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Survey paper

A comprehensive survey on digital twin for future networks and emerging Internet of Things industry

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ABSTRACT

The rapid growth of industrial digitalization in the Industry 4.0 era is fundamentally transforming the industrial sector by connecting products, machines, and people, offering real-time digital models to allow self-diagnosis, self-optimization and self-configuration. However, this uptake in such a digital transformation faces numerous obstacles. For example, the lack of real-time data feeds to perform custom closed-loop control and realize common, powerful industrial systems, the complexity of traditional tools and their inability in finding effective solutions to industry problems, lack of capabilities to experiment rapidly on innovative ideas, and the absence of continuous real-time interactions between physical objects and their simulation representations along with reliable two-way communications, are key barriers towards the adoption of such a digital transformation. Digital twins hold the promise of improving maintainability and deployability, enabling flexibility, auditability, and responsiveness to changing conditions, allowing continuous learning, monitoring and actuation, and allowing easy integration of new technologies in order to deploy open, scalable and reliable Industrial Internet of Things (IIoT).

A critical understanding of this emerging paradigm is necessary to address the multiple dimensions of challenges in realizing digital twins at scale and create new means to generate knowledge in the industrial IoT. To address these requirements, this paper surveys existing digital twin along software technologies, standardization efforts and the wide range of recent and state-of-the-art digital twin-based projects; presents diverse use cases that can benefit from this emerging technology; followed by an in-depth discussion of the major challenges in this area drawing upon the research status and key trends in Digital Twins.

1. Introduction

The emerging 5G network is expected to bring instantaneous connectivity to billions of Internet of Things (IoT) devices, in turn enabling the digital transformation of Industry 4.0 for companies, customers, and investors. According to a recent study [1], 85 percent of IoT platforms will contain some form of digital twinning by 2025, driving projections of market growth from \$3.1 billion today to \$48.2 Billion in the next five years. A digital twin (DT) is a virtual model or representation of a physical object, a process, or a system, synchronized and updated from real-time data, at a specific frequency and fidelity [2]. The concept of *twins* was initially introduced by the United States National Aeronautics and Space Administration (NASA) Apollo program in the 1970s, where virtual replicas of space vehicles on Earth were built to mirror the condition of the equipment during the mission [3]. Then, the concept of *DT* was introduced by John Vickers and Michael Grieves [4] in the Product Lifecycle Management (PLM) as a virtual instance (twin) of a physical system [5].

Presently, the concept of DT is used in a wide variety of domains, such as manufacturing [6], healthcare [7], smart cities [8], smart agriculture [9], smart grids [10], and mechanical engineering [11], to enhance the performance, enable proactive maintenance to extend

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the physical system's life [12], enhanced productivity, and faster innovation with reduced costs [13]. Typically, DT systems are generated and then synchronized using bidirectional data flows between the real-world physical components and their virtual replica counterparts [14]. Furthermore, a DT can enable continuous prototyping and testing on-demand without interruption, thereby assuring and self-optimizing use cases, such as 5G network and beyond [15,16]. In IoT use cases, it creates virtual replicas of IoT devices in various application scenarios [17] and maintains a device twin for every connected device.

Despite the promise of DT, existing work on DT focuses primarily on the modeling perspective [18,19] and pays less attention to simplifying the control and management of industrial IoT networks. Additionally, technology adopters report several barriers to this digital transformation including prohibitive complexity with network deployments, security risks, and need for new business models and practices. Security and privacy are the main concerns for sharing IoT data among distributed DT infrastructures [20]. In particular, data in theDT Network (DTN) is fed back between the physical object and the virtual model, thus making the virtual model vulnerable to cybersecurity attacks [21]. Defending against such attacks is critical for scenarios like remote robot surgery, intelligent transportation systems, and federated EU-US airport operations [22].

Similarly, DT require continuous interaction between real-world objects and their virtual representation in real-time and with reliable two-way communications [23]. However, due to the dynamic behavior and frequent changes in the network environment, it becomes challenging to ensure stringent reliability, low latency, and real-time requirements over the future wireless broadband 5G and 6G networks [24]. Research on DTs for 5G networks and beyond is still in its infancy, and the current implementations focus on limited and specific scenarios, such as network optimization, in which DTs act as a simple network simulation tool to solve the operation and maintenance problems. Yet, DTs could be considered an indispensable part of the entire lifecycle of the physical network in the future, serving more important issues in future networks beyond 5G, such as in network planning, construction, maintenance, optimization, automation, orchestration, etc.

Additionally, since different standardization bodies are developing various DT standards, it is more challenging to define a more unified reference architecture of DTs. For example, Tao et al. [13] proposed a five-dimensional framework of DTs that involves physical entities and represents a virtual entity, service, twin data, and the connection between various components. ISO [25] is developing a standard for a DT manufacturing system; the Digital Twin Consortium (DTC) is drafting a DT architecture that embodies the entire domain of devices and processes [26]; the Digital Twin Web Association (DTWA) is defining the concept of Web of Digital Twins (WoDT) [27] to exploit service-oriented architectures to build digital twins document specification for the web of things; and the Building Digital Twin Association (BDTA) is promoting another DT architecture in the construction sector.

In spite of the promising benefits of DT that are analyzed in few survey reports, none of them focus on articulating the fragmented international standards and dealing with the diversity of software implementations. Rather, existing surveys mainly review DT from the modeling perspective and focus on physical objects and their virtual twins, while reference architectures and networks which provide communication support for DT, are often missing. For instance, Schleich et al. [28] surveyed the recent advances in DT and its enabling technologies and showcased different use cases across the product lifecycle involving the design, manufacturing, use, and recycling phases. Likewise, Lim et al. [29] analyze the state-of-the-art of DT approaches in smart manufacturing and Product Life Management (PLM), and highlight tools and models used for creating DT for PLM engineering. Similarly, Wu et al. [2] surveyed recent advances in DT Network deployment in different application domains. Regardless of how a DT is defined, the literature provides very little insights into its deployment in future IoT applications with the forthcoming 5G network. Moreover, the discussion about the challenges, prospects, and trends in future networks have not been investigated either. Finally, there are no studies to understand and fill the gap between a company's awareness of the DT and their current levels of adoption.

To address these limitations, this paper makes the following contributions:

- We present findings based on a comprehensive literature survey on DTs in IoT and 5G scenarios, comprising both research projects and tooling;
- We discuss standardization efforts in the realm of DTs ;
- We describe a number of use cases, explaining how DTs can help these use cases;
- We present open research challenges, trends, and prospects; and
- Finally, we present details of our project called Hyper-5G that is addressing some of these challenges.

The organization of this paper is as follows: Section 2 provides a deep introduction to the DTs concept and discusses its properties. In Section 3, we delve into diverse DTs standardization, specifications, and describe their different reference architectures. Section 4 delves into available open source and commercial software implementations of DT tools to enable the future digitalized industry. We present in Section 5 recent projects that have been initiated to facilitate the integration of DT in real-world applications. Section 6 describes diverse use cases and how DT can serve various applications. Section 7 discusses open challenging issues that still represent barriers towards large-scale adoption of DT. Section 8 articulates key research directions towards enhancing the digital twin lifecycle towards removing organizational, technical and technological barriers and increase its acceptance level in many industries. Finally, Section 9 provides concluding remarks describing potential future directions in this realm.

2. Overview of the digital twin concept

The concept of DT is poised to make drastic changes in the future of industrial IoT environments. This section delves into the central concept of digital twins and discusses its main properties.

2.1. Understanding the key concepts of the digital twin

The purpose of a DT is to build effective communication between the physical world and the information world. This means using a large amount of data collected effectively from the physical world to create a virtual representation of the physical world. In this section, we delve into its key concepts.

2.1.1. Types of digital twins

There are different types of digital twins, depending primarily on the use cases and real-world scenarios in which they are used. We will describe different use cases in Section 6. Shyam et al. [30] identify four types of digital twins as follows:

- **Discrete versus Composite:** The scope and scale of the DT depend on the use case in which it will be used. One type of DT known as *Component/Part Twins* is one where the DT represents the model of an individual part of the production system. For example, more complex systems will involve multiple DT instances and aggregates that will be assembled and composed together to form the whole DT representation. Conversely, small-scale systems may involve a single/atomic DT instance to represent the physical assets in the DT, which is therefore called a discrete DT. Hence, a discrete DT is a lower level of abstraction of more complex systems, i.e., systems of systems or composite DTs.

- **Product versus Facility:** This type of DT is also known as *Asset Twins*. It represents a manufactured product, which encapsulates the exact manufacturing conditions of each final product, such as a pump, gas turbine, electric motor, etc. The main objective of this type is to monitor the use of a specific asset or entity, which may involve information about its failure and real-time operations. The facility DT revolves around manufacturing or production, which consists of the union of different individual assets, e.g., an assembly of unique product twins.
- **Simulation versus Operational:** In the early stages of a product life cycle, a DT often focuses on modeling and simulation scenarios before the asset begins to be processed. Next, once the asset is made available in the physical real-world system, the focus is more on the operational and maintenance challenges. Comparable to DevOps (Development and Operations), this type is considered Simulation and Operational (SimOps) DT; thus, the simulation is more project-oriented. At the same time, the operations involve the entity's operation and maintenance life cycle.
- **Analytics-versus Physics-based:** This model uses historical and real-time data for representing an entity and predicting its current and future states, either based on empirical/analytic models or physics-based algorithms. The former use artificial intelligence techniques (e.g., statistics) to predict the behavior of an asset using available historical data. The latter makes use of physical laws (e.g., fluid dynamics, atomic, molecular, and optical), material properties (size, shape, the density of the particles, tensile strength, compressive resistance, elasticity, grain, and their intrinsic mechanical properties), etc. to generate insights to allow predicting the behavior of an asset or a product.

Similarly, Alves et al. [31] have introduced typology of different types of Digital Twins for smart farming. For example, *imaginary DT* represent objects that imagined by designers but has not been created in physical world. *Monitoring DT* are connected to physical objects or processes in near real-time to supervise its operations and condition in the surrounding environment. *Predictive* DT use mathematical and statistical modeling to forecast the future states and behavior of physical objects. *Prescriptive* DT use artificial intelligence to provide corrective and preventive actions to help the physical process in decision-making. *Autonomous* DT does not need human intervention to feed decisions to the physical system, but autonomous provides fully control of the system behavior. Finally, *Recollection* DT stores large amounts of variant data and extract significant value from it for providing the traceability of products and keep a historical record. However, these types remain conceptual, as they can be implemented as part of the main DT, e.g., they can be considered as small instances of the main DT.

2.1.2. Characteristics of a DT

Since DT has been applied to different use cases and since each use case generates its own DT characteristics [32–34], there are no generic characteristics that can be applied to all scenarios. In this section, we will discuss, without loss of generally, the main characteristics that a DT should possess. These properties are described in Table 1.

A key characteristic of any DT is the presence of network connectivity. This is needed since the physical object and its virtual replica communicate to exchange the physical twin status and changes along the lifecycle, and share context representation about their surrounding dynamic environment. Thus, the networking interfaces/devices should guarantee seamless connection, synchronization, and continuous data stream exchange, either using direct point-to-point communication, or even indirectly, through brokers, proxies, gateways, or cloud-based connections.

