Chapter 2
Digital Twin Models and Networks

Abstract A digital twin (DT) model reflects one or a group of physical objects that exist in a complex real system to a virtual space. By interconnecting and coordinating multiple independent models, a DT network (DTN) can be built to map the associations and interactions between physical objects. In this chapter, we present DT models in terms of modelling frameworks, modelling methods, and modelling challenges. Then we elaborate the concept of DTNs and compare it with the concept of DT. The communication mechanisms, application scenarios, and open research issues of DTNs are then discussed.

2.1 Digital Twin Models

The main goal of DT technology is to reflect the physical world into a virtual space composed of DT models corresponding to different physical objects. As the basic element for realizing the DT function, a DT model describes the characteristics of objects in multiple temporal and spatial dimensions. More specifically, the model always contains the physical object's geometric structure, real-time status, and background information and can further include a fully digital representation of the object's interaction interfaces, software configuration, behavioural trends, and so forth. In this section, we review the DT modelling framework and introduce three categories of DT modelling approaches. Moreover, we discuss the challenges and unexplored problems of DT modelling.

The framework acts as a roadmap of the DT modelling process, which guides the twin system planning, digital model design, mapping step implementation, and performance evaluation. In particular, the DT modelling framework breaks down the complex modelling process into explicit parts and helps to elucidate the factors or interactions that affect the mapping accuracy. Several previous works have focused on the DT modelling framework.

A general and standard framework for DT modelling was first built by Grieves [4]. In the framework, the DT model was described in three dimensions, that is, the

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physical entity, the virtual model, and the connection between the physical and virtual parts. This framework has been widely applied to guide DT model construction for industrial production.

Inspired by Grieves' general framework, several studies have extended its hierarchical structure. For instance, Liu *et al.* [13] presented a four-layer DT modelling framework consisting of a data assurance layer, a modelling calculation layer, a DT function layer, and an immersive experience layer. Schroederet *et al.* [14] further introduced a framework composed of a device layer, a user interface layer, a web service layer, a query layer, and a data repository layer. Compared with Grieves' framework, the frameworks proposed in [13] and [14] consider the interactions between the users and DT models, in addition to physical–virtual interactions, and further emphasize the function of DT.

Different from the aforementioned studies, Tao *et al.* [5] described the DT model architecture from the perspective of components. The authors proposed a five-dimensional DT model that encompasses the physical part, the virtual part, the data, connections, and services. This multidimensional framework fuses the data from both the physical and virtual aspects into a DT model to comprehensively and accurately capture the features of the physical objects. Moreover, the framework can encapsulate DT functions, such as environment detection, action judgement, and trend prediction, into the unified management of virtual systems and the on-demand use of twin data. The framework in [5] mainly highlights the influence of system characteristics composed of physical data, virtual data, service data, and historical experience on both virtual twins and mapping services. Due to the completeness of the architecture in terms of DT system composition and element association analysis, it has become one of the main references in the DT modelling process.

2.1.1 DT Modelling Methods

Along with the advancement of wireless technologies and the ever-increasing demand for ubiquitous Internet of Things (IoT) services, a vast number of interconnected smart devices and powerful infrastructures have spread around the world, making physical systems much more complex and diverse while adding significant difficulty to modelling physical objects in virtual space. In response to this problem, three types of DT modelling approaches catering to different physical systems and application requirements have been introduced: a specific modelling method limited to a given application field, a multidimensional modelling method with multiple functions, and a standard modelling approach for generic DT models. Figure 2.1 compares these modelling approaches in terms of their applicable scenarios, advantages, and disadvantages.

Specific modelling refers to a method that selects only the parameters most relevant to a given application scenario as the input data for the mapping and uses a unique mathematical model for the object's model construction. For instance, in [15], specific DT modelling for a power converter was described as a real-time prob-

	Specific model	General model	Multi-dimensional model
Scenarios	Specific scenario	Commonly used in most scenarios	• Multiple sub-models • Satisfy diverse requirements of a scenario
Methods	Mathematical model	CAD, DELMIA, FlexSim, Automod	Machine model + Sensing & control model + Statistical model + Machine learning model
Advantages	• Low computation resource consumption • Satisfy specific requirements	• Apply to large -scale complex systems • High scalability • Interact with each other	• Match various requirements of a scenario
Disadvantages	• Not applicable to large-scale complex systems	• No obvious shortcomings	• Low scalability • Difficult to interact with each other

Fig. 2.1 Comparison between different DT modelling approaches

abilistic simulation process with stochastic variables developed through polynomial chaos expansion. The most important consideration in this scenario was the energy efficiency of the converter, so only parameters relevant to this objective were used as input data. Consequently, this converter DT model has a significantly lower computational cost than similar models. Similarly, in [16], a DT for structural health monitoring based on deep learning was proposed to perform real-time monitoring and active maintenance for bridges. In this work, the modelling method focused on mechanical calculus and quality assessment.

Benefiting from its specificity, the specific DT modelling approach can theoretically be perfectly adapted to given environmental characteristics and to meet particular application requirements. However, due to dynamic and nonlinear relations between physical objects, in most complex application scenarios it is very challenging to generate accurate system mapping in virtual space through a single mathematical model. The use of multidimensional DT modelling based on associated mathematical models seems a promising way to address this challenge.

The multidimensional modelling approach decomposes the entire DT model construction into several submodel building processes, where each submodel corresponds to an explicit task requirement or mapping function. Some work has adopted this modelling approach. In [17], the individual combat quadrotor unmanned aerial vehicle (UAV) model is constructed as a combination of multiple specific models, including a geometric model, an aerodynamics model, a double closed-loop control behaviour model, and a rule model. In the DT modelling process, a submodel can use specific software, extract parts of parameters, and reflect an aspect of the physical objects. For instance, the three-dimensional (3D) modelling software SolidWorks has been leveraged to build the geometric model of the quadrotor UAV. Position coordinates, inertia moment, materials, and other parameters of the UAV are set according to the actual physical conditions. The aerodynamics model is used to realize the flight of the UAV model in the virtual environment. Moreover, a double closed-loop cascade control behaviour model is adopted to ensure the accurate mapping of the UAV. Through iterative optimization, feedback, updates, and adjustment of the UAV's position and altitude parameters, a highly efficient and accurate DT model is ultimately achieved.

In modern industrial manufacturing, 3D DT models of products can be used as experimental objects in production process optimization. Taking into account the diverse attributes of the products, the authors in [18] constructed a 3D printed DT model, using a mechanistic model, a sensing and control model, and a statistical model together with big data and machine learning technology. In the proposed modelling scheme, each model has a specific use. The mechanistic model is used to estimate the metallurgical attributes, such as the transient temperature field, solidification morphology, grain structure, and phases present. The sensing and control model is then used to connect multiple sensors, such as an infrared camera for temperature measurement, an acoustic emission system for capturing surface roughness, and an in-situ synchrotron for monitoring selected geometric features. Besides the models, machine learning technology is leveraged to compare the expected results of the mechanical models with the results obtained from big data sets to determine strategies for tuning the modelling approach.

Although multidimensional modelling can match various application requirements arising in complex environments, the coordination between heterogeneous submodels is not always efficient. Especially for some scenarios with dynamic and variable requirements, this multidimensional but fixed modelling approach can have poor scalability and is not suitable for flexible DT deployment. To address this problem, we can resort to a general modelling mechanism. The general model is always oriented to the multiple requirements of a certain application field. Based on the premise of comprehensively extracting the characteristic parameters of the physical objects, a general but complex DT mapping system is constructed by using standard software tools. For instance, in the field of industrial manufacturing, there are several instances of software development in general modelling for production design and operation analysis, such as Modelica [19], AutoMod [20], FlexSim [21], and DELMIA [22].

Modelica is an open, object-oriented, equation-based general modelling language that can cross different fields and easily model complex physical systems, including mechanical, electronic, electric, hydraulic, thermal, control, and process-oriented subsystems models. Unlike Modelica, AutoMod is a computer modelling software package based on the AutoMod simulation language. It is mainly suitable for establishing DT models of material handling, logistics, and distribution systems. AutoMod contains a series of logistics system modules, such as conveyor modules, automated access systems, and path-based mobile equipment modules. It covers 3D virtual reality animation, interactive modelling, statistical analysis, and other functions.

Compared with the previous two general modelling tools, FlexSim and DELMIA have broader application scenarios. FlexSim is the only simulation software that utilizes a C++ integrated development environment in a graphical model environment. It is designed for engineers, managers, and decision makers to test, evaluate, and visualize proposed solutions on operations, processes, and dynamic systems. It has complete C++ object-oriented function, super 3D virtual reality, and an easy-to-follow user interface. Moreover, due to its excellent flexibility, FlexSim is customized for almost all industry modelling scenarios. Another modelling tool, DELMIA, focuses on a combination of front-end system design data and the resources of a manufacturing site and thus reflects and analyses entire manufacturing and maintenance processes through a 3D graphics simulation engine. The acquired digital data encompasses the visibility, accessibility, maintainability, manufacturability, and optimum performance of the production process. This tool provides a group of production-related libraries and smart visualizers in digital space for factory management.

Scientific studies have also addressed general modelling methods. In [23], Schluse *et al.* proposed a DT modelling technology called Virtual Testbeds that provides comprehensive and interactive digital reflections of operation systems in various application scenarios. Moreover, these testbeds consistently introduce new structures and processes for simulations throughout their life cycle. In [24], Bao *et al.* designed a model-based definition technology to provide digital information carriers and twin images for industrial products during their design, manufacturing, maintenance, repair, and operation phases. As a typical general DT modelling technology, model-based definition technology fuses multidimensional model parameters into a single data source and enables industrial production and services to operate concurrently in virtual space.

2.1.2 DT Modelling Challenges

Although several DT modelling methods for industrial production, modern logistics, and wireless communications have been introduced in both academia and industry, there are still challenges to be addressed to achieve generalization, flexibility, and robustness of the modelling process.

First, there is a lack of standardized frameworks that guide DT modelling in its various forms. A complete DT system is usually composed of a variety of heterogeneous subsystems. These subsystems differ significantly in their functions, structures, and elements. Therefore, different DT models, including geometric models, simulation models, business models, and so forth, need to be used to describe the respective subsystems. Although various modelling frameworks have been developed, none can simultaneously satisfy different virtual modelling requirements while accurately mapping the entire physical system. A standardized modelling framework is expected to be able to cope with various application requirements in different scenarios and stages and realize interoperability among the multiple heterogeneous submodels it contains. However, the design and implementation of this framework remain an unexplored problem.

The second challenge is how to achieve high accuracy in DT modelling. Traditional DT modelling approaches are based on general programming languages, simulation languages, and software to construct the corresponding models. The model can serve only as a reference for the operation process of the physical system and cannot provide the core data required for virtual model construction with high-precision object descriptions and state prediction. In addition, traditional DT modelling can suffer from poor flexibility, complex configurations, and error proneness.

Finally, how the DT models respond and react in real time to events occurring in the physical space is a critical challenge. In the real world, the characteristics of physical objects, such as their geometric shape, energy consumption, topological relations, and so on, change dynamically. To cope with these changes, the DT modelling should be updated accordingly. However, limited by sensing capability and data transmission capacity, it can be difficult to obtain comprehensive and real-time system state data in practical scenarios. How to perform high-fidelity model updates based on incomplete information acquisition in DT space is a problem worthy of future investigation.

2.2 DT Networks (DTNs)

A DTN is defined as a many-to-many mapping network constructed by multiple one-to-one DTs. In other words, a DTN uses advanced communication technologies to realize real-time information interactions between a physical object and its virtual twin, the virtual twin and other virtual twins, as well as the physical object and other physical objects. A DTN realizes the dynamic interactions and synchronized evolution of multiple physical objects and virtual twins by using accurate DT modelling, communications, computing, and physical data processing technologies. In a DTN, physical objects and virtual twins can communicate, collaborate, share information, complete tasks with each other, and form an information-sharing network by connecting multiple DT nodes. In this section, we first analyse the difference between DT and a DTN. Next, the communications in DTNs are discussed. Further, we depict some typical DTN application scenarios such as manufacturing, sixth-generation

(6G) networks, and intelligent transportation systems. Finally, we point out open research issues related to DTN.

2.2.1 DTN Concepts

Figure 2.2 compares the concepts of a DT and a DTN in terms of application scenarios, composition structure, and mapping relationships.

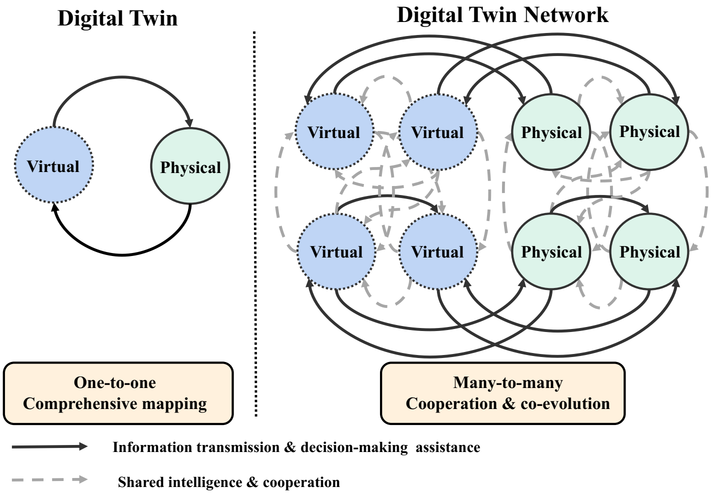

Fig. 2.2 Comparison between a DT and a DTN

First, from the perspective of application scenarios, the concepts of DT and a DTN are different. DT is suitable for reflecting a single independent object, whereas a DTN models a group of objects with complex internal interactions. For example, modelling a building in virtual space through the DT approach helps optimize the entire life cycle of the building in terms of design, maintenance, and so on. The building model depends only on the analysis and decision making according to the building's state data. In contrast, when building a virtual model of an industrial automation production line, a DTN should be used to model and reflect the collaborative relationships between the multiple industrial components involved in the production process.

Second, from the perspective of the operation mode, DT focuses on modelling an individual physical object in virtual space, and a DT model always gathers and processes the object's state information in an independent mode without interacting with other models. Constrained by an individual DT model's information collection and processing capabilities, the constructed object model might not be accurate enough, while both the time and energy consumption of this construction process can be high. In contrast to DT, a DTN collaborates between multiple DTs to model a group of objects. The information of the physical object, the processing capability of the DT model, and some intermediate processing results can be shared among the collaborative DTs. This cooperation approach significantly reduces processing time delays and energy consumption and greatly improves modelling efficiency.

Finally, from the perspective of physical and virtual mapping relationships, DT provides comprehensive physical and functional descriptions of components, products, or systems. The main goal of DT is to create high-fidelity virtual models to reproduce the geometric shapes, physical properties, behaviours, and rules of the physical world. Enabled by DT, virtual models and physical objects can maintain similar appearances as twin brothers and the same behaviour pattern as mirror images. In addition, the model in digital space can guide the operation of the physical system and adjust physical processes through feedback. With the help of two-way dynamic mapping, both the physical object and the virtual model evolve together. Considering the mirroring effect of each physical and logical entity pair, we classify the mapping relationship between physical and virtual space in a DT system as one to one. We then characterize the mapping relationship of a DTN as many to many.

In summary, DT is an intelligent and constantly evolving system that emphasizes a high-fidelity virtual model of a physical object. The mapping relationship between physical and virtual spaces in the DT system is one to one, with high scalability. A DTN is extended as a group of multiple DTs. By applying communications between DTs, a one-to-one mapping relationship can be easily expanded to a DTN. The mapping relationship is also more conducive to network management. Combined with advanced data processing, computing, and communications technologies, DTNs can easily facilitate information sharing and achieve more accurate state sensing, real-time analysis, efficient decision making, and precise execution on physical objects. Compared with DT, a DTN, which uses a network form to build complex large-scale systems, is more reliable and efficient.

2.2.2 DTN Communications

The establishment of a DTN relies on the information exchange and data communication between the physical objects in the real world and the logical entities in virtual space. According to different combinations of communication object pairs, these communications can be divided into three types: physical-to-virtual, physical-to-physical, and virtual-to-virtual communications.

Physical-to-virtual communications can be considered the process of transferring information from a physical system to virtual entities. This type of communication meets the requirements of the DT modelling process for the characteristic parameters of physical objects, and it can also feed back the modelling results to the physical space to guide parameter collection and transmission adjustment. Physical-to-virtual technology mainly uses wide area network wireless communication paradigms, such as LoRa and fifth-generation/6G cellular communications. In these paradigms, the physical objects are wireless terminals connected to a wireless access network through a wireless communication base station that further relays data to a virtual twin connected to the Internet. The communication infrastructures are robust to support real-time interactions between the physical and virtual.

Physical-to-physical communications ensure information interactions and data sharing between physical objects. Various wireless or wired devices, such as sensors, radio frequency identification, actuators, controllers, and other tags, can connect with IoT gateways, WiFi access points, and base stations supporting physical-to-physical communications. In addition, the network connections are enabled by diverse communication protocols, such as wireless personal area networks and Zigbee, and low-power wide area network technologies, including LoRa and Narrowband IoT.

Virtual-to-virtual communications, which logically encompass the virtual space, mirror the communication behaviour in the real physical world. For instance, in the Internet of Vehicles use case, virtual-to-virtual communications refer to data transmission between the DT model entities of the vehicles. Unlike communications between physical vehicles that consume vehicular wireless spectrum resources and radio power, this virtual mode depends mainly on DT servers' computing capability to model data transmission behaviours. Another key benefit of virtual-to-virtual communications is the data transmission modelling, which breaks through the time constraints of the physical world. We note that communications between actual vehicles consume a certain amount of time. However, in virtual space, the same communication behaviour can be completed much more quickly. Thus, we can reflect or simulate a long period of communication behaviour with a low time cost. Furthermore, a given communication behaviour can logically occur in virtual space earlier than it actually occurs in physical space. The effect of logical communications can be leveraged to guide resource scheduling in the real world. Edge intelligence, which consists of artificial intelligence–empowered edge computing servers, is a critical enabling technology for achieving virtual-to-virtual communications. Edge servers thus provide the necessary computing capability for channels' model construction and data transmission while artificial intelligence learns the characteristics of the physical network and adjusts the communication modelling strategies.

2.2.3 DTN Applications

With the development of DT technology, many application scenarios using DTN to assist process management and policy adjustment have emerged, such as smart manufacturing, 6G networks, and intelligent transportation systems.

Subject to the high costs of updating production, traditional manufacturing has problems with low production efficiency and outdated product designs. The introduction of DTNs in new smart manufacturing can effectively address these problems. For the factory production line, by establishing a virtual model of the entire line, the production process can be simulated in advance and problems in the process found, thereby achieving more efficient production line management and process optimization. Moreover, in the real production process, the virtual twin of the factory can be continuously updated and optimized, including the DT model of factory construction, product production, industrial equipment life prediction, system maintenance, and so forth. DTNs that match production requirements are helpful for achieving efficient digital management and low-cost manufacturing.

6G networks aim to integrate a variety of wireless access mechanisms to achieve ultra-large capacity and ultra-small distance communications. In reaching these goals, 6G networks could face challenges in terms of security, flexibility, and spectrum and energy efficiency. The emergence of DTNs provides opportunities to overcome these challenges. DTNs enable 6G networks to realize innovative services, such as augmented reality, virtual reality, and autonomous driving. A DTN can virtually map a 6G network. The virtually reflected 6G network collects the traffic information of the real communication network, implements data analysis to discover data traffic patterns, and detects abnormal occurrences in advance. The 6G network uses the information fed back from the virtualized network to prepare network security protection capabilities in advance. In addition, by collecting and analysing the communication data in the DTN, communication patterns can be determined. Then, by reserving communication resources, the demand and supply of data delivery services can be automatically achieved.

In recent years, the urban transportation system has experienced road network congestion and frequent traffic accidents. DTNs leverage multidimensional information sensors, remote data transmission, and intelligent control technology to provide information assistance services for intelligent traffic management and autonomous vehicle driving. First, a DTN provides a virtual vision of the transportation system, helping to dispatch traffic and optimize public transportation services. Next, by processing massive amounts of real-time traffic information, the virtual system of a DTN can accurately predict traffic accidents and thus help avert them.

2.2.4 Open DTN Research Issues

As an emerging technological paradigm, DTNs have demonstrated strong physical system mapping and information assistance capabilities. Both DTN operation technologies and application scenarios have been studied, but further research questions remain.

Security is one of the key research issues of DTNs. A DTN is a complex system composed of virtual mappings of various networks and objects. This complex structure makes its security difficult to protect. Moreover, information sharing within virtual networks can raise security concerns. In a DTN, a pair of twins has a bidirectional feedback relationship. Even if the physical system in the real world is well secured, an attacker can easily change the parameters of the virtual model or the data fed back by the virtual model. Such attacks are particularly harmful to data-sensitive applications such as intelligent transportation systems and medical applications.

DTNs rely on real-world information, whose gathering process can cause privacy leaks. For example, in intelligent medical care, the virtual modelling of the human body needs to collect various types of biological information and monitor the patient's daily activities. In treatment, sensitive data can be sent to and processed on edge servers. Edge service operators can share these data with other companies without user consent, which increases the risk of privacy breaches. How to balance data utilization and privacy protection turns out to be a critical challenge for DTN exploration.

Another research issue to consider is resource scheduling. The construction of a DTN consumes a variety of heterogeneous resources, including sensing resources for information collection, communication resources for data transmission, computing resources for modelling processing, and cache resources for model preservation. These resources jointly affect the efficiency and accuracy of DTN operation. The way to optimize resource scheduling is worthy of future investigation.