacturing control optimization.

4.2.3 Cyber-physical production system

Zhang *et al*.[69] first discussed a common structure of DT-based cyber-physical manufacturing system and developed a cyber-physical production system on the basis of AutomationML, which was eventually evaluated for blisk machining. Liu *et al*.[70] also developed a DT-based cyber-physical manufacturing system by combining cyber-physical system, DT modeling and simulation techniques, event-driven distributed collaboration mechanisms, networking techniques, and cloud computing, which could ensure the easy operation of the DT-based cyber-physical manufacturing system.

4.2.4 Layout of manufacturing lines

Guo *et al*.[71] presented a flexible honeycomb manufacturing model with digital twin to deal with the coupling issues of irrational layout of manufacturing lines, imbalanced process competence, imprecise logistics and distribution, and lack of intelligence in device inspection.

4.3 PHM

Due to the special capabilities of digital twins, many researchers have applied the digital twin technology to industrial PHM. Hence, there are several papers in the literature on this topic.

4.3.1 Predictive maintenance

To monitor the operation status of the Five-hundred-meter Aperture Spherical radio Telescope (FAST), Li *et al*.[72] developed a PHM system on the basis of the most advanced DT techniques to deal with this issue, which could also anticipate the durability of its elements in the cable-net. The developed PHM system could efficiently safeguard the healthy status and reliable operation of the FAST, significantly enhancing maintenance efficiency and reducing maintenance engineering costs[72]. Ye *et al*.[73] developed a DT framework which had several different capabilities, such as fault diagnosis, model renewal, performance assessment, and data management, to track the lifetime of spacecraft architecture. Experimental results show that, with this framework, the fracture generation model can be refreshed with relatively low uncertainty. Using the modified model, future crack growth and repeatable lifetime can be forecasted more accurately. By quantifying the structural lifetime of the spacecraft through the framework, the mission success of repeatable flights can be maximized at a lower cost[73].

4.3.2 State monitoring

Health monitoring and management of industrial equipment plays an important role in industry. Failure of industrial facilities can result in tremendous economic costs and casualties[74]. Hence, the digital twin framework has been used by many researchers to monitor the state of industrial devices, including thermal power plants, telescope, automotive, spacecraft, battery management system, *etc*. For instance, Yu *et al*.[75] developed a DT model to monitor the health state of thermal power plants, which could ensure safety and orderly working of thermal power plant. Moreover, the DT model could provide chances to generate more renewable power without sacrificing productivity and security[75]. Li *et al*.[76] developed a cloud battery management system based on a digital twin, which could enhance the calculation capability and data memory size on the basis of the cloud computing. Wang *et al*.[77] presented a digital twin framework consisting of a conventional machine structure which could connect siloed devices to an interactive network and monitor the status of machine operations in real-time. Yu *et al*.[52] proposed a DT method for health monitoring on the basis of some several artificial intelligent algorithms. This digital twin framework could get a good performance in monitoring the working status due to its self-learning ability[52].

4.3.3 Fault detection and diagnosis

Oluwasegun *et al.*[78] developed a DT framework for the prognosis of the control element drive mechanism, which was combined with artificial intelligent algorithms. They concentrated on developing artificial intelligence algorithms and processes for analyzing the control element drive mechanism, which used recorded coil current data. This framework could efficiently improve the plant safety and availability on the basis of the recorded data[78]. To monitor the health status of critical structures, Leser *et al.*[79] realized the DT technology to surveillance the health state of the structures. The method is a versatile approach to decrease the uncertainty in fatigue lifecycle estimation that combines *in-situ* diagnosis and prediction in a probabilistic framework[79]. Booyse *et al.*[80] proposed a deep digital twin model in combination with deep learning algorithms and digital twin, which could efficiently diagnose incipient malfunctions, follow asset deterioration, and distinguish between fault patterns in stationary and non-stationary working conditions.