Table 1
Key characteristics of a DT.

Characteristics	Description
Network connectivity	It involves both the connection from the physical to a virtual environment and the connection from the twin to the physical world.
Physical entity/asset	An asset, an object, an entity, a process or a product that exists in the real physical world.
Physical environment	The real world environment in which the physical entity exists, such as a factory, construction, hospital, manufacture, smart city, etc.
Virtual entity	The virtual replica of the physical entity, i.e., the DT prototype and its instances when synchronized with their physical replica
Virtual environment	A virtual representation of the physical environment, which may involve Unity 3D, AR/VR, and metaverse tools.
Synchronization	The virtual replica (object, system, or process) should be synchronized with the real world so that any change in the physical world should be reflected in its digital representation, which feeds back insights into the reverse direction.
Twinning Rate	As the physical and twin worlds should be synchronized, they should therefore agree on the frequency with which data is exchanged, i.e., the rate with which synchronization occurs.
State	The current behavior or values of all parameters that define a state (or multiple states) of either the real-world or virtual entity/environment.
Physical Process	The process in the real-world environment within which the physical entity engages changes or impacts the behavior of the physical twin.
Virtual Process	The virtual process (e.g., analytics, computational techniques, etc.) employed in the virtual twin that will change or impact the state of the virtual replica.
Fidelity	The accuracy of the DT model to describe the physical assets, no matter how complex the physics or geometry are. Fidelity can be assessed when considering the frequency of the model updates.
Parameters	Includes all kinds of information, meta-data, and processes exchanged between the physical entities and their twins, e.g., temperature, production scores, and processes.

2.1.3. Data and models

The DT exists in the virtual environment in a digital format, i.e., represented in different data sources and models (e.g., file structures like JSON and XML that hold DT meta data) that transform data into DT information for various applications.

The DT data can present itself in the following forms:

- **Time Series Data:** Time series insights are used to collect and analyze historical data about physical assets and perform data analytics (e.g., regression) on them [35]. They also provide timestamped temporal and real-time data that can be stored in time series, as well as NoSQL databases that can be used to synchronize the physical assets with their twins.
- **Master Data:** Typically, those data are stored in enterprise data stores (e.g., Enterprise Resource Planning (ERP), Enterprise Asset Management (EAM)). For example, physical assets comprise multiple sensors capable of gathering ERP real-time data and transmitting operational status [36]. DT requires an Enterprise Knowledge Graph [37]. The latter comprises concepts and instances defined using ontologies and computational agents to ensure that Master Data Management (MDM) represents generic data of physical objects belonging to organizations, such as clients, providers, products, and locations, through distinct layers.

- **Transactional Data:** Operational, transactional data represent the next frontier in Digital Process Twins. It describes the virtual representation of an actual business process, which in turn describes the accurate model of the business process and the real-time status data received from the process that helps to exert control over the process through adjusting the DT . An example of transactional data can be found in Computerized Maintenance Management Systems (CMMS), Manufacturing Execution Systems (MES), Business Process Management (BPM), and production systems.

The DT models can be of the following types:

- **Physics-based Models:** This is one of the traditional models used in simulation and co-simulation, where multi-physics get real-time data, engineering calculations, discrete physics, and where machine learning are integrated with physics-based models to investigate several predictive scenarios. The latter are used for predicting damaged structures, maintenance planning, uncertainty, operational parameters, etc. [38].
- **Analytics-based Models:** Typically, advanced machine learning algorithms and mathematical and statistical models are used in the virtual twin environment to predict the current and future of the physical asset. They can also create recommendations, operate on analytical data, and extract insights to help predict future behavior, simulate different scenarios, and perform other analytics tasks [39].
- **Visual Models:** the recent advances in Augmented Reality (AR), Virtual Reality (VR), metaverse, Geographic Information systems (GIS), and Building Information Modeling (BIM) makes it possible to integrate visual models (e.g., Unity 3D models, Internet of 3D worlds) into the DT [40]. For example, integrating Google Maps Street View with the DT can make updates in real-time as objects move and change on it continuously.
- **Discrete Event Simulation (DES) Models:** DES models [41] can be used to create a full DT of the production and manufacturing process, as they abstract the machine group's behaviors into complex event-driven operations. For example, by combining computer-aid modeling method to create higher multi-fidelity simulation models provides higher accuracy analysis and rapid decision-making in Industrial 4.0.

2.2. Key properties of digital twins

In this section, we discuss four main properties of DT using which they can be evaluated for their effectiveness. These include: (i) representativeness and contextualization; (ii) reflection and replication (iii) persistency; and (iv) composability.

- **Representativeness and Contextualization** Digital twins represent the physical objects as logical objects in specific application context [17]. Indeed, representativeness of a DT refers to how effective are the models' behavioral representation of real-world objects, how virtual replicas are built, and how synchronize their states by reasoning about events and modifications to the context. Therefore, any DT framework should consider the source of data and the surrounding environment in which data are collected and to support context-awareness features to understand the context of data collection [42]. The representativeness and contextualization in DTs are made possible through the simplification and generalization of the models' behaviors
- **Reflection and Replication** DT mirrors the states and the behavior of the real-world objects and reflects all the changes that happen in the physical systems, i.e., features, status, data, events, actions, and all the other information characterizing the physical object to their virtual replicas. Reproducing the status of the physical entities requires reliable communication that reflects any changes to the virtual entities at the same rhythm and rate of these changes. Additionally, physical objects can be virtualized, instantiated, and replicated several times in a virtualization space. The replicated instances should be consistent and synchronized (i.e., time and status synchronizations) with the physical one [43]. Replicability is, therefore, a desirable property to support the intertwining between real-world space and DT replicas.
- **Persistency** As the DT is expected to replicate the physical objects, it must always be highly available and provide persistent data in the digital system [44]. The availability of DT is provided during the lifecycle of the process, i.e., during the design, creation, operation, crashes, maintenance, upgrade, and even after the destruction of the physical objects. Hence, the DT should always be persistent in all possible scenarios, i.e., virtual objects should be resilient and stay available all the time.
- **Composability** The DTs can often aggregate different entities to represent more complex systems in the virtual space. This ability of grouping together different objects into a single, composed object to perceive the changes and behavior of individual objects and the whole system represents the composability of digital twin [45]. Digital twins need to take care of complex aggregation of physical objects.

2.3. Comparison of DT against other concepts

DT can be compared to different existing other concepts, e.g., simulations, emulations, digital shadows, digital thread, etc. While digital twin itself refers to a virtual replicate of the real-world system that receive data from the physical system and send decisions to perform closed-loop control, it differs significantly from other concepts. In particular, DT can be distinguishable from simulation, which attempts to simulate the internal state of an object as close as possible to what could happen to an object. DT can be also be differentiated from emulation, as an emulation involves an emulator that tries to imitate the external behavior of an object as closely as possible. Furthermore, DT can be confused to digital shadows, as both offer digital representation of objects and processes. However, data flow in digital shadows is a one-way process [46], i.e., data can only go from the physical object to the virtual object so that changes in the physical world results in changes to the virtual world, but not vice versa. Additionally, DT uses the digital thread [47] data to perform custom closed-loop control and build on powerful representations for the design, evaluation, and recording of the life cycle management of a product or system. The digital thread is considered as the framework that connects siloed elements of the DT and provides an integrated view of an asset throughout the manufacturing lifecycle.

3. Standardization efforts for digital twins

Different standardization efforts are undertaken by multiple foundations and organizations, such as the International Standards Organization (ISO), the Industrial Digital Twins Association (IDTA) and the Digital Twins Consortium (DTC). These multiple efforts create some challenges for unifying digital twins into systems. In this section, we discuss the current standardization efforts in the area of the DT. Table 2 summarizes the list of projects with the same aim.

3.1. DTC reference architecture

The DTC Reference Architecture has been established by the Digital Twin Consortium in collaboration with the Object Management Group to drive awareness, adoption, security, and interoperability for unifying multivendor digital twin ecosystems [48]. It also provides

Table 2
Digital twin standardization efforts.

Project name	Description	Use cases	Link
Digital Twin Consortium	Provides composable DT, Uses microservices to build DT components, Introduces Packaged Business Capabilities	Natural Resources (gas, oil, etc.), Aerospace and defense, Construction, Manufacturing	DTC
Digital Twin Web Association	Exploits SOA document for creating HTML for DT, provides web-based DT for 3D web interaction and supports web of things (WoT)	Web applications, Automated processing, AR/VR and Mixed Reality, Traffic radar data discovery, Factory control	DTWA
Industrial Digital Twin Association	Introduces AAS tools for DT representation, ensuring interoperability between manufacturers, and supports many data formats (JSON, XML, etc.) and OPC Unified Architecture	Manufacturing, Healthcare, Industries 4.0, Supply chain	IDTWIN
Digital Twins Working Group	Builds a BIM tool for data modeling and processing to accelerate DT adoption	Construction, Engineering, Manufacturing	DTWG
Industry IoT Consortium	Delivers transformative business value to industry and offers interoperable DT for diverse industries	Construction, Manufacturing, IoT, Oil, gas, Process automation, Energy, and Utilities	IIoT Consortium
Internet Research Task Force	Build DT for cellular and mobile network, and enable network DT	Mobility management, Network Monitoring and optimization, Intent based network	IETF
International Organization for Standardization	Build IoT DT architecture for industrial IoT, measurements, and manufacturing	Industrial Processes	iso23247
Digital Twin Computing Reference Model	As for IIC, builds DT models for industrial IoT and accelerating the adoption of DT for manufacturing	Factories	DTC
ITU-T Requirements and Architecture of DT Network	Provides DT architecture for telecommunication and mobile networks	Telecommunication and Mobile and cellular networks	T17-SG13
International Electrotechnical Commission	Builds DT models and architectures for Energy	Energy, Oil, gas,	IEC

insights towards designing and building scalable industrial manufacturing processes by enabling continuous improvement in lifecycle management [49], enabling a circular product-based approach and influencing policies, standard requirements, and the development of DT technology. The DTC group defines standard requirements and use cases. Specifically, it defines the reality capture [26] that embodies the entire domain of devices and processes, which collects conditions of a physical object or space to provide a faithful and transparent representation of real-world conditions in the virtual representation of the DT framework. Additionally, the group advocates consistent best-practices methodologies, formal methods for digital master, digital twin representation and interlinking, and DT maturity model [50]. Furthermore, the DTC group provides a library of reference implementations for digital twins, publishing and amplifying architectures [51], leveraging frameworks and open-source code implementation [52] that help build an extensive, multi-faceted DT ecosystem in large-scale, complex environments. The group also introduced a Security Maturity Model [53] to identify the appropriate approach to security mechanisms for IoT.

The Capabilities Periodic Table (CPT) [51], shown in Fig. 1, has been established to elaborate a requirements-definition framework that works with any architecture or technology and makes it easier to design, deploy, and run digital twins for a wide range of industrial purposes. At its core, the architecture uses a Composable Digital Twins (CDT) reference model to help with the development of digital applications based on composable enterprise architectural patterns. These CDTs focus on developing microservice-based orchestration and reusable Packaged Business Capabilities (PBC) to support interoperable, multi-technology, and multivendor applications [51].

