Front. Eng. Manag. 2022, 9(4): 668–676
https://doi.org/10.1007/s42524-022-0216-2

RESEARCH ARTICLE

Jiehan ZHOU, Shouhua ZHANG, Mu GU

Revisiting digital twins: Origins, fundamentals, and practices

© Higher Education Press 2022

Abstract The digital twins (DT) has quickly become a hot topic since it was proposed. It appears in all kinds of commercial propaganda and is widely quoted by academic circles. However, the term DT has misstatements and is misused in business and academics. This study revisits DT and defines it to be a more advanced system/product/service modeling and simulation environment that combines most modern information communication technologies (ICTs) and engineering mechanism digitization and characterized by system/product/service life cycle management, physically geometric visualization, real-time sensing and measurement of system operating conditions, predictability of system performance/safety/lifespan, and complete engineering mechanisms-based simulations. The idea of DT originates from modeling and simulation practices of engineering informatization, including virtual manufacturing (VM), model predictive control, and building information modeling (BIM). On the basis of the two-element VM model, we propose a three-element model to represent DT. DT does not have its unique technical characteristics. The existing practices of DT are extensions of the engineering informatization embracing modern ICTs. These insights clarify the origin of DT and its technical essentials.

Keywords virtual manufacturing, digital twins, modeling and simulation, digitization, computational engineering

Received January 22, 2022; accepted May 20, 2022

Jiehan ZHOU (✉)
University of Oulu, Oulu 90570, Finland
E-mail: jiehan.zhou@ieee.org

Shouhua ZHANG
University of Oulu, Oulu 90570, Finland; Hebei University, Baoding 071002, China

Mu GU
Beijing Aerospace Smart Manufacturing Technology Development Co., Ltd., Beijing 100043, China

1 Introduction

With the in-depth integration of computer, information and communication technology (ICT), mechanical engineering, automation, and other disciplines, researchers and practitioners in the industry put forward demands on advanced system modeling and simulation environments (ASM&SEs) for computational engineering. Following the introduction of the concept of virtual manufacturing (VM) 30 years ago (Onosato and Iwata, 1993), its derived term, digital twins (DT), was born recently and is frequently cited by business and academic articles.

Gartner has listed DT as one trend of the top 10 strategic technology for three consecutive years (2017–2019) (Liu et al., 2021). The General Electric Company has built a DT system of capital flow based on the Predix platform, in which engineers and operators can respectively predict the product life cycle (Todorovic et al., 2016). Siemens proposed to use DT to help manufacturing enterprises build an entire production line in the digital space and digitalize the entire cycle from product design to manufacturing in the physical space (Tao et al., 2018). In November 2017, the Intelligent Manufacturing Alliance of China officially listed DT as one of the top 10 scientific and technological advances in intelligent manufacturing (Wu et al., 2021).

DT has also received extensive attention in academia and has been introduced into industrial applications. Although major research institutions and related enterprises have presented their own DT concepts, many different definitions of DT emerged since it was proposed (Opoku et al., 2021). With the continuous interpretation of DT in industry and academia, its meaning has become more confusing, and the boundaries between DT and other related concepts have become more obscure. What exactly is a DT, what can it do, where is the boundary, and what is its relationship with modeling and simulation? These questions confuse researchers and practitioners. Given the unclear definition of DT, its technology is ambiguous and even more ambiguous under the

entertainment of the nascent metaverse. Numerous researchers across the fields of computer, manufacturing, and automation are overwhelmed by the influx of literature terminology. Even more notable phenomena in academia are that many researchers added DT in the title of articles based on traditional engineering informatization to gain popularity (Zhang, 2020).

In response to the misuse and abuse of the term DT, this study profoundly traces the source of DT by consulting many first-hand materials, and corrects such claim that DT originated from the mirrored space model (MSM). This study also corrects the misstatement that DT first appeared in the technical report on *Modeling, Simulation, Information Technology and Processing Roadmap* by the National Aeronautics and Space Administration (NASA) in 2010 and defines the basic concept of DT as a more ASM&SE. The DT-based system has the characteristics of geometric visualization of the physical system, real-time sensing and measurement of system operating conditions, the predictability of system performance/safety/lifespan, the complete engineering mechanisms-based simulation, and the symbiosis of physical/virtual systems. The terms such as system, product, and service are used interchangeably in the paper. Based on this novel understanding and the two-element model of VM, we present a three-element model of DT: The geometric shape, information, and engineering mechanism of the real system. Based on the analysis of DT practices, the study pointed out that the current industrial application of DT is essentially an informatization solution that combines the engineering requirements and expands the application of modern ICT.