4.3.4 Performance prediction

Mi *et al.*[81] integrated digital twin technology to enhance the precision of fault diagnosis and prediction and to enable making repair schedules with greater precision and dependability. The framework can direct industrial corporations to execute predictive repairs with greater precision and credibility.

4.4 Digital twins in other fields

In addition to the aforementioned usages in design, production, and PHM, the digital twin technology is frequently utilized in other fields as well, such as machining process, construction, engine performance optimization, automotive engineering[82], *etc*.

4.4.1 Engine performance optimization

Bondarenko *et al.*[83] presented a modeling framework that integrates a continuous time-domain cyclic mean engine model with a crankshaft-angle analytic phenomenal combustion model to fulfill real-time performance constraints. The solution of the digital twin framework would achieve rapidity and precision compared to the conventional method based on differential equations and Runge-Kutta solver[83]. To build a multi-physics digital twin model, Liu *et al.*[84] presented a framework based on biomimicry principles. This excellent multi-physics digital twin model consists of several digital twin sub-models, which can mutually impact and comprise an integrated real representation of physical processes[84].

4.4.2 Construction

Lu *et al.*[85] presented a semi-automatic method to address the time-consuming problem with a building information model. This framework is based on images and CAD drawings. In addition, they also provided several advanced geometric digital twin methods and described the methodological framework of this semi-automatic geometric digital twin approach[85]. Wang *et al.*[86] proposed a new model which could improve cooperation of all stakeholders in the customization process on the basis of DT techniques. A case study of the elevator industry illustrated the efficacy of the proposed framework[86]. Wang *et al.*[87] improved the efficiency of visual question answering on the basis of the DT techniques. This framework could implement human-computer interactions and product counting in the case of full sensory perception[87].

4.4.3 Automotive engineering

For the vehicle development aspect, Siemens[88] wrote a white paper about the vehicle's structural durability.

5. SMART CITY APPLICATIONS OF DIGITAL TWINS

As IoT and cloud computing technologies advance, digital twins have been applied in the smart city. This section summarizes the smart city utilization of digital twins that have been described in the literature.

Smart city applications of digital twins focus on the areas of agriculture, city transportation, urban health management, and security in the smart city[89]. Figure 6 shows the main applications of digital twin in the field of smart cities.

5.1 Smart agriculture

The digital twin technology has a huge range of successful use cases in sustainable agriculture: the distribution of natural resources and greenhouse production, design of a livestock farm, *etc*. The relevant developments are outlined below.

5.1.1 Distribution of natural resources

Sreedevi *et al*.[90] described a review of studies on the applications of digital twins in intelligent agriculture. For example, to deal with the distribution of natural resources across various stakeholders and platforms, Moshrefzadeh *et al*.[91] presented the distributed digital twin for the farming landscape by combining existing, historical, and live data.

5.1.2 Greenhouse production

For the commercial greenhouse production procedure, Howard *et al*.[92] proposed a DT model which could predict the future conditions of the greenhouse by integrating past and real-time data inputs from different databases and sensors. In addition, to ensure the accuracy of the data, they discussed the structure of the data needed through the smart industry architecture model framework[92].

5.1.3 Design of a livestock farm

To improve the habitat of animals, Jo *et al*.[93] developed a new framework of a smart pig farm based on the digital twin techniques. With the properties of digital twins, the data coming from the farm in the virtual world could lead to improved livestock farming in the real world. Based on the integrated spatiotemporal information model for arable landscapes, Machl *et al*.[94] presented a digital twin model which could be used to design the agricultural key route grids.

5.2 City transportation

The digital twin technology could achieve success in the field of city transportation, such as the driving safety and railway turnout. The relevant applications are summarized as follows.

5.2.1 Driving safety

Liu *et al*.[95] combined data fusion technologies and a digital twin model which could improve the visual guidance system performance to ensure the safety of drivers by integrating the camera pictures and position information from the cloud service. Wang *et al*.[96] improved an advanced driver assistance system based on the digital twin model. This is due to the features of the digital twin model and the development of cloud computing and communication technology. For the development of the automated smart vehicles, Mavromatis *et al*.[97] tried to apply the digital twin model to automated smart cars, which could deal with several disadvantages of conventional vehicular and cyber emulators. Besides, this digital twin framework could facilitate the development of driverless cars in a big city[97].