The Composable Digital Twin Reference Model is a layered architecture that encompasses the following layers:

- Composed Digital Twins Experiences: PBCs are provided to offer a unique modular composition that targets the goals and opportunities offered by the DT, i.e., by combining different configurations, real-time data, decision-support tools, data types, models, etc., to create reusable business capabilities.
- Digital Twins Composition Platform: it provides necessary tools for orchestrating, integrating, and composing applications based on the necessary use case requirements, which offers a high level of agility and flexibility towards fulfilling the business requirements.
- Packaged Business Capabilities: PBCs can be used in the DT platform to compose the DT and offer a certain level of security and trustworthiness across the DT orchestration platform.
- Data Fabric: it provides the tools, algorithms, and mechanisms to enable digitalization, supply services and processes, and bring alive the DT, i.e., by ensuring data availability at the right time at the right place.

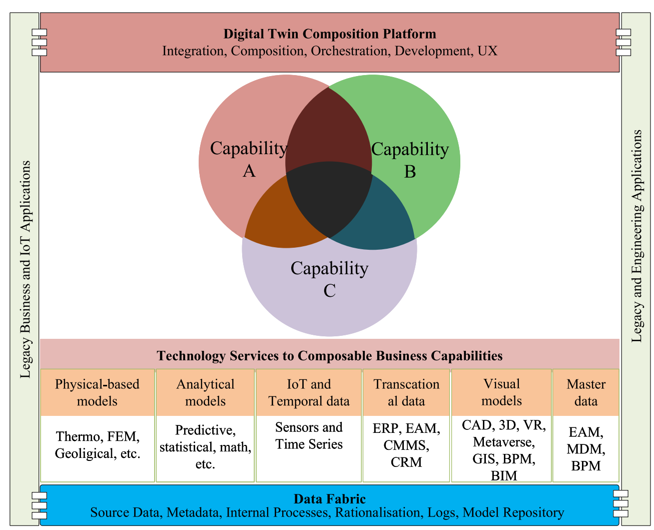

Fig. 1. Composable digital twin reference model.

3.2. Industrial digital twin association (IDTA)

The Asset Administration Shell (AAS) [54–56] has been introduced by the IDTA as a standardized digital asset representation to ensure

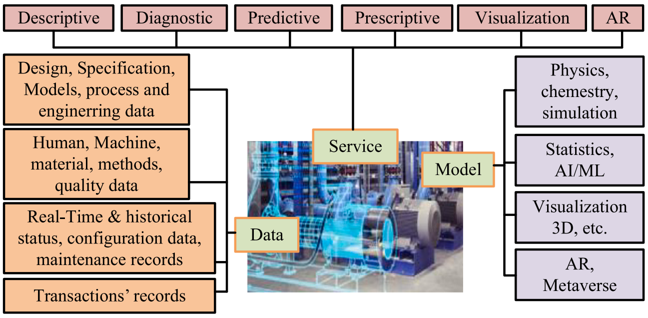

Fig. 2. Constituents of the IIC's digital twin.

manufacturing systems' interoperability. Part 1 of the AAS specification [54] defines several protocols to serialize AASs in different formats, such as JSON, XML, or AML. AML (Automation ML) [57] is an open, vendor-neutral, XML-based, and free data exchange format for industrial automation and control systems, defined in the IEC 62714 series. It describes how information about assets can be exchanged safely between industrial partners. The document describes the metamodel for information of an Asset Administration Shell and its submodels, as well as the exchange format for the transport of information from one partner in the value chain in an interoperable way. It introduces a comprehensive UML model and XMI representation of details of the AAS for mapping suitable technologies to be used in different life cycle phases (such as XML and JSON for exchange between partners via the *.aasx* exchange format, AutomationML for the engineering phase, OPC UA information models, and RDF for reasoning). The definition of attribute-based access control (ABAC) protects system resources from unauthorized access [58].

The specification includes APIs and interfaces for getting to AAS information so that you can view, change, query, and run information and active functionality. It also includes the infrastructure for connecting multiple AASs through a registry, discovery services, endpoint handling, and other things [Wagner2017].

3.3. Industry IoT consortium (IIC)

A reference architecture for DT [59] has been introduced by the IIC to integrate many vendors and technologies and help them to manage their complexity. Common features have been introduced to fulfill many DT vendors requirements, including Document Management, 3D representation, modeling, simulation, data modeling, model synchronization, connected analytics, etc. Additionally, the IIC introduced practical guidance [60] on digital twins that includes the definition, benefits, architectures, and building blocks to implement them. The proposed document describes the relationship among DT systems as a level of abstraction (e.g., discrete, composite, hierarchical, association, peer-to-peer DT). Fig. 2 illustrates the DT data, computational models, and service interfaces.

Data: a DT should contain data about its real-world twin that are required by the models to represent and understand the states and behaviors of the real-world twin. In many cases, it may consist of data in the full lifecycle of the real-world object, in the case of equipment, data during the design phase (specifications, design models, production process, and engineering data), production phase (data about a worker, production equipment, material and parts, production methods and quality assurance data), operation phase (data about installation and configuration, real-time and historical state and status, as well as maintenance records) and even end-of-life procedural data. It may also contain business data, such as transaction records.

Models: A DT should contain computational or analytic models that are required to describe, understand, and predict the twins' operational states and behaviors and models that are used to prescribe actions based on business logic and objectives about the corresponding real-world object. These models may include physics or chemistry, engineering or simulation models, data models based on statistics, machine learning, and Artificial Intelligence (AI). It may also include 3-D and augmented reality models to aid human understanding of real-world objects' operational states or behaviors.

Service (interface): a DT should contain a set of service interfaces for industrial applications or other digital twins to access its data and invoke its capabilities.

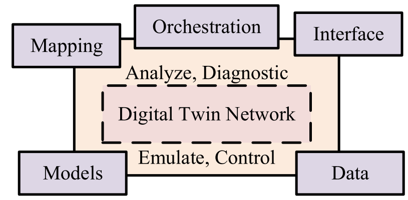

Fig. 3. Key elements of IETF digital twin network.

3.4. Internet engineering task force (IETF)

IETF has recently introduced a reference architecture for network digital twin [61] in which it identifies four key elements to compose a DT network, i.e., data, models, interfaces, and mapping, as shown in Fig. 3. First, *data* are collected from the network elements (e.g., physical and virtual equipment, links, routers, middleboxes, controllers, NFV functions, etc.). Then they are stored inside the data repository to provide timely and accurate data service support to build various DT models. The collected information includes configuration data, operational state data, topology data, trace data, metric data, and process data. Data are also used by the DT platform to represent the states of both physical and virtualized network instances and describe their behavior inside the DT .

Second, data are used to develop a comprehensive representation of the data using DT *models*. Diverse models can be composed, e.g., service models, data models, dataset models, or knowledge graphs, to represent a high-level abstraction to provide insights and dynamics on how the live physical network operates and infer reasoning data that the DT can utilize to serve various network applications. Third, *interfaces* are used to ensure the interoperability of the DT network with existing business applications. Standardized southbound and northbound interfaces are needed to (*i*) interface with the physical network infrastructure to provide real-time data collection and control on the physical network, and (*ii*) interface between the DT network platform and applications to help in delivering application requests to the DT network platform and exposing the various platform capabilities to applications.

Finally, the *mapping* is needed to establish a real-time interactive relation between the physical network and the twin network or between two twin networks. One-to-one (pairing, vertical) mapping also helps to keep the physical network and its virtual replicated network in sync with continuous flows, give a clear picture of the current situation, improve the network's performance and upkeep, and get the system to behave the way you want it to. One-to-many (coupling, horizontal) mapping is also needed to synchronize among virtual twin networks with occasional data exchange. Furthermore, the mapping enables the (*i*) repeatability of the experiments, as it offers the capacity to replicate network conditions on demand; and (*ii*) reproducibility by enabling replaying successions of events under different controlled variations of the network state to validate changes in different use cases, such as network optimization and network fault recovery.

IETF has introduced a three-layer DT reference architecture that encompasses the Application Layer, Digital Twin Layer, and Physical Network Layer, as illustrated in Fig. 4.

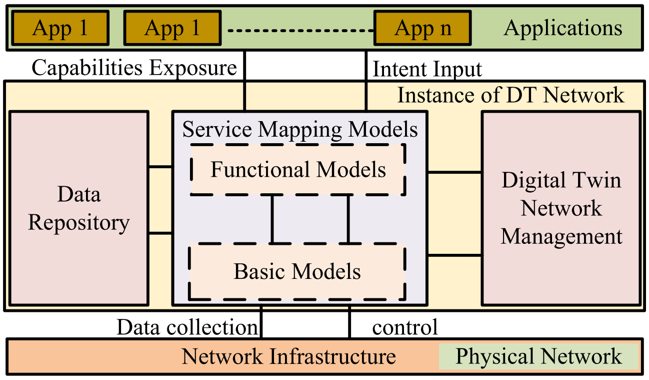

Fig. 4. IETF reference architecture of DT network.

- **Physical Network:** it represents network infrastructure (mobile access/core network, a transport network, a datacenter, an IP bearer network, a backbone, etc.) that span across single or multiple autonomous systems and in which all or parts of their equipment exchange data with their virtual replicas in the DT instance.
  Digital Twin Layer: represents the virtual replicas of the physical layer and includes three key subsystems: (i) *Data Repository subsystem*, which is responsible for collecting and storing real-time operational and historical network data from different networks to build and update various models used by the DT; (ii) *Service Mapping Models subsystem* offers data metamodel instances that can be used by the network applications to improve the flexibility, agility, and programmability of the network. It includes both *basic models* (i.e., network element models and network topology models) implemented in the DT model, describing the basic configurations such as environmental information, operational state, link topology, etc. In addition, *functional models* encompass various data models used for different tasks such as network analysis, emulation, diagnosis, prediction, quality of service assurance, etc. functional models are constructed and expanded by multiple complex dimensions, i.e., by network types (mono, multi, heterogeneous domains) or by function types ranging from simple state monitoring and traffic analysis to more advanced tasks such as network planning, maintenance, optimization, and operation. It is possible to combine multiple models to create a more complete and complex data model for more specific application scenarios; and (iii) *Digital Twin Network Management* functions that record the lifecycle of all twin entities' transactions, monitor and supervise the execution of individual models, supervise the performance and resource consumption of the digital network twin, and visualize and control other elements of the network such as topology management, model management, and security management.
- **Application Layer:** represents all the network applications, such as cognitive management, predictive control, closed-loop management, operations, administration, maintenance (OAM), and management and orchestration (MANO) that can run on the DT platform. The application communicates with the DT platform through open network interfaces using request/response-based or event-based communication patterns.

3.5. International organization for standardization

The ISO 23247 [25] has been investigating a novel standardized framework to support the creation of digital twins of observable manufacturing elements that include four domains, shown in Fig. 5: physical manufacturing, data collection and device control, digital twin representations and user domains.

The scope of this framework covers the following standards:

- ISO 23247-1: Overview and General principles [25].
- ISO 23247-2: Reference architecture [62].
- ISO 23247-3: Digital representation of manufacturing elements [63].
- ISO 23247-4: Information Exchange [64].