The remainder of the paper is organized as follows. Section 2 traces the source of the DT idea. Section 3 defines DT as an ASM&SE based on a digital gearbox product life cycle management case analysis. Section 4 reviews the two-element model for representing VM and proposes a three-element model representing DT. Section 5 briefly describes some practical research in the name of DT and points out that current practices are an extension of traditional engineering informatization, which partially reflects the characteristics of DT, such as the geometric visualization of a physical system. Section 6 draws a conclusion.

2 The origin of DT

The idea of DT is essentially an ASM&SE. The current widely circulated version is that DT originated from MSM coined by Michael Grieves at the Florida Institute of Technology (Tao et al., 2019; VanDerHorn and Mahadevan, 2021). This MSM model was first mentioned in a report by Grieves in late 2002 when he was studying virtual-real-driven product life management (PLM). The term MSM was used in the first PLM courses at the University of Michigan in 2003 (Kritzinger et al., 2018). In 2005, the MSM term appeared in article *Product life cycle management: The new paradigm for enterprises* (Grieves, 2005b). In 2006, the MSM term was changed to the Information Mirror Model (Grieves, 2005a). In the book *Transdisciplinary Perspectives on Complex Systems*, Grieves and Vickers (2017) co-published the article *Digital Twin: Mitigating unpredictable, undesirable emergent behaviour in complex systems*. In the study, Grieves stated that DT originated from his MSM. John Vickers from NASA and others then borrowed his MSM idea and applied it to NASA's technical report in 2010. His claim in 2017 was not mentioned in NASA's technical report published in 2010, and no conclusive documentary or photographic evidence has shown that DT originated from Grieves' MSM.

The team led by Prof. Iwata at Osaka University proposed VM as the "virtual manufacturing modeling and simulation environment" and developed its prototype as early as 1993 from the perspective of the original idea of DT on "the virtual representation of a physical system". The concept of VM is nearly 10 years earlier than MSM and has a history of 30 years. VM combines concepts such as real physical system (RPS), virtual physical system (VPS), real information system (RIS), and virtual information system (VIS). VM identifies four categories of VM systems based on ICT. Among the numerous DT review papers, Iwata's VM is gradually attracting the eyes of a few scholars. For example, Semeraro et al. (2021) cited and explicitly mentioned the contribution of Iwata's team in their review article *Digital twin paradigm*: VM is defined as a system aimed at generating a virtual representation of a physical system without using real facilities/entities (Onosato and Iwata, 1993).

Second, the industry generally believes that the term DT first appeared in *Modeling, Simulation, Information Technology and Processing Roadmap* published by NASA in 2010 (Deng et al., 2021). This statement is also inconsistent with facts. The term DT first appeared in the article written by Hernández and Hernández (1997). Although Hernández and Hernández (1997) did not define DT, semantically, DT is a three-dimensional digital model of the urban road network, and it is expected that the model can be iteratively modified and coexist with the physical system in implementation. DT, which appeared in NASA's technical report 13 years later, explores the digitization of advanced manufacturing; integrates and drives modern aircraft design, manufacturing, operation, and maintenance; copes real time with the complexity of hardware operation and maintenance; and expects to reduce product cost and time to market significantly. It emphasizes presenting techniques that can digitalize multidisciplinary physical models that characterize physical materials and system operation. These models can be used in the production and operation of spacecraft (Shafto et al., 2010).

Two other concepts that have contributed to the idea of DT are model predictive control (MPC) and building information modeling (BIM). The core idea of MPC is that applying models in each control cycle predicts the dynamic characteristics of a system and then seeks the finite-time open-loop optimal control strategy in the current control cycle (García et al., 1989). DT and MPC simulate current states to predict future conditions, but the goal of DT is to create virtual models in synchronization with their physical systems. BIM keeps accurate and interoperable records of building information to enhance planning, construction, and maintenance over the life of a facility (Khajavi et al., 2019). The main difference between architectural BIM and DT is that BIM is designed to increase design and construction efficiency, not real-time data. DT leverages real-time data to simulate and control physical systems, improve operational efficiency, and enable predictions. Table 1 presents the timeline of DT ideas and terminology.

Table 1 Timeline of DT ideas and terminology

	Earliest publication	
Source of DT	VM, 1993	Onosato and Iwata (1993)
	MPC, 1970s	Richalet et al. (1978)
	BIM, 2000s	Laiserin (2002)
Earliest reported DT	Hernández and Hernández (1997)	

The idea of DT has been bred since humankind developed and used computers. The earliest and most persuasive research on DT can be traced back to the VM system modeling and simulation environment proposed by Onosato and Iwata (1993). Their idea on VM is still applicable as a system modeling and simulation environment, as targeted by its derived version (i.e., DT). Therefore, either early VM or its derived DT, their theoretical development and engineering practice depend on the in-depth development and integration of interdisciplinary engineering knowledge informatization, industrial software, and ICT.