5.2.2 Railway turnout

Kaewunruen *et al*.[98] built the first 6D BIM to monitor the healthy management of the railway turnout system. This framework could track the material carbon emission, even in the production phase[98].

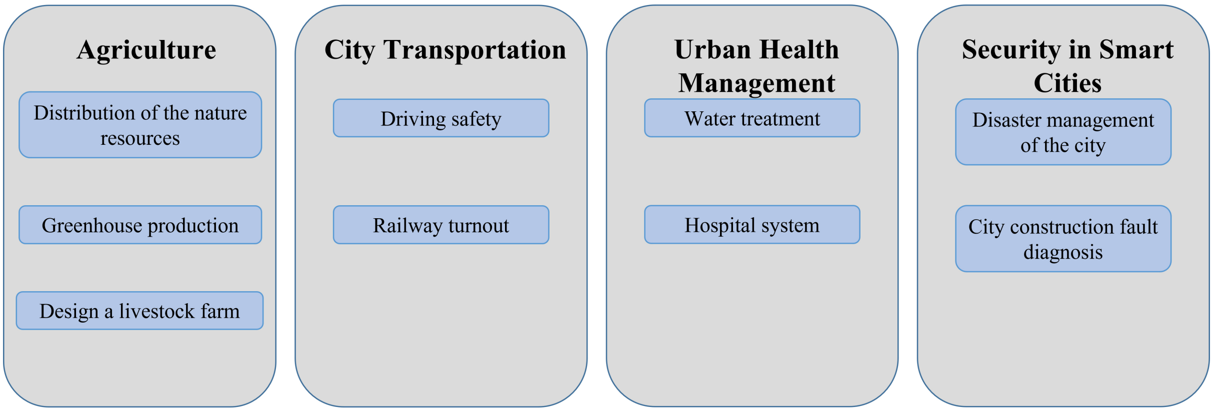

Figure 6. Applications of digital twins in smart city.

5.3 Urban health management

Digital twins have achieved great success in the field of urban health management, especially for water treatment and the hospital system. The relevant applications are summarized as follows.

5.3.1 Water treatment

Carvalho[99] developed a digital twin model to deal with sewage in Brazilian cities, which combined BIM and asset management.

5.3.2 Hospital system

Rodríguez-Aguilar[100] developed a digital twin model for the city's public health emergency system by integrating the city modeling and simulation. Karakra *et al.*[101] proposed a digital twin model for their hospital system, including IoT, artificial intelligent algorithms, and cloud computing technologies. According to the advantages of the DT technology, this framework could provide real-time monitoring of the patient status and protect the patient in time[101]. Barbiero *et al.*[102] developed a DT model that combined machine learning algorithms, deep learning algorithms, and some physical models, which could offer a panoramic map and upcoming physiological situations. The results show that this framework was efficient to get the future trajectories state of the patient based on the collected clinical data[102].

5.4 Security in smart cities

DTs have had huge success in urban security[103], especially the disaster management of the city and construction. The relevant applications are summarized as follows.

5.4.1 Disaster management of the city

Ford *et al.*[104] developed a DT model of the city for its disaster management and concluded that the digital twin model could bring two dangerous points which could be dealt with by disaster management. Ham *et al.*[105] developed a DT model for inputting realistic data into a 3D virtual city. The results show that the proposed digital twin framework is effective in scenarios such as local vulnerability, risk-informed decision-making for urban infrastructure management, and analysis of disaster situations[105].

5.4.2 City construction

Lu *et al.*[106] proposed a novel industry-based class data structure based on the digital twin, which could be used to realize anomaly diagnosis of the city construction based on data that contain diagnostic information on the operating status of assets.