3.6. ITU-T recommendations

The ITU-TY.3090 [65] recommendation has been initiated by the ITU-T to describe the functional and service requirements and the architecture for twining the physical network with a DT network. The recommendation identifies four key characteristics of DTN: (i) *Data* is the cornerstone of DTN, is collected from the physical network and stored in a single source of truth, the data store that can be usable by DTN models; (ii) a *mapping* of the physical network infrastructure into its virtual twin replica; (iii) a *model* is a virtual abstraction that accurately reflects a physical network and can be used to interact with network applications, and (iv) open *interfaces*, southbound interfaces connect physical networks and virtual twin networks while northbound interfaces exchange information between virtual twin networks and network applications.

The ITU recommendation has developed a three-layer, three-domain, and double closed-loop architecture as shown in Fig. 6. It can digitally show the running status and health state. It can perceive the network state, efficiently mine valuable network information, and explore innovative network applications with friendly immersive interactive interfaces.

3.7. European telecommunications standards institute (ETSI)

A new DT standardization effort [92] has been recently initiated by ETSI recommendation to define a reference architecture, communication functionality, and properties for smart machine-to-machine communication (SmartM2M). The scope of the ETSI recommendation involves the following:

- *D1 Digital Twins and standardization opportunities in ETSI:* aims to analyze the major characteristics and architectures of Digital Twins, identify their significant functionalities, select the candidate communication functionalities for standardization, and collection, identify and define use cases for industrial IoT, and identify their potential requirements.
- *D2 Digital Twins communication requirements:* based on the previous recommendation *D1*, they aim to elaborate a common definition of Digital Twins' communication functionality and properties and standardize their communication requirements.
- *D3 Digital Twins Functionalities and Reference Architecture:* aims at providing a DT reference architecture by introducing a guideline for the adoption of Digital Twins in SmartM2M industries.
- *D4 Digital Twins support in oneM2M:* aims at mapping the reference architecture developed in *D3* to the oneM2M architecture and capabilities by clarifying the existing functionalities in oneM2M and developing their extensions, and developing new functionalities and functional entities to support the Digital Twins concepts.

Furthermore, Context Information Management API (NGSI-LD) Specification [93] has been introduced by ETSI to describe different ways to publish, consume and subscribe to context information in multiple scenarios involving context entities, *aka* "digital twins", that represent real-world assets. NGSI-LD describes how the context information can be modeled as attributes of DT entities.

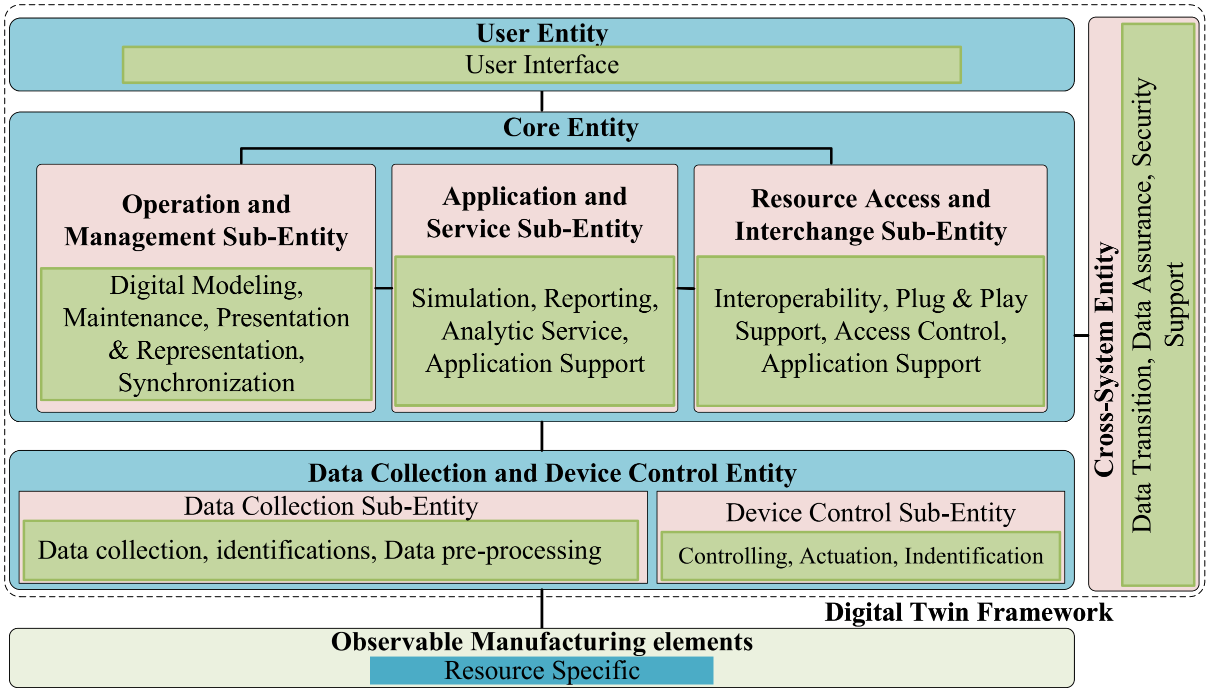

Fig. 5. The ISO DT framework for manufacturing.

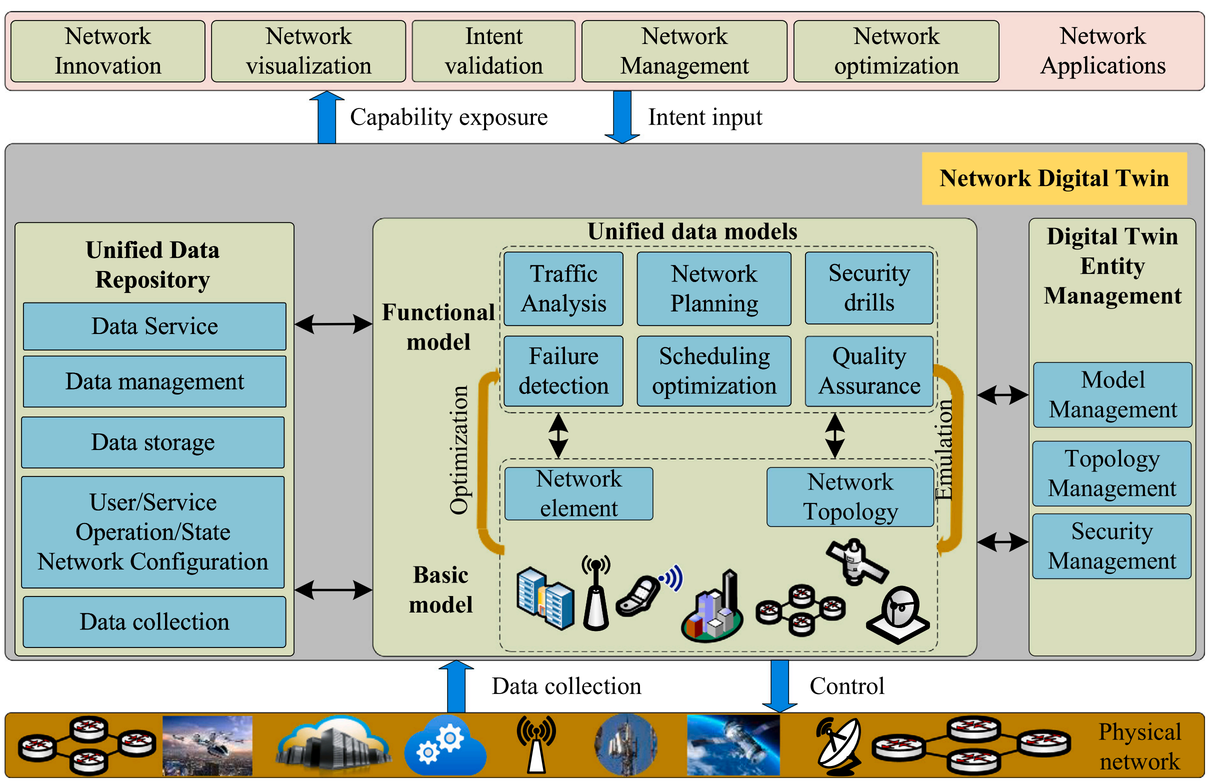

Fig. 6. ITU-T DT reference architecture.

4. Digital twin frameworks and prototypes

The emergence of the DT has increased the development of software solutions and frameworks for creating and maintaining digital twin solutions in different industries. Table 3 illustrates state-of-the-art software implementation of digital twin technology. We identified the following criteria to evaluate different DT implementations: (i) open source or commercial, (ii) scalability, i.e., the ability to support an increasing number of remote connections from a physical system; (iii) latency, i.e., is minimized latency is obtained by optimizing both the communication and the computation; (iv) elasticity, i.e., implements a reactive elasticity between the cloud and the edge; (v) mobility, i.e., supports mobile physical systems; (vi) robustness, i.e., supports reliability of fidelity; (vii) context-awareness,

Table 3
Selected digital twin software frameworks.

Software name	Open source	Scalability	Latency	Elasticity	Mobility	Robustness	Context awareness	Geo distribution
Eclipse Ditto [66]	✓	✓	✓	✓	✓	✓	✓	✗
Eclipse Vorto [67]	✓	✓	✗	✓	✗	✓	✓	✗
Eclipse BaSyx [68]	✓	✓	✓	✗	✗	✗	✓	✗
ScaleOut [69]	✗	✓	✓	✓	✗	✗	✗	✓
Davra Platform [70]	✓	✗	✓	✗	✗	✗	✓	✗
Fiware [71]	✓	✓	✓	✓	✗	✓	✓	✓
iTwin Platform [72]	✓	✓	✓	✗	✗	✗	✓	✗
Open Digital Twin [73]	✓	✓	✓	✓	✗	✗	✗	✗
White Label [74]	✓	✓	✓	✗	✗	✗	✗	✗
FAAAST-Service [75]	✓	✓	✓	✗	✓	✗	✗	✗
CPS Twinning [76]	✓	✗	✓	✗	✓	✗	✗	✗
XMPro [77]	✗	✓	✗	✓	✓	✗	✓	✓
Reflexer Digital Twin [78]	✓	✗	✗	✗	✗	✗	✗	✗
Twined [79]	✓	✗	✓	✗	✗	✗	✓	✗
Virtual Festo Twin [80]	✓	✗	✓	✗	✗	✗	✓	✗
Twinbase [81]	✓	✗	✓	✓	✗	✗	✓	✗
Gemini Plugin [82,83]	✓	✗	✓	✗	✗	✗	✓	✗
Equinox [84]	✓	✓	✓	✗	✗	✗	✗	✗
Mathworks QLabs [85]	✓	✗	✓	✗	✗	✗	✗	✗
Azure DT [86]	✗	✗	✓	✗	✗	✓	✓	✓
Oracle DT [87]	✗	✓	✓	✓	✗	✗	✗	✓
IBM DT [88]	✗	✓	✓	✓	✗	✗	✗	✓
AWS IoT TwinMaker [89]	✗	✓	✓	✓	✗	✗	✗	✓
Bosch IoT Suite [90]	✗	✓	✓	✓	✗	✓	✓	✓
Nvidia Omniverse [91]	✗	✓	✓	✓	✗	✓	✗	✓

Legend: ✓: supported feature; ✗: unsupported feature.

and (viii) geo-distribution, i.e., highly distributed DT through elastic orchestration of service containers.