3 Case study and definition of DT

This section introduces DT by taking an example of the modeling and simulation of a gearbox, assuming that a gearbox consists of a pair of gears A and B. In the design stage, a designer applies computer-aided design (CAD) to produce a digital copy of the gearbox according to the design requirements. Before the actual manufacturing, computer-aided engineering (CAE) is adopted to simulate and analyze the structure/strength/wear/lifespan performance of the gear pair. The analysis results are fed back to the design stage. The designer optimizes and corrects the digital copy. The designs with satisfied simulation results enter the manufacturing/assembly stage. Before the actual manufacturing/assembly, computer-aided manufacturing/assembly software is necessary to simulate the machining and assembly process of the gear pair. During the actual operation and maintenance of the gearbox, the staff applies the embedded software and sensor systems to collect various physical parameters generated by the running gearbox in real-time, such as temperature, rotational speed, and stress/strain. The staff applies the data to create a digital 3D gearbox model in the computer world corresponding to the gearbox in the real world. This re-constructed digital gearbox model (i.e., gearbox twin) can help operators visually observe and predict system abnormalities and send out maintenance and control commands in time.

The above case study briefly describes the digitization of a gearbox from the conceptual phase to the manufacturing, operation, and maintenance phases (Fig. 1). Various computer-aided tools, such as CAD, CAE, computer-aided manufacturing (CAM), and embedded real-time monitoring systems are deployed for gearbox design, performance simulation, operation, and maintenance. Following this case study, we will further clarify what is DT by answering the following questions.

Can we call the computational geometric model (CAD) of the gearbox and gear pair the DT of the gearbox and gear pair? Our answer is yes. It is their geometric DT.

Giving gears a number of teeth and rotational speeds for a computer motion simulation, can we call the computational motion simulation the DT of the gears? Our answer is yes. It is their physically motional DT.

Meshing gear pairs A and B for a relative motion simulation based on the gear transmission mechanism in the computer, can we call the gear transmission simulation the DT of the gear pair? Our answer is yes. It is its physical transmission mechanism DT.

A series of computational collision/meshing simulations evaluate the contact/stress/strain/deformation of the gear pair with various speeds and stiffness. Can we call meshing collision simulation the DT of the gear pair? Our answer is yes. It is its contact/collision engineering mechanism DT.

We need to operate the coating simulation of gears to enhance the wearing lifespan of the gear surface. Can we call the carburizing simulation the DT of the gear pair? Our answer is yes. It is its carburizing/stiffness/materials engineering mechanism DT.

The global digital gearbox connects and communicates with the running physical gearbox in operation and maintenance phases. The static and dynamic characteristics of the real physical gearbox are one-to-one mapped to the computer world, such as geometric models, various information on temperatures and speeds, and various engineering mechanisms in real-time. Can we call this global digitization the DT of the gearbox? Our answer is yes. It is the global DT.

Defining DT as an advanced computational modeling

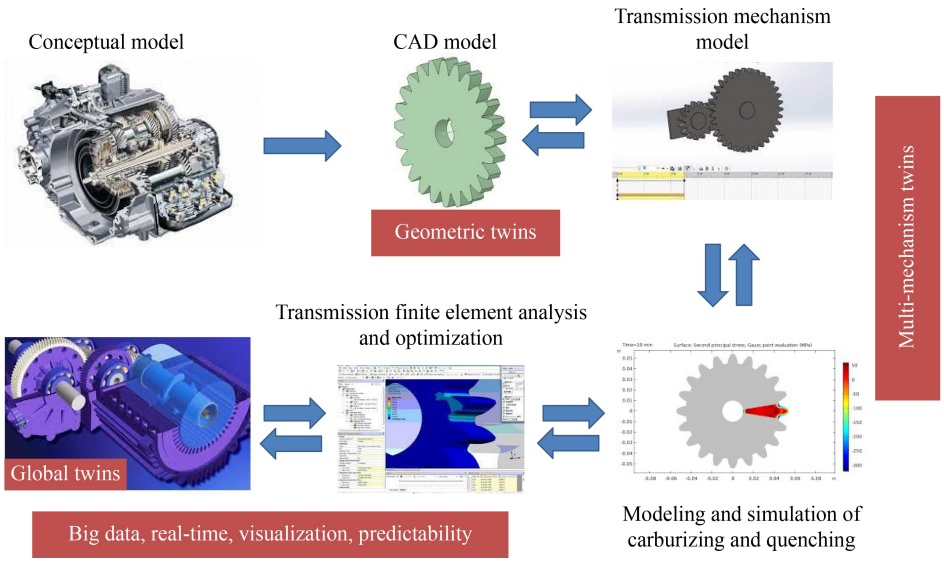

Fig. 1 The schematic diagram for the digitization of a gearbox life cycle supported by DT modeling and simulation environment.

and simulation environment for system/product/service life cycle management is reasonable. This computational environment supports the life cycle management of products/services/systems from the digitization of conceptual design, computational mechanisms simulation, and the real-time operation and maintenance with possible geometric mirroring. DT comprehensively applies modern ICTs, industrial software, and engineering knowledge, such as computational geometry, computational engineering, and Internet of Things (IoT), for collecting and transmitting data on system operating conditions in real-time, computational fluid dynamics (CFD) for simulating fluid mechanisms, and artificial intelligence for predicting system health. DT-transformed industrial application has the following characteristics.

1) System/Product/Service life cycle management support. DT emphasizes building a modeling and simulation environment for the entire system life cycle management in the computer world, rather than only for the modeling and simulation of the global system in operation and maintenance stage.

2) 3D geometric modeling of real systems. Hernández and Hernández (1997) first used the term DT, and regarded DT as a 3D digital model of an urban transportation network. Most works generally acknowledge this characteristic, including Grieves' MSM (Kritzinger et al., 2018), but it should not be the essential feature of DT.

3) The real-time sensing and measurement of system operating conditions. With the development and penetration of the IoT in industrial applications, DT can collect and transmit data and information on system operating conditions in real-time and provide big data for the subsequent various mechanisms simulations and system performance predictions.

4) Multi-mechanism modeling and simulation. Mechanism modeling (from data to model) is the digitization of engineering knowledge resulting in industrial software such as the solver for CFD. Mechanism simulation is the inverse modeling process (from model to data) for system functional and non-functional evaluations. The system modeling and simulation under the DT paradigm emphasizes the modeling and simulation for the system complexity and multiple mechanisms, such as simulations on materials, geometric structures, structural strength, and system lifespan.

5) Proactive system performance prediction. DT makes full use of big real-time data and employs machine learning, deep learning, and distributed software and hardware architecture, such as cloud computing, to predict system performance, such as equipment failures, load balance, and system lifespan.

6) Real-time system simulation and control. In addition to supporting system simulation, another core goal of DT is to perform real-time simulation for system operation and maintenance and send real-time control commands to extend system lifespan.

Leng et al. (2021) presented the enabling technology map for DT. DT itself is not like the concepts of Virtual Machine and Cloud Computing with distinct technical characteristics but is a collective term with two major technology clusters of modern ICTs and computational engineering know-how (i.e., digitalized engineering knowledge/industrial software). These modern ICTs include industrial IoT, real-time synchronization, discrete event simulation, visualization, big data analytics, industrial artificial intelligence, industrial blockchains, and cloud computing. The computational engineering know-how digitalizes engineering knowledge with CFD and finite element analysis as a result (Fig. 2).

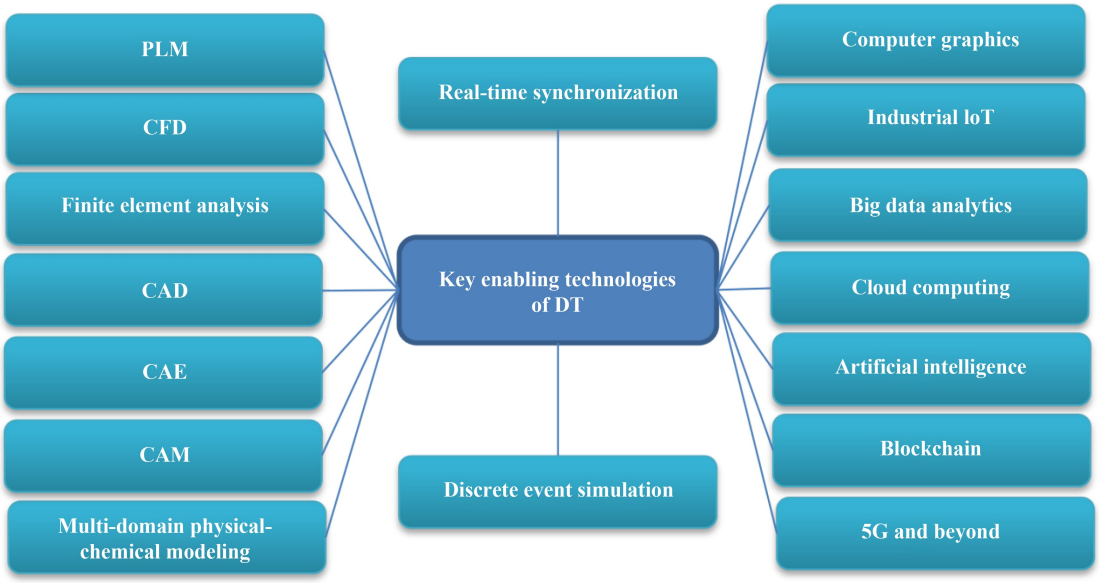

Fig. 2 Key enabling technologies for DT.

4 Three-element DT model

As mentioned in the review by Semeraro et al. (2021), the idea of DT mainly originated from VM, MPC, and BIM. This section focuses on reviewing the two-element model of VM proposed by Onosato and Iwata (1993) and proposes an extended version, a three-element model of DT. Readers interested in MPC and BIM can refer to the literature (García et al., 1989; Qin and Badgwell, 2003; Miettinen and Paavola, 2014; Volk et al., 2014).

Figure 3(a) presents the modeling and simulation architecture of a VM system composed of seven functional modules (Onosato and Iwata, 1993; Zhou et al., 2000). Figure 3(b) presents the core idea of the two-element model of VM as follows: A real manufacturing system consists of RPS and RIS, and a VM system consists of VPS and VIS. VPS and RPS have similarities in geometric structures and logical functions, and VIS and RIS are equivalent in the amount of information. This two-element model emphasizes more computational modeling and simulation of a real manufacturing system; that is, a real physical system and a computerized system can interact in information.

The two-element model assumes that the real world is composed of RPS and RIS, which ignores engineering knowledge or generally includes engineering knowledge in the information system. We divide the information system in the two-element model into two parts: Information and engineering knowledge/know-how (i.e., engineering mechanisms) and propose a three-element model of DT (Fig. 4). We believe that a real world can be represented with three elements: A real physical system (shape), a real information system, and a real mechanism system. The purpose of building a DT is to use a computer to represent approximately the three elements in the real world, such as using computer graphics to generate the 3D geometric model of a real scene and using CFD to simulate the motion performance of a real aircraft. The three-element model is also in line with the gradual human cognitive processes from shapes, information to mechanisms of a real system.

5 Review and analysis of DT practices

With the rapid development of geometric modeling and simulation, data perception, high-performance computing, and high-speed wireless communications, the concept of DT has been gradually applied to engineering practices and implemented at the system operation and maintenance level. However, based on our definition of DT as ASM&SE, the following DT practices are largely the extension of traditional informatization and digitization or the informatization solution to an engineering problem in a professional field. They may support some of the given DT features by this study, such as geometric visualization, real-time data collection, and the predictability of operating conditions with deep learning.

5.1 Smart manufacturing

Ghosh et al. (2021) proposed the concept of twin based on sensor signals, developed a DT construction system (DTCS) and DT adaptation system (DTAS) on a JavaTM-based platform, and used real-time processing of milling torque signals as an application case. DTCS constructs DT based on a delay-embedded signal processing method.

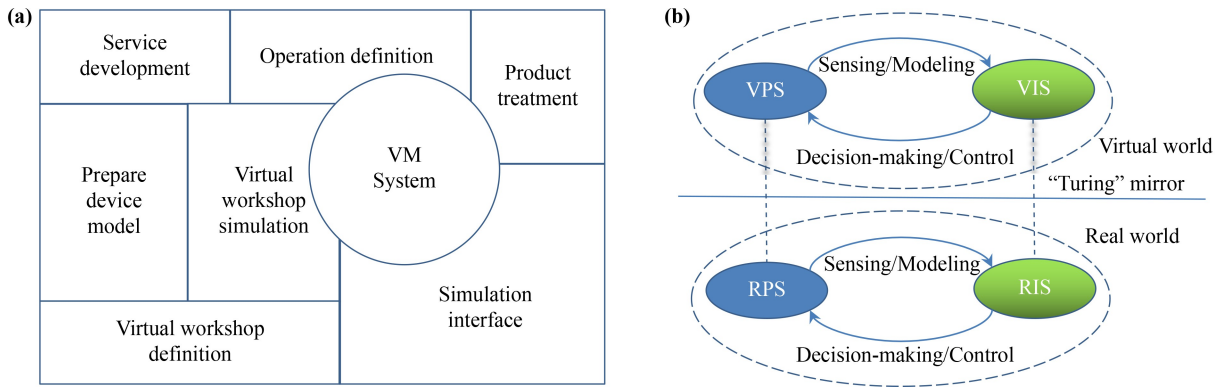

Fig. 3 The two-element model of VM.

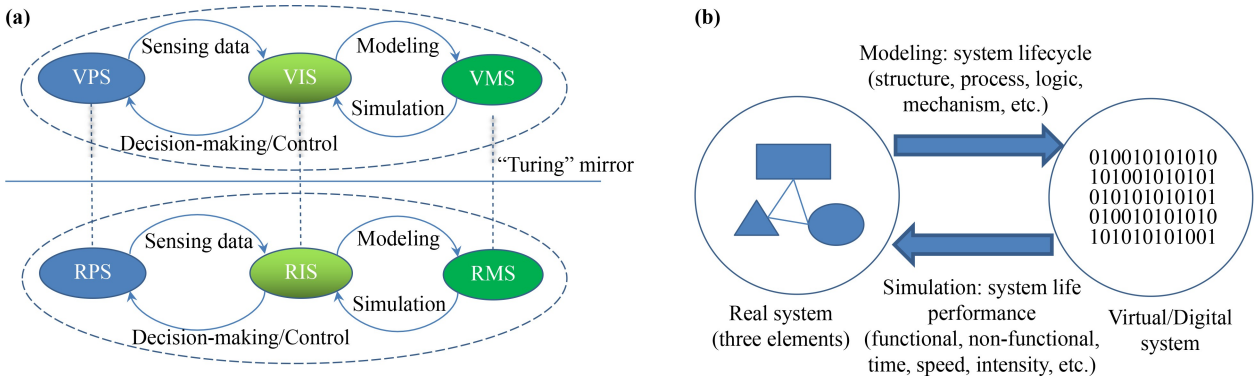

Fig. 4 Three-element model of DT (Notes: RMS stands for real mechanism system, and VMS stands for virtual mechanism system).

DTAS adapts constructed DT. DTCS consists of five modules: Input, modeling, simulation, validation, and output. DTAS only uses simulated signal datasets that the validation module tests positive while monitoring progress. It receives real-time signals from the machine tool for monitoring purposes. Any update in DTCS will change the content. DTAS will also update itself and confirm the changes in DTCS in real-time, which makes the two systems highly coupled.

This DT practice covers RPS given that sensor signal delays are real in intelligent machine tools. It covers RIS because the simulated and real delayed signals are compared to determine the course of action. This DT practice covers VPS and VIS by modeling and simulating delayed signals from sensor signals. This DT practice covers RMS and VMS because the mechanism of delayed signals is applied when modeling and simulating delayed signals.

Ghosh et al. (2021) pointed out that the goal of DT is to provide a computer system that helps build and use twins, which is consistent with the idea of VM modeling and simulation environment. The studied case is real-time monitoring of machine tools based on embedded sensor networks. Compared with the traditional monitoring system, the case emphasizes the feature of real-time modeling and simulation.

5.2 Smart building

Khajavi et al. (2019) proposed a method for establishing a sensor network to create the DT of a building, which is achieved by collecting and analyzing specific environmental factors in the exact surrounding of the building in real-time. Although this study utilizes only a limited sensor network and three environmental parameters for sensing (i.e., light, temperature, and humidity), the introduced step-by-step framework can be used to create a more comprehensive DT of a building facade and a building interior.

This DT practice constructs a geometric model of a building facade and presents the light, temperature, and humidity of the building facade in real-time. Therefore, it covers RPS and VPS. We can adjust equipment such as lighting and air conditioners according to the environmental parameters in real life. Thus, this DT practice covers RIS and VIS. It has no further processing and utilization of the environmental parameters. Thus, it does not cover RMS and VMS. Compared with BIM, it emphasizes the real-time requirement.

5.3 Smart energy

Singh et al. (2021) presented a toolbox for implementing

DT to enhance modeling and simulation practices. The toolbox can realize the DT of a battery system for a micro-robot vehicle. They reviewed DT from the perspective of modeling and simulation, proposed the implementation method, including the DT framework and process model, and gave a case analysis of a battery system. The battery DT can estimate the state of health of a battery and optimize battery life by evaluating the capacity fading with the number of cycles. Compared with the existing tools for implementing DT models, this approach focuses on defining the required features of a DT model and then selecting the relevant tools.

This DT practice does not construct a geometric model for the battery. Therefore, it covers RPS but not VPS. It covers RIS and VIS because of health monitoring based on real-time collected battery data. It estimates capacity decay using an extended Kalman filter and uses an equivalent circuit model to simulate the electrical behavior of a battery. Thus, it covers RMS and VMS.

5.4 Smart agriculture

Pylianidis et al. (2021) analyzed the value-added services of DT for agriculture and gave the development route of agricultural DT. They believe that no unified definition of DT exists for various disciplines. A feasible definition emphasizes a virtual representation of a dynamic physical object/system, which spans multiple life cycle stages and provides decision-making using data analysis methods. The so-called agricultural DT is another term for agricultural informatization or smart agriculture with the help of new ICTs. Most current DT practices in smart agriculture cover RPS, RIS, and VIS.

Other practices include the marking robot DT prototype exhibited in Hannover Messe 2018 (Fig. 5). The exhibition showed that the robot/arm in the real world performs marking tasks such as lifting and rotating, which are digitally mapped to the computer world in real-time, accompanied by the real-time visualization of multiple physical signals. Based on the rapid scene constructing, design model optimization, and configuration simulation, this DT reconstructs a digital marking robot and realizes mapping a physical marking production line to a virtual world based on MODBUS TCP protocol. The marking robot DT can dynamically make plan scheduling and operation optimization by transmitting the optimized parameters back to the physical system in real-time. Therefore, this marking robot DT covers RIS, RPS, RMS, VIS, VPS, and VMS. Table 2 summarizes the reviewed DT practices from the perspectives of the three-element DT model.

Several major features of DT applications include product/service/system life cycle management, geometric visualization of physical shape, real-time operating conditions sensing and measurement, real-time mechanisms modeling and simulation, and predictability of system health. However, DT application does not need to present all these features one time. We define DT as an ASM&SE, and its goal is to provide digitization methods and techniques to support these features. Compared with the traditional real-time marking robot, the DT system (Fig. 5) added the visualization of the 3D robot model. This addition may have value in the safety evaluation of human–robot interaction. However, this addition may not be necessary in the case of robot failure prediction, where it will increase the development costs and difficulties. Therefore, applying DT needs to consider its necessity and build the suitable DT (Zhang et al., 2021).

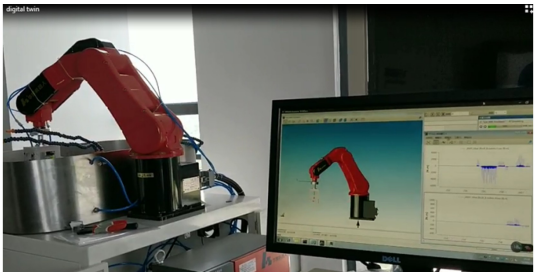

Fig. 5 Marking robot DT prototype exhibited in Hannover Messe 2018.

Table 2 DT practices

Application	RPS	RIS	RMS	VPS	VIS	VMS
Smart manufacturing	√	√	√	√	√	√
Smart building	√	√		√	√	
Smart energy	√	√	√		√	√
Smart agriculture	√	√			√	
The marking robot DT	√	√	√	√	√	√

6 Conclusions

Many different opinions, misstatements, and misuses have been heard about DT and its relevant practices. This study revisits the origin of the DT idea from the perspective of an ASM&SE. According to literature records, VM and its practice proposed by Onosato and Iwata (1993) is the earliest research and practice on DT to our knowledge. DT is an ASM&SE that deeply embraces contemporary ICTs and computational engineering knowledge with software to reconstruct the three elements of a product/service/system: Physical shape, physical information, and engineering mechanisms. The ultimate goal of DT is to achieve the transparent and predictable operation and maintenance of a real physical system. A DT application is characterized by the geometric visualization of a real system, real-time data collection of its operating conditions, complete engineering mechanisms modeling and simulation, and health prediction. Modern ICTs and the digitization of engineering knowledge are the fundamental

enabling technologies of DT. Existing DT practices are trying to apply or extend modern ICTs to propose an informatization solution to a professional problem.

For DT researchers and practitioners in engineering, the cornerstone of DT relies on engineering mechanisms modeling and simulation. Reflected in manufacturing, DT is the research and development (R&D) of modeling and simulation tools for engineering knowledge. The results are collectively referred to as industrial software, such as CAD, CAE, CAM, and CFD. With the rapid development of cloud computing, industrial software as a cloud service is gaining widespread attention from academia and industry. Recently, traditional giant industrial software companies claim to provide customers with DT solutions, for example, CATIA 3D Experience Virtual Twin by Dassault (2022) and Fusion 360 by Autodesk (2022). Essentially, they are selling similar modeling and simulation services with the label of DT.

For DT researchers and practitioners in ICTs, the cornerstone of DT relies on advanced ICTs, such as computer graphics, artificial intelligence, IoT, 5G and beyond, blockchain, mixed reality, and mathematics to address high-performance 3D reconstruction, rendering and simulation, real-time data sensing, predictable system maintenance, high-speed data communications, transaction security, unbounded interaction between virtual and real worlds, etc.

Acknowledgments Thanks to Dr. Haibin Yang from Wuhan Huazhong Numerical Control Co., Ltd. and Dr. Xudong Cai from CASICloud for sharing the demo exhibited in Hannover Messe 2018.

References

Deng T, Zhang K, Shen Z J M (2021). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. Journal of Management Science and Engineering, 6(2): 125–134

García C E, Prett D M, Morari M (1989). Model predictive control: Theory and practice — A survey. Automatica, 25(3): 335–348

Ghosh A K, Ullah A S, Teti R, Kubo A (2021). Developing sensor signal-based digital twins for intelligent machine tools. Journal of Industrial Information Integration, 24: 100242

Grieves M W (2005a). Product Lifecycle Management: Driving the Next Generation of Lean Thinking. New York: McGraw-Hill

Grieves M W (2005b). Product lifecycle management: The new paradigm for enterprises. International Journal of Product Development, 2(1/2): 71–84

Grieves M W, Vickers J (2017). Digital Twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In: Kahlen F J, Flumerfelt S, Alves A, eds. Transdisciplinary Perspectives on Complex Systems. Cham: Springer, 85–113

Hernández L A, Hernández S (1997). Application of digital 3D models on urban planning and highway design. WIT Transactions on the Built Environment, 33: 391–402

Khajavi S H, Motlagh N H, Jaribion A, Werner L C, Holmström J (2019). Digital Twin: Vision, benefits, boundaries, and creation for buildings. IEEE Access, 7: 147406–147419

Kritzinger W, Karner M, Traar G, Henjes J, Sihn W (2018). Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine, 51(11): 1016–1022

Laiserin J (2002). Comparing pommes and naranjas. The Laiserin Letter, 15

Leng J, Wang D, Shen W, Li X Y, Liu Q, Chen X (2021). Digital twins-based smart manufacturing system design in Industry 4.0: A review. Journal of Manufacturing Systems, 60: 119–137

Liu M N, Fang S L, Dong H Y, Xu C Z (2021). Review of digital twin about concepts, technologies, and industrial applications. Journal of Manufacturing Systems, 58(Part B): 346–361

Miettinen R, Paavola S (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. Automation in Construction, 43: 84–91

Onosato M, Iwata K (1993). Development of a virtual manufacturing system by integrating product models and factory models. CIRP Annals, 42(1): 475–478

Opoku D G J, Perera S, Osei-Kyei R, Rashidi M (2021). Digital twin application in the construction industry: A literature review. Journal of Building Engineering, 40: 102726

Pylianidis C, Osinga S, Athanasiadis I N (2021). Introducing digital twins to agriculture. Computers and Electronics in Agriculture, 184: 105942

Qin S J, Badgwell T A (2003). A survey of industrial model predictive control technology. Control Engineering Practice, 11(7): 733–764

Richalet J, Rault A, Testud J L, Papon J (1978). Model predictive heuristic control: Applications to industrial processes. Automatica, 14(5): 413–428

Semeraro C, Lezoche M, Panetto H, Dassisti M (2021). Digital twin paradigm: A systematic literature review. Computers in Industry, 130: 103469

Shafto M, Conroy M, Doyle R, Glaessgen E, Kemp C, LeMoigne J, Wang L (2010). Modeling, simulation, information technology & processing roadmap. Technical Report. National Aeronautics and Space Administration

Singh S, Weeber M, Birke K P (2021). Advancing digital twin implementation: A toolbox for modelling and simulation. Procedia CIRP, 99: 567–572

Tao F, Cheng J F, Qi Q L, Zhang M, Zhang H, Sui F Y (2018). Digital twin-driven product design, manufacturing and service with big data. International Journal of Advanced Manufacturing Technology, 94(9–12): 3563–3576

Tao F, Zhang H, Liu A, Nee A Y C (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4): 2405–2415

Todorovic M H, Datta R, Stevanovic L, She X, Cioffi P, Mandrusiak G, Rowden B, Szczesny P, Dai J, Frangieh T (2016). Design and testing of a modular SiC based power block. In: Proceedings of International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management. Nuremberg: VDE, 1–4

VanDerHorn E, Mahadevan S (2021). Digital Twin: Generalization, characterization and implementation. Decision Support Systems, 145: 113524

Volk R, Stengel J, Schultmann F (2014). Building Information Modeling (BIM) for existing buildings: Literature review and future needs. Automation in Construction, 38: 109–127

Wu Y, Wang X J, He Y, Huang X W, Xiao L J, Guo L X (2021). Review on the technology and application of digital twin in manufacturing industry. Modern Manufacturing Engineering, (9): 137–145 (in Chinese)

Zhang L (2020). Cold thinking about digital twins and the modeling and simulation technologies. Journal of System Simulation, 32(4): 1–10 (in Chinese)

Zhang L, Zhou L, Horn B K (2021). Building a right digital twin with model engineering. Journal of Manufacturing Systems, 59: 151–164

Zhou J H, Wu B, Yang S Z (2000). Overview of virtual manufacturing system. Bulletin of National Natural Science Foundation of China, 14(5): 279–283, 27 (in Chinese)