6. HEALTHCARE APPLICATIONS OF DIGITAL TWINS

This section addresses the healthcare applications of digital twins presented in papers published in recent years. Healthcare applications of digital twins focus on the areas of personal health management and precision medicine. In the review of Bagaria *et al.*[107], the core technologies and applications needed to apply digital twin techniques to personal health and well-being are summarized. Ahmadi-Assalemi *et al.*[108] have also discussed the role of the digital twin in personal health and some of the challenges that would be encountered in this regard. Figure 7 shows the application of digital twins in the smart health sector.

6.1 Personal health management

Personal health management, such as patient recovery, is also one of current research interests. The relevant applications are summarized as follows.

6.1.1 Patient recovery

Rivera *et al.*[109] integrated data-driven methods (e.g., machine learning) and digital twins, which served as a noteworthy mechanism to not only track the health status of patients continuously but also evaluate the application and evolution of medical treatments virtually. They elaborated on the definition of internal structures for digital twin to support precision medicine techniques in the context of continuous monitoring and personalized data-driven medical treatments[109]. Fagherazzi[110] developed a personal digital twin model based on real-world clinical data and omics features, which could help doctors protect patients carefully. As is known, personalized medicine demands the integration and handling of massive volumes of data. Björnsson *et al.*[111] developed a framework to deal with the problem of excess data based on the digital twin. This framework could find the best medicine for the patient's disease among numerous drugs based on the strong data processing capabilities of digital twins[111]. To improve the health state of humans, Lutze[112] developed an integrated model based on digital twin, machine learning, and deep learning methods to improve the health situation of humans.

6.2 Precision medicine

With the development of the Internet and communication technology, precision medicine has gradually become a hot topic for researchers. The digital twin has attracted a large number of researchers to apply it to precision medicine[17].

6.2.1 Drug development

Lopes *et al.*[113] built a pharmaceutical quality control laboratory based on the digital twin, which could be used as a reference to predict the performance of a new medicine. Corral *et al.*[114] presented the early stages of digital twins in cardiovascular medicine and discussed the difficulties and opportunities in the future. They highlighted the synergistic role of mechanistic and statistical models in speeding up cardiovascular study and realizing the precision medicine vision[114].

6.2.2 Drug management

Based on the features of digital twin, Liu *et al.*[115] developed a model that combined digital twin and cloud computing service, which could effectively track the health status of the elderly patients and reasonable use of medication.

6.2.3 Treatment of diseases

Subramanian[27] proposed a digital twin model to cure the liver disease, based on massive clinical data. Subramanian's analysis revealed that the digital twin model can also be applied to drug development, management, and treatment of other diseases[27]. Geris *et al.*[116] applied a digital twin framework to the tissue

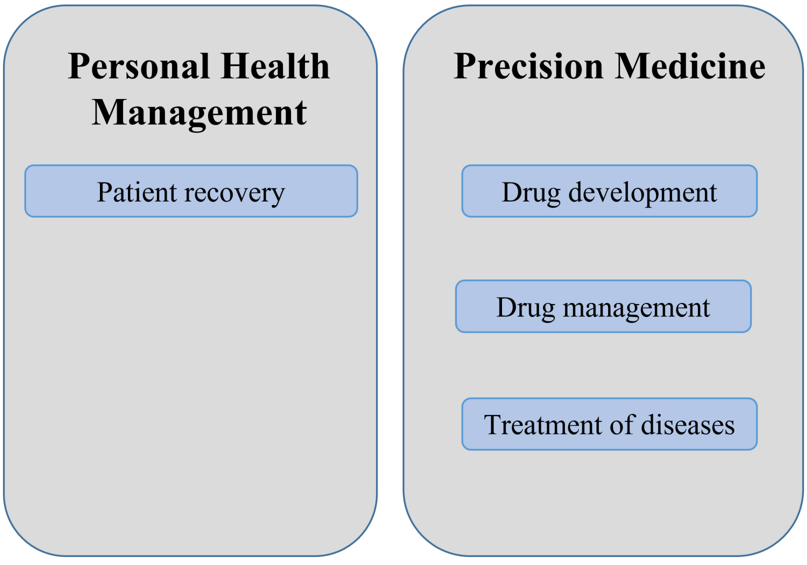

Figure 7. Applications of digital twins in smart healthcare.

engineering processes. They also compared this framework with other data-driven models through the skeletal tissue engineering process. Finally, the results show that the performance of the digital twin and model should comply with the regulatory guidelines[116].

7. CHALLENGES

The digital twin technology has been used in a wide variety of fields with good performance. As discussed at the beginning of this paper, DTs are usually based on several kinds of technologies. Therefore, there are still several challenges that need to be overcome for its further applications in industry or other areas. They are discussed below.

The main challenges for DTs are IT infrastructure, useful data, security, standardized modeling, and domain modeling.

7.1 IT infrastructure

These facilitates could ensure the effective operation of DTs. The developments in 5G can be instrumental in this respect. To ensure the performance of DTs, it is necessary to guarantee high data transfer and data processing speeds.

7.2 Useful data

DTs need a high-quality, uninterrupted, continuous stream of data. IoT technology could produce a large amount of data. The validity of the data will affect the performance of digital twins, especially in the data analytics and processing parts. Hence, it is necessary to ensure that the input data of the digital twin technology are effective and of high quality.

7.3 Security

With the developments in cloud computing and service, there is a huge amount of private information being saved in the cloud. Therefore, it is necessary to consider its security as well as privacy, especially in smart cities and smart health. Hence, the data encryption technologies and intrusion detection systems will become key components into DTs.

7.4 Standardized modeling

Since the digital twin technology is still in development stages, there is no standardized digital twin model for the modeling and simulation of specific events. If there were a standardized approach, it would be convenient for users who wish to apply a digital twin model to deal with specific events.

7.5 Domain modeling

Due to the features of digital twins, it is crucial for a digital twin model to fuse data from different domains. Hence, if these data could not be transferred efficiently, digital twins would face a huge difficulty in the future.

8. CONCLUSIONS

Digitization and digitalization are transforming the world. The published papers testify that digital twins can be applied in several fields with good performance. This paper surveys some important articles to highlight the advanced digital twin research and application. The primary contributions of this survey are outlined below:

(1) It summarizes the development of digital twins, including its concept and theoretical foundation. In addition, it also introduces key techniques for using the digital twin framework.

(2) It highlights the present usages of digital twins in industry, indicating that digital twins are most popular in the field of PHM, the crucial step in the development of a digital twin is modeling and simulation, and the imperative is data fusion and data transfer.

(3) It addresses the current applications of digital twins in smart city and concludes that DTs are most popular in smart agriculture, city transportation, urban health management, and security in smart cities. The core of DTs in smart city applications is related to how to collect, harmonize, integrate, and analyze data.

(4) It puts forward the current applications of digital twins in healthcare, summarizing that DTs are most popular in the personal health management and precision medicine, with the core of DTs in healthcare being how to collect, harmonize, integrate, and analyze data.

Finally, this survey intentionally does not consider the emerging area of personal twins and, at a higher level, cognitive digital twins, the prospects about which are not only exciting but also may be alarming. It requires not only a technical analysis but also a deeply philosophical one. As Harari[117] stated in his book, titled Homo Deus, "What will happen to society, politics and daily life when non-conscious but highly intelligent algorithms know us better than we know ourselves?" The concluding remark could be that stated by Gail Carr Feldman: "There has never been a time more pregnant with possibilities".

DECLARATIONS

Authors' contributions

Concept development: Yang DG, Karimi HR, Kaynak O, Yin S
Drafting the manuscript: Yang DG
Modify the manuscript: Yang DG, Karimi HR, Kaynak O, Yin S
Approval of the version of the manuscript to be published: Karimi HR, Kaynak O

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