4.1. Eclipse Ditto

Eclipse Ditto [66] has been introduced as an open-source project under the Eclipse IoT initiative to provide a ready-to-use functionality to manage the state of DTs. It offers functionalities to perform (i) *Device-as-a-Service,* by mirroring physical assets/devices, offering a high-level web API to access devices remotely and interact with digital twins; (ii) *State management for digital twins,* by enabling event-based notification of state changes and offering a single source of truth'' for a physical asset; and (iii) *Digital Twin Management,* by providing meta-data and metamodel support to query, search, and select specific attributes from both the physical system and the virtual DT replicas. To this end, Eclipse Ditto offers a range of RESTful APIs [94] that can be used to build backend-less IoT applications and help developers to concentrate on the application's business logic to build an enhanced user experience while simplifying the integration of various network protocols, brokers, and messaging systems [95]. Eclipse Ditto, combined with Eclipse Vorto (explained next), offer a generic and flexible Digital Twin framework.

4.2. Eclipse Vorto

Eclipse Vorto[1] [67] has been introduced as an open-source project that provides a language for describing models and interfaces for IoT DTs. In IoT scenarios, digital twins are models of entities in the physical world, such as a multi-sensor device, a smart power plant, and other entities participating in IoT solutions. Modeling enables IoT solutions and IoT platforms to provision, use, and configure IoT devices and logical entities from multiple sources in a single solution.

Eclipse Vorto addresses the subject of device abstraction, device description, and device integration. Digital twins are described using *vortolang,* which is a domain-specific language. Vortolang is used to describe the entities' capabilities, IoT platforms and IoT solutions that can leverage the semantics of these IoT entities. It uses information models to provide abstract descriptions of device properties and features. The Vorto repository allows the management and sharing of these information models. Device manufacturers can publish information models, and developers can then download these information models. Vorto's code generators make it possible to generate platform-specific source code from the information model. As a result, integrating a device with a specific platform is easier.

The vortolang comprises a set of metamodel classes defining the capabilities of digital twins. Two top-level classes: Information Model and Function Block, describe a DT, and the capabilities of digital twins, respectively. Three metamodel classes describe capabilities: Properties, Events, and Operations. An Information Model describes a complete DT, such as a physical device, and defines the set of interfaces as Function Blocks implemented by the DT. A Function Block describes related capabilities that a DT implements. Function Blocks are reusable and can be reused across different Information Models. A Function Block is composed of properties, events, and operations.

4.3. Eclipse BaSyx

Eclipse BaSyx[2] project has been initiated as an open-source Industry 4.0 middleware to support various functionalities and software components and implement digital twins that conform to the specification of Asset Administration Shell (AAS). BaSyx components include a registry component, persistency providers, and several container applications for Industry 4.0 applications [96]. BaSyx implements a service-oriented middleware architecture [97]. Eclipse BaSyx proposes the Virtual Automation Bus (VAB) architecture to offer end-to-end connectivity between physical assets and the DT through many heterogeneous communication protocols, brokers, and messaging services [68]. BaSyx also allows performing traditional CRUD (create, retrieve, update, delete and invoke) operations while ensuring interoperability among heterogeneous protocols and facilitating cross-layer interaction with the DT through VAB.

[1] https://github.com/eclipse/vorto

[2] https://wiki.eclipse.org/BaSyx

4.4. Nvidia Omniverse

Nvidia Omniverse [91] has been introduced as a platform for building and operating metaverse applications wherever the digital and physical worlds meet. It has been updated to support various features for the metaverse, such as 3D internet to connect virtual 3D worlds and be viewed through a simulation engine. It offers Generative Adversarial Networks (GAN)-based, diffusion model-based neural rendering tools and graph execution engines to control behavior, motion, and action procedurally. Thus, it makes it the most advanced commercial tool to process the kinematics of complex multipart objects for synthetic data generation and DT simulations [98]. In particular, Omniverse includes (i) the Replicator application, which is used to generate synthetic data to train self-driving cars, robots, and all kinds of computer vision models; *ii* JT Connector for the Siemens JT industry-standard language of product lifecycle management; (iii) and the interoperability format of CAD systems, like NX, Creo, Catia, and Inventor.

4.5. ScaleOut digital twin

ScaleOut DT [69] has been seen as a cloud and on-premises service that offers a set of tools for building real-time DT models. It defines an in-memory data grid that uses the JSON format to serialize instances of digital twins. It also provides machine learning and statistical analysis tools for spike and trend change detection using unsupervised learning, as well as for anomaly detection for sets of numeric values using supervised learning. Additionally, ScaleOut provides cloud-hosted stream processing services through its two components, i.e., the ScaleOut Digital Twin Builder software toolkit and the ScaleOut Model Development Tool. The streaming service connects to data sources using popular event hubs, such as Microsoft Azure IoT Hub, Amazon AWS IoT Core, and Azure Kafka, and allows connections via an integrated REST messaging service. It offers a user interface (UI) to aggregate real-time continuous analytics and report dynamic changes in the state of data sources to the UI

4.6. Davra platform

Davra[3] [70] has been introduced as a full-stack open source Industrial IoT (IIoT) platform that helps to define, build and prototype digital twins for building single reliable, secure and scalable IoT applications. It offers an open library that facilitates making secure API calls to the connecting APIs on the DT. To this end, it defines a TwinType Object that retrieves the details of an existing twin, add new objects to the platform, add or update (key/value pairs), modify or delete a key from it, list all attachments of all Twins, etc.

4.7. FIWARE

FiwareDT has been introduced in [71] to build real-world physical assets that can be represented as a static or dynamic digital entity using a Universal Resource Identifier (URI). These assets can have several attributes or properties that hold data and relationships that bring the Digital Twin entities together. FIWARE Ecosystem allows modeling DT data using a catalog of components and smart data models [99]. FIWARE Community has developed NGSI RESTful API to simplify access to DT data and NGSI-LD API as the data integration API in the Fiware DT architecture through an open-source Context Broker component (e.g., Orion-LD, Scorpio, and Stellio) to simplify the development of interfaces to integrate with IoT, robotics, and many other third-party systems, as well as to support Digital Twin data processing and monitoring and data processing engines (e.g., Apache Spark, Apache Flink), monitoring tools (e.g., Grafana), and analysis platforms (e.g., Apache Superset). Additionally, to ensure interoperability with existing data models, the FIWARE Foundation has developed the Smart Data Models initiative,[4] which provides a library of Data Models[5] in JSON/JSON-LD format compatible with schema.org and NGSIv2/NGSI-LD APIs.

4.8. iTwin platform

iTwin[6] has been expanded to become an open source[7] platform for creating, querying, modifying, and displaying Infrastructure Digital Twins for any scenario. iTwin has been developed using JavaScript to visualize and interact with DT assets using web browsers using Bentley cloud services [72,100]. Additionally, it offers iModels API to access and manage DT information and bring DT infrastructure with existing servers, silos, politics, and hierarchy, and supports a federated data access layer to allow users to query the entire Federated Digital Twin as a whole for analytics and insights.

iTwin is compatible with existing data format specifications (e.g., XML), drawings, documents, and BIM models, allows visualizing and analyzing BIM data, reality data, GIS, and IoT data streams in 3D and 4D using a web browser, and offers robust tools for viewing, interrogating, and interacting with the DT.

4.9. White label digital twin (WLDT) framework

The WLDT[8] [74] platform has been envisioned as an open-source Java-based framework to create Digital Twins for IoT applications. It intends to maximize modularity, re-usability, and flexibility to effectively mirror smart physical objects in their digital counterparts [101]. It implements all the features and functionalities of a DT that can run in cloud and edge environments, and support a wide range of communication protocols and normalized data formats (e.g., CoAP, MQTT, Request/Response, Pub/Sub).

The WLDT framework supports scalability and extensibility. It allows the creation of a modular IoT microservice architecture that easily integrates into the DT network through an extensible API. The core layer of the framework, called WLDT Engine, allows for defining, handling, and orchestrating the behavior of the twin and active modules (denoted as Workers). A Worker can be easily customized through a Processing Pipeline layer for processing incoming data or integrating with external third party services for data format translation and adaptation. The WLDT framework is expected to improve the modularity, re-usability and flexibility of digital twins by simplifying twin design and development.

4.10. Fraunhofer advanced asset administration shell tools (FA3ST)

The FA3ST DT ecosystem[9] has been developed as an open-source implementation of the AAS specification (including both Part 1 and Part 2) to support Industry 4.0 [54,102] applications. It has been augmented with a built-in open web service interfaces based on custom AAS model instance [103]. FA3ST provides an easy configuration via a JSON file and implements several other data formats (e.g., JSON, JSON-LD, XML, AML, RDF, OPC UA NODESET) for the AAS environment. It can also interconnect with several communication protocols (e.g., pull, pub/sub, MQTT, COAP, and IPv6) and interface and synchronize with several 3rd party implementations for the endpoint (e.g., HTTP, OPC UA), such as message bus, persistence, and asset connection. Furthermore, FA3ST uses the existing implementation of the AAS data model to enable data serialization and deserialization. It also offers a hybrid DT by intertwining different DT models using stream processing with Apache StreamPipes [104].

[3] https://github.com/Davra

[4] https://smartdatamodels.org/
[5] https://github.com/smart-data-models
[6] https://www.itwinjs.org/
[7] https://github.com/iTwin
[8] https://github.com/wldt
[9] https://github.com/FraunhoferIOSB

4.11. Cyber–physical systems (CPS) twinning

The CPS Twinning [76] platform has been conceived as an open-source framework for developing, generating, and executing digital twins for cyber–physical systems (CPS). CPS twinning uses automation ML (AML) [57] data exchange format to generate DT artifacts and automatically generate virtual environments for digital twins entirely from the specification. Additionally, the CPS twining framework implements another tool called *CPS State Replication*[10] to enable the replication mode of CPS Twinning so that digital twin entities follow the states of their physical replicas by passively monitoring stimuli. The framework[11] offers various security modules to support security analysts in monitoring the current state of CPS and implement customized security features, such as intrusion detection, access control, audit, and accountability.

4.12. XMPro

XMPro[12] enterprise framework has been developed to build real-time applications with fewer efforts at coding. It is a business process management (BPM)-based DT platform that consists of three main software components: (i) The *XMPro App Designer* is a low-code visual programming UI to create digital twin applications. It offers a visual environment for creating customized web pages by dragging blocks from the toolbox, configuring their properties, and connect them to diverse data sources; (ii) *XMPro Data Stream Designer* is a low-code integration and orchestration environment to connect real-time IoT data with analytics and actions. It provides an intuitive drag-and-drop interface to enable the design of stream processing through data pipelines, bring real-time data processing to a variety of sources, add and remove external data, and apply diverse types of machine learning and data mining algorithms to perform data analytics; and (iii) *XMPro Connectors*, which is an extensible library that includes hundreds of connectors for various industrial automation solutions, such as cloud PaaS environments, IoT platforms, AI/ML tools, etc. In particular, XMPro Connector implements the Azure Digital Twin Connector to interact with the Microsoft Azure Digital Twin platform.

4.13. Twinbase

Twinbase [105] has been developed as an open-source platform for merging, managing and distributing DT documents. It creates a single interface to access the systems via an API gateway, called *Data Link* [106], which connects the features of a DT to make physical product data available and accessible from a single interface [107]. To this end, it stores metadata about the systems in a YAML document and implements a microservices' architecture to offer better scalability, maintainability, and robustness against monolithic and single service failures. The API gateway facilitates requests and delivery of data and services, and ensures authentication.

Twinbase contributes to the development of DT Web (DTW) [108], an approach introduced by the Digital Twin Web Association (DTWA) to develop, maintain and promote the Digital Twin Web initiative. At the core of this initiative is the development of DT document, often written in YAML, to combine the advantages of existing standards such as Industry 4.0 *Asset Administration Shell* specification, the W3C *Web of Things Thing Description* and Microsoft *Digital Twin Definition Language*.

4.14. Azure DT

Azure Digital Twins [109] has been introduced by Microsoft as a cloud-hosted enterprise-grade DT platform in the form of a Platform-as-a-Service (PaaS). Azure DT is a more generic framework that allows the creation of twin graphs based on digital models for diverse use cases and scenarios. To this end, Azure DT models are created and defined in a JSON-like language called Digital Twins Definition Language (DTDL), which describes all data types, entries, states, properties, events, commands, relationships, etc., of the physical assets.

Azure DT proposes a set of tools[13] to define, create, and build DT applications. For example, the Azure DT Builder allows the development of DT processes more effectively by building and transforming building information modeling (BIM) into digital twins. Additionally, Microsoft has adopted the DTDL industry ontology to build diverse applications such as smart buildings (e.g., modeling smart buildings using industry standards (like BRICK Schema or W3C Building Topology Ontology)), smart cities (i.e., supporting Open gile Smart Cities (OASC) and Sirus to provide a DTDL-based ontology for smart cities, starting with ETSI CIM NGSI-LD.), energy grids (e.g., monitoring grid assets, outage and impact analysis, simulation, and predictive maintenance), etc. In the energy grid, the ontology was created and adapted from the Common Information Model (CIM), a global standard for energy grid assets management, power system operations modeling, and the physical energy commodity market. The Azure Digital Twins Explorer is a visualization tool that demonstrates the interaction with a DT graph of a physical building.

4.15. AWS digital twin

Amazon has been developing the AWS IoT TwinMaker [89] platform as a cloud-hosted commercial service to create digital twins of real-world systems, such as buildings, factories, industrial equipment, and production lines. Amazon IoT TwinMaker supports commonly used IoT protocols such as Message Queuing and Telemetry Transport (MQTT), Hypertext Transfer Protocol Secure (HTTPS) and low-power, long-range wide-area network (LoRaWAN). It can also easily interact with the Amazon Sumerian service, which offers capabilities to build 3D modeling and AR/VR interfaces to build applications along the lines of a DT.

Furthermore, Amazon provides a Device Shadow service, which allows the creation of a shadow of a physical device and provides its states to the application. Device shadow metadata (i.e., states, version, security token, properties, etc.) are stored in JSON file format and communication with DT services through RESTful APIs. One example of such a DT service is the Hexagon Digital Reality (HxDR) platform, which offers DT capabilities for building structures on top of AWS. HxDR creates accurate, real-world digital representations of the physical assets (e.g., cities, buildings, structures, and landscapes) using data captured from airborne, ground, mobile sensors, etc. Similarly, Vertex (Vertex Software Visualization Platform for the Digital Twin) is another provider of capabilities for DTs on top of the AWS platform.

4.16. Bosch IoT suite

The Bosch IoT Suite [90] has been developed as an advanced DT platform to provide manufacturing companies with all the needed tools and technologies to build and scale their own IoT solutions and to help manage DTs. It offers an open data model to enable digital representations of physical devices with unified device APIs based on the Eclipse Vorto Information Models.

The Bosch IoT Suite[14] is built on top of Eclipse IoT open-source projects and industry standards. This open approach allows customers

[10] https://github.com/sbaresearch/cps-state-replication

[11] https://github.com/sbaresearch/cps-twinning

[12] https://xmpro.com/

[13] https://docs.microsoft.com/en-us/azure/digital-twins/

[14] https://www.bosch-iot-suite.com/

Table 4
Selected digital twin research projects.

Project name	Description	Domain
SPIDER	Digital Twin Network and Cybersecurity	5G network and Industrie 4.0
LEAD	Data-Driven Dynamic Application System Build Model Library	Urban Logistic Supply Chain and Smart City
DUET	Cloud design for model calibration and simulation IoT stack and API specifications	Smart city Urban Planning
5G-DIVE	Support for zero defect manufacturing	Industry 4.0 and predicative maintenance
5GROWTH	Business Model Design and ML-Based DT AIML-as-a-Service for SLA management Digital Twin application over Ethernet	5G Network Modeling and Optimization Service Management and Orchestration Augmented Zero Defect Manufacturing
IoT-NGIN	Build IoT Engine for unified global factory maps Localization and Tracking BIM model for construction	AR enabled factory worker AR based factory planning Use case: AR/ VR assisted construction
DIGIPREDICT	Predict the evolution of Covid-19	Healthcare
SWAMP	Build smart farming simulator Software SDK SWAMP Information Model	Smart water management precision irrigation Smart Farming
Hexa-X	AI-driven communication and computation co-design 5G and 6G service management and orchestration High-Resolution Localization and Sensing	Massive Twining and Immersive Telepresence Collaborative robots Wireless Mobile Network
PREDIS	Run processes on different compositions Predict upcoming/future waste packages	Radioactive Waste Management

to enjoy all the benefits of fully managed cloud services while avoiding vendor lock-in. As another advantage, partners and customers can influence the future development of the Bosch IoT Suite by participating in the underlying open-source project communities. Furthermore, the Bosch IoT Suite can integrate with AWS and connect to devices using diverse communication protocols (MQTT and Advanced Message Queuing Protocol (AMQP))

5. Digital twin-based research projects

In the past few years, we have seen an increase in research efforts by academia and industry for facilitating the transition to DT. We highlight in Table 4 a number of these projects, which we will deeply explore in this section.

5.1. SPIDER

The SPIDER [110] project, which stands for *cyberSecurity Platform for vIrtualiseD 5G cybEr Range services*, aims at developing a digital twin to enforce cybersecurity in 5G wireless cellular network [111]. The project aims at driving a new intelligent evolution to wireless network by replicating customized 5G networks and enabling the execution of real-time cyber-exercises [112]. The project allows gathering and sharing data between physical and virtualized network equipment and developing adaptive operational procedures to predict and manage security incidents, complex attacks, and propagated vulnerabilities [21]. SPIDER project relies on a Service Mapping Model component for creating replicas of the 5G network, including User Equipment (UE), RAN and the 5G Core. Moreover, SPIDER leverages the Digital Twin Entity Management in the Mouseworld testbed [113] to generate network topologies and provision an executable service graph.

5.2. LEAD

LEAD [114] project has been driven by European research teams to create DTs of urban logistics networks in six European cities (e.g., Madrid, The Hague, Budapest, Lyon, Oslo, and Porto) to evaluate city logistics solutions by reproducing digital replicas of complex real-world urban environment, including different processes, actors, and their interactions to improve the resilience of the logistics chain. The long-term vision of the project is to develop an *Open Physical Internet-inspired framework for Smart City Logistics* that creates the foundations for the future European large-scale cities' network of DTs.

The project has been used to deliver efficient last-mile logistics and parcel delivery services and operations through forecasting and predictions of future states of the entire logistics lifecycle [115]. Furthermore, LEAD has been developing a variety of logistics solutions for shared, connected, and low-emission logistics operations. LEAD is empowered by adaptive agent-based models (ABM) approach that involves modeling, predictive analytics and decision-making methods, through the use of historical and real-time operational data to build lifecycle-oriented knowledge to develop integrated systems of logistics/freight operations in urban, metropolitan and urban areas.

5.3. DUET digital twins

DUET project [73] has been developed to build an urban DT that creates virtual replicas of city environment, by modeling the interactions and the data exchange in urban ecosystems to better understand the interrelation between traffic, air quality, noise, and other urban factors. DUET project has been used to create the so-called T-Cell framework that acts as container for integrating together models, data, and simulations in a common environment that emulates real-world city ecosystem and helps to monitor and to synchronize the state and behavior of the DT with the physical environment [116]. Individual models are mirrored and integrated through APIs to form a federation of composable models that can be used to perform various analytics-based on both real-time feeds, and historical data gathered from IoT devices connected in smart cities' environments. To this end, the DUET project builds large datasets, from both historic and real-time data, provides a dashboard to remotely monitor, in closed-loop control procedures, the anomalies, and deviations before a disaster strikes. It also builds embedded ML and AI functions to better predict different situations [117], such as the depreciation of road infrastructure or carbon footprint, thereby transitioning to a new age of responsive cities.

5.4. 5G-DIVE

The 5G-DIVE [118] project has been devoted to the development of 5G connectivity solution that supports distributed edge computing use cases, such as deep AI/ML twinning for replica of a robotic arm for teleoperation [119], Zero Defect Manufacturing (ZDM), Massive

Machine-Type-of Communication (mMTC), Drone Collision Avoidance System (DCAS) and Intelligent Image Processing for Drones (IIPFD), etc. For example, for robotic arm, the project creates a digital replicas of the Niryo One Robotic manipulator and synchronizes their movements in different scenarios. It has been used to send continuous stream of commands from the DT applications to the robot arm, compares and analyzes joint state vectors of both twins. Another use case developed in the project concerns the Business Automation Support Stratum (BASS), which is a orchestrator drivers different orchestrator frameworks (e.g., K8s and FogO5). First, 5G-DRIVE creates a Docker-based lightweight containerized service to deploy IoT applications. Then, these containers are migrated inside Kubernetes pods to achieve global. Next, the BASS Vertical Service Descriptor was created to deploy the service through the BASS. Finally, DT containers are chained to form en end-to-end system that involves a Fog Orchestration Manager (FOM) and a Fog Infrastructure Manager (FIM) [120].

5.5. 5GROWTH

The 5GROWTH [121] research project, which stands for *5G-enabled Growth in Vertical Industries*, has been dedicated to empower multiple European vertical industries, such as industry 4.0, transportation, and energy with AI and DT -driven automated 5G end-to-end solutions [122]. The project has been foreseen to optimize the production line in manufacturing industry, improve the service delivery and Service Level Agreement (SLA) in 5G virtualized edge network, offload edge computation resources through deployment configurations, and support efficient data exchange between physical devices and their virtual components [123].

The project has been used to reduce the cost of physical connected objects, improving real-time operations for edge network, and achieving faster response to environment changes across diverse real-time applications such as visualization and remote control, that require ultra-low latency and high reliability [124]. 5GROWTH project develops a DT as a Service (DTaaS) [125], in which an Edge Robotic DT can be remotely controlled, coordinated and monitored while performing different industrial tasks in a factory floor, thereby open new opportunities towards the future manufacturing systems, by eliminating defective pieces and repetitively performing accurate tasks at high-speed [126]. Finally, 5GROWTH develops a protocol stack published as open source[15] to enable online network resource allocation [127], service provisioning, and autonomous and dynamic management of a 5G network infrastructure [128].

5.6. Iot-NGIN

IoT-NGIN [129] has been focusing on implementing Meta-Level Digital Twins that allows on-usage interpretation and application of data and information and delivers improved efficiency and traffic congestions, in human centered twin smart cities. IoT-NGIN supports novel digital twins' functionality to enable high-availability and what-if scenarios. It relies on a microservices-oriented architecture to build a distributed ledger (i.e., blockchain) to enforce the security (detection of network intrusions, detection of fraudulent ML model poisoning activities) and trust of federated DT network, manage the entire lifecycle of multi-faced data sharing and metadata management based on the ontology meta-level digital twins' data interfaces [130]. The meta-level DT layer abstracts the underlying implementation details, by providing a unique interface for utilizing decentralized security. Such an approach has been seen in other DT projects such as Asset Administration Shell (AAS) [54] and the Web of Things (WoT) Thing Description (TD) [131].

Furthermore, within the context of IoT-NGIN, digital twins are employed to mimic the behavior of connected IoT devices, facilitate the interaction between the physical and the virtual twins, in order to increase the service reliability, boost the performance of data services provisioning, and increase lifetime trackability and traceability. Additionally, IoT-NGIN is expected to use Self-Sovereign Identities (SSI) to control of the identity of the physical twins and guaranteeing virtual device identity uniqueness in distributed federated DT network. Machine learning services are foreseen to deliver the needed abstraction to operate transparently in the physical-digital continuum. Finally, the IoT-NGIN project builds a DT models for diverse scenarios, e.g., training distributed AI models on traffic flow and parking prediction, event detection, crowd management, etc.

5.7. DIGIPREDICT

DIGIPREDICT [132] has been used to develop a DT to predict the progression of disease in infectious and cardiovascular diseases. It deploys edge AI technologies to create digital representation of a patient [133] to predict whether COVID-19 patients will develop severe cardiovascular complications. the project develops a smart patch with wearable technology for collecting a range of medical data and monitor how well the treatment is working.

5.8. SWAMP project

SWAMP [134] has been used to create a DT for smart farming [135], by enabling precision irrigation for agriculture [31], optimizing the use of water, reducing the energy consumption and improving the quality of crops [136]. The project aims at reducing the development effort for IoT-based smart farming applications, automating smart agriculture platforms by integrating heterogeneous technologies such as IoT, Big Data, flying sensors, and Cloud/Fog to predict the usage of IoT in smart water management settings

5.9. Hexa-X

Hexa-X[16] has been an immensely successful 6G research project that aims at integrating digital and physical worlds with human interaction for a privacy-preserving high-availability DTs [137]. It develops a set of use cases including massive network twinning services, cooperative robots, human in the loops, telepresence, as well as AI-driven communication and computation co-design [138]. Hexa-X develops fully immersive digital twins for twinning of the physical sensing/actuators and programmable digital representations. Moreover, it helps to flexibly assign heterogeneous resources and dependable network services in carrier-grade mobile communication networks beyond 5G, while ensuring network slices isolation, privacy-preserving, tightly coupled and seamlessly intertwined network, and ensure resilient services. The project extends the concept of DT of industrial processes to smart manufacturing, sustainable food production, healthcare, ailments of crops and livestock.

5.10. IoTwins

IoTwins[17] [139] has been used to create distributed digital twins for industrial SMEs. It delivers large-scale industrial testbeds by leveraging big-data stream processing and combining data coming from diverse sources, such as data APIs, embedded sensors in manufacturing, maintenance, operations, facility management, and Open Data sources. The project goal is to build a reference architecture for distributed and edge-enabled digital twins deployed at plant gateways of production plants and processes. Furthermore, the project proposes to create hierarchical organization of edge twins for orchestrating IoT sensors and actuators in a production locality and cloud twins for performing time-consuming and typically off-line parallel simulation, physical simulation, on-line and off-line optimization, and deep-learning.

15 https://github.com/5growth

16 https://hexa-x.eu/

17 https://www.iotwins.eu/

5.11. MeDiTATe

MeDiTATe [140] has been established as a medical DT as a service for aneurysm prevention and treatment, which aims at integrating big data analytics, augmented reality, haptic devices, Reduced Order Models (ROM), automated computer aided engineering and additive manufacturing in order to implement in silico analysis into clinical practice [141]. The project helps to prevent cardiovascular diseases and improve clinical practice through the development of software solutions to provide advanced training in the healthcare DT domain [142]. Specifically, MeDiTATe proposes to develop a healthcare DT pipeline based on reduced order modeling to enable fast and interactive evaluation of the hemodynamic parameters of a modified Blalock–Taussig shunt to augment pulmonary blood flow in single ventricle lesions [143].

5.12. PREDIS

PREDIS [144] has been developing a DT framework including models and methods for handling data in radioactive waste management in the nuclear back-end [145]. The DT framework is used for visualizing, optimizing and supporting work processes in decommissioning, performing safety-critical processes under strict qualification requirements, dealing with radiological hazards and associated data types, models, and sensors in nuclear power plants. Furthermore, PREDIS uses different tools, such as geochemical models and chemo-mechanical models, to predict the years-long evolution of radioactive waste packages under different scenarios. To this end, the project builds an interoperable BIM platform along with 2D and 3D visualization of architectural models to demonstrate the viability of waste package management and the complexity of involved processes/models.

5.13. Zero-SWARM

Zero-SWARM [146] has been developing a private 5G network that connects to edge-cloud continuum, data analytics, and digital twins to create agile and climate-friendly cyber–physical production systems of systems (CPSoS) to address the manufacturing sector in Europe. It builds innovative tools[18] to improve the reliability of the energy system in Europe and make them more resilient to future shocks, improve maintenance operations, detect anomalies, forecast demand, etc. Furthermore, Zero-SWARM [147] CPSoS' architecture, specifications, and requirements strive to achieve climate-neutral and digitized manufacturing and develop a human-centric, open swarm framework to minimize waste and pollution in manufacturing.

6. Digital twin use cases

Digital twin use cases are applicable across multiple industries and functions, and the number of domains that aim to enable DT is growing significantly. We present in Table 5 a summary of some DT applications, which we deeply discuss in this section.

6.1. Smart cities

Digital twins are progressively receiving considerable attention in several domains, like smart cities [148]. The DT city is expected to offer a model of urban planning and construction for future sustainable cities by combining metaverse and AI tools to improve urban operational mechanisms and simplify urban upgrading. Lehtola et al. [149] have discussed different technologies in the DT ecosystem that help city planning and urban development, implement autonomous updating of city DTs and build semantic matching with the (BIM) model, geometrical matching with the model, and model validation. Bauer et al. [151] have developed open-source software components atop of the FIWARE [93] DT ecosystem, which combines the lifecycle model for DT with a conceptual model to offer reactive, predictive, and forecasting functionalities to extract knowledge to build an urban DT model that gathers data from dispersed IoT infrastructure in smart cities. To this end, the authors used the ETSI NGSI-LD [71] Information Model and APIs to represent IoT entities and their data (e.g., URI, location, properties, sensor information or characteristics, etc.) in smart cities.

Table 5
Summary of DT applications.

Area	Applications	Articles
Smart Cities	Urban planning	[148,149]
	Strategy evolution	[150,151]
Smart Agriculture	Farm management	[152,153]
	Remote sensing and control	[154,155]
	Smart Water Management	[9,31]
	Agri-Food Sector	[9,156,157]
	Weed pressure	[136,158]
Healthcare	Health monitoring	[159,160]
	Personalized Medicine	[160,161]
	healthcare supply chain	[7,162]
	Medical resource allocation	[132]
Energy	Power monitoring and management	[163,164]
	Failure analysis	[165,166]
	Smart grid operation and maintenance	[24,167]
Network	Satellite Network	[168,169]
	Cellular network planning	[170,171]
	Network SLA monitoring	[137,138]
Building	Progress monitoring	[172,173]
	Budget control and adjustment	[174]
	Quality assessment	[175]
	Resource allocation and waste tracking	[176]
Transportation	Travel schedule	[177]
	Transportation monitoring	[178]
Manufacturing	Design verification	[179,180]
	Layout planning	[181,182]
	Predictive maintenance	[183,184]
	Production planning & control	[185,186]
	Process optimization	[187–189]

Similarly, Wolf et al. [150] have developed a DT platform for smart cities towards enabling accident-free urban life and making cities more inclusive, safe, resilient, and sustainable. The authors identified different needs of stakeholders involved in an incident response, as well as the available data before accidents to process (e.g., topography, buildings, administrative borders, existing hazard maps, fire and ambulance services, police, local authorities, Environment Agency, NHS bodies, and critical infrastructures such as gas, water, etc.). Hence, we argue that DT can accelerate livability, workability, and sustainability, by treating city-wide data as an asset, thereby removing barriers, enhancing energy efficiency, and reducing the environmental impact, helping in mitigating risks, and managing resources more effectively.

6.2. Smart agriculture

Nowadays, there is significant interest in enabling DTs in smart framing, improving the digitalization of agricultural and food production, offering advanced data processing techniques in agricultural field [136,152–155]. DT for smart farming can be designed as a service aggregator that offers farmers have an ergonomic and simple plug-and-play interface to query relevant data, support the farmers in understanding the change better, propose playful and explainable solutions using explainable AI, and help to promote knowledge sharing and collaborative and inclusive learning. For example, the authors in [9] proposed a conceptual framework for designing and implementing a smart agriculture DT system to plan, monitor, control, and

[18] https://zero-swarm.eu/

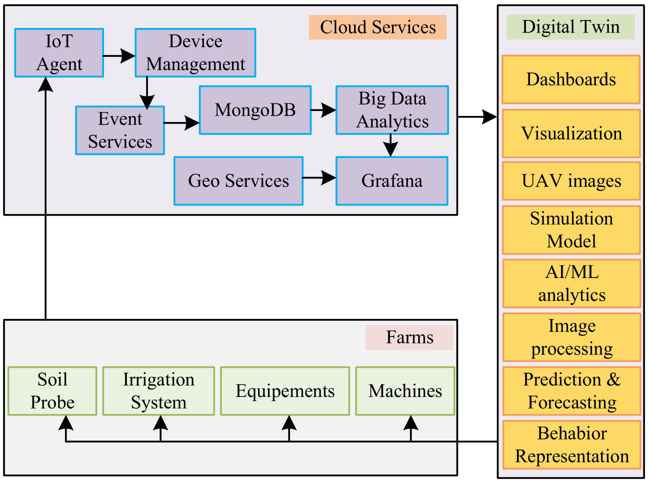

Fig. 7. DT framework for smart agriculture.

optimize farm processes, as illustrated in Fig. 7. The framework seamlessly integrates sensing and monitoring, smart analyses, and planning of smart farming operations. Besides, it offers different features for crops monitoring, predictive maintenance of farming machines, autonomous decision-making and recollection, prescriptive management of the entire farming lifecycle.

Alves et al. [31] have presented a DT solution for smart water management in the agriculture domain, which creates a virtual replica of a soil probe to build a DT environment that displays its information in a dashboard to help farmers better understand the state of their resources and equipment. Likewise, Nasirahmadi et al. [158] have announced a DT framework in soil, irrigation, robotics, farm machinery, and food post-harvest processing in the agricultural field. The authors proposed including emerging technology such as artificial intelligence, big data, simulation, analysis, prediction, and IoT to support the future generation of smart farming. For example, gathering real-time data for the lands (physical world) and updating its virtual twin to provide a straightforward monitoring tool through the DT interfaces for evaluating the soil quality and monitoring the moisture, temperature, organic matter, and soil pollutants. Furthermore, it also enables the decision-making process of smart farming and digital soil mapping, supervising crop health and productivity, identifying key soil characteristics, quantifying the trend of agricultural soil conditions, evaluating and forecasting plants' irrigation requirements, supporting irrigation and water distribution planning to reduce chemical fertilizer and pesticide dosages, improve the underground water, reduce climate degradation and protect human health. For instance, soil moisture information can be used to assess irrigation efficiency in agricultural fields

6.3. Healthcare

Digital Twins can accelerate healthcare transformation [159]. The central idea is to generate a patient-specific DT from different data sources, including laboratory tests, ultrasounds, imaging devices, and genetic tests. It helps to develop digital health services that help people assess and treat simple medical conditions using AI, i.e., capturing health data in DTs, such as medical history, mood tracker, symptom tracker, and auto-capture from fitness equipment and wearable like the Apple Watch. That is, the DT can provide baseline first-line information or help guide priorities and interactions with physicians to treat more serious or persistent conditions [190].

SHENGLI et al. [161] have described the possibility of constructing a Human Digital Twin, its architecture, security, and other main issues. The authors review the origin of the Digital Twin and present the concept of the Augmented Digital Twin (ADT), an extended Digital Twin which is the basis of the Human Digital Twin (HDT). The HDT application layer architecture is composed of the following layers:

- The Data Collection Layer collects data such as Blood Pressure.
- These data need to be pre-processed and will be gathered to the sink center through local area
- All data are stored in the Cloud Database, where many mathematical digital models, representation, and computing platforms which construct the core of the HDT are deployed to provide function interface to the Application Layer.
- The Application Layer provides healthcare management, disease diagnosis, exercise suggestion, diet recommendation.

Healthcare DT helps to improve the caregiver experience, e.g., helps caregivers capture and find information shared between physicians and multiple specialists. A DT can model the patient, then use technologies like Natural Language Processing (NLP) to understand all the data and cut out the noise to summarize what is happening. It saves time and improves the accuracy of capturing and presenting information such as specific medications, health conditions, and other details that providers need to know in context to make clinical decisions. Additionally, DT can help in surgery planning, i.e., improve the planning of surgical interventions and evaluate the results afterward. Digital twins help to generate the shape of a cuff between the heart and the arteries, helps brain surgeons treat aneurysms by using simulations to improve patient safety. It can also improve the ability to plan and perform less invasive surgery using catheters to place single implants. Hence, individual patient data helps customize simulations that run on an integrated DT simulation and therefore the DT simulation results can greatly reduce the need for follow-up surgery.

6.4. Smart manufacturing

Digital twin has been introduced to simply and automate the generation of simulation models in smart factories [179–182]. In the light of the recent advances in smart manufacturing, the authors in [183] introduced a framework to capture changes in the asset across its life-cycle within a DT from the perspective of data architecture. This contributes to research with the ability for synchronization between the physical and the digital world to establish closed loops. The developed ontology-based approach offers opportunities for model and model-traceability to apply model-based systems engineering development approaches for DT solutions.

The authors in [184] presents a proof of concept cyber–physical production system CPPS demonstrator which uses an open-source low-cost microcontroller to enable data communication between a V-bending machine and its DT. OPC UA was successfully used as a communication protocol, where the microcontroller was established as the OPC UA server, while the PC used to run the stress prediction algorithm and database was established as the OPC UA Client. Data from the physical process was transmitted to the DT, which used data analytics to predict maximum stress and strain, giving a deeper insight to the manufacturing process. An information dashboard presented the end user with process key performance indicators and DT information.

AHELEROFF et al. [185] have presented a Digital Twin reference architecture and show its application in an industrial case. The authors also introduce Digital Twin as a Service (DTaaS) for the digital transformation of unique wetlands with considerable advantages, including smart scheduled maintenance, real-time monitoring, remote controlling, and predicting functionalities. The findings indicate that there is a significant relationship between Digital Twin capabilities as a service and mass individualization. Furthermore, the authors present a literature view about Industry 4.0, and describe a reference model and a DT architecture, and individualization. And how Digital Twin enables monitoring, controlling, and schedule maintenance for wetlands as a representative for a massive number of unique and dynamic physical assets.

The authors in [187] present a modeling framework for self-adaptive manufacturing that supports modeling domain-specific cases, describing rules for case similarity and case-based reasoning within a modular Digital Twin. Automatically configuring Digital Twins based on explicitly modeled domain expertise can improve manufacturing times, reduce wastage, and, ultimately, contribute to better sustainable manufacturing. Indeed, integrating CBR (Case-Based Reasoning) into DTs to make it possible to adapt to new conditions autonomously. The CBR cycle is divided into four phases: (*1*) retrieve the case most similar to the current situation; *(2)* reuse the solution of the most similar case; *(3)* revise that solution if the case differs too much from the current situation; and *(4)* retain the revised case in the knowledge base.

Kafkes and al. [188] present continuing work on a real-time artificial intelligence (AI) control system for precisely regulating the Gradient Magnet Power Supply (GMPS), an important subsystem of the Fermilab Booster accelerator complex, by training a Long Short-Term Memory (LSTM) to capture its full dynamics. They implement a simple multi-layer perceptron (MLP)[19] as a policy model. Additionally, they use of a Long-Short Term Memory (LSTM), which are LSTMs are able to learn about previous inputs through the accumulation of weights in a hidden global state variable.

6.5. Wireless networking

The concept of DT network (DTN) [61,191] has recently emerged as a virtual representation of the physical network infrastructure that aims at analyzing, diagnosing, simulating and controlling the physical network based on data, model and interface, to achieve the real-time interactive mapping between physical network and virtual twin network [167]. Specifically, the next-generation (NextG) wireless technologies (e.g., 5G-and-Beyond networks) are expected to simplify the deployment of DT at different communication layers in order to fulfill the monitoring and control requirements of the future IoT applications and services [24]. In this context, Lu et al. [192] have introduce the Digital Twin Wireless Networks (DTWN) by incorporating DTs into wireless networks, to migrate real-time data processing and computation to the edge plane. Then, they propose a blockchain empowered federated learning framework running in the DTWN for collaborative computing, which improves the reliability and security of the system, and enhances data privacy by formulating an optimization problem for edge association and exploit multi-agent reinforcement learning to find an optimal solution to the problem. Numerical results on real-world dataset show that the proposed scheme yields improved efficiency and reduced cost compared to benchmark learning method.

Khan and al. [170] argue that in order to enable future Internet of Everything (IoE) in the forthcoming 6G network, there is a need for novel framework can be used to manage, operate, and optimize the wireless network infrastructure and its underlying IoE services. Such a framework should be based on DTs, with the support of advanced continuous machine learning and optimization techniques, along with edge and cloud computing, network augmentation, and privacy and security-related technologies such as blockchain, homomorphic encryption, etc.

Sun et al. [193] have presented a new vision of Digital Twin Edge Networks (DITEN), where DTs of edge servers estimate edge servers' states and DT of the entire MEC system provides training data to minimize the offloading latency under the constraints of accumulated consumed service migration cost during user mobility. A mobile offloading scheme is proposed based on deep reinforcement learning (DRL) in DITEN to minimize the offloading latency under the constraint of accumulated consumed service migration cost during user

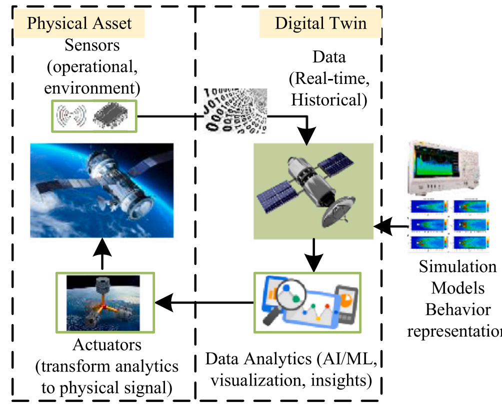

Fig. 8. Example of DT for satellite industry.

mobility. The formal problem of dynamic multi-objective optimization is simplified by using Lyapunov, and the simplified problem is solved by deep reinforcement learning.

Hexa-X project [137,138] proposed to implement a digital system for the forthcoming 5G and 6G wireless cellular networks towards supporting future industrial use cases such as autonomous and collaborative robots, massive twinning, holographic telepresence. Furthermore, Hexa-X proposed to study radio channel characterization and beam forming in mm-wave and sub-THz bands. As a part of the future 6G design, Hexa-X foresees to develop digital models for air-interface above 100 GHz and the development of low-cost, energy-efficient, and high-performance network monitoring, management, and orchestration solutions. It envisions seamless unification of the physical, digital, and human worlds, by providing fully immersive CPS integration using both metaverse and massive DT representations. Besides, the DT approach developed in Hexa-X project enable dynamic control of 5G slicing, ensuring that QoS guarantees are met for each slice with the respect of the diverse traffic patterns, and ensure the resource allocation is achieved for each slice with the respect of SLA agreements. It also envisions fair capacity assignment and planning for future 6G infrastructure on-the-fly.

6.6. Satellite communication

Digital twin has been adopted to build satellite network emulator and implement small satellites management system, as depicted in Fig. 8, to monitor the health state of wireless links (e.g., delay and bandwidth), by retrieving and compiling information, logs and other data collected from the satellite segment [194]. For example, Petersen et al. [168,169] have implemented an architecture for a dynamic link network emulator to fuel satellite digital in order to increase service availability. Similarly, Zhao et al. [91] have implemented an inter-satellite handover scheme to transfer existing users' connections from one satellite to another satellite, by reducing frequent disconnection and improving the capacity of wireless satellites' links. The authors implemented a genetic algorithm as part of the DT to improve the quality of data delivery, reduce the latency and enhance the bandwidth between satellites.

Furthermore, DT is promising technology to address the requirements of space congestion, as it contributes to the reduction of space debris. Specifically, DT helps to develop AI-based collision detection and signal interference prediction models to enhance collision avoidance and improve tracking methods of satellites, hence helps to avoid potential collisions with debris while achieving self-repair, warning against cyberattacks, and optimizing the fuel usage.

[19] MLPs are standard feedforward neural networks, which take in and iteratively feedforward data through many layers of perceptrons (neurons)

6.7. CyberSecurity

As DT becomes more open to different industries stakeholders, however, the cybersecurity risks associated with its integration with traditional industries are often insufficiently explored. Holmes et al. [195] have surveyed different risks related to employing DT into these traditional use cases and studied different opportunities to mitigate cybersecurity risks. Eckhart et al. [76] have proposed a framework to generate virtual environment from specification and tested security risks on live systems. The authors developed security modules on top of the framework for monitoring security threads and safety rules. Filippo et al. [21] have suggested a security testbed to automate offensive tactics using Generative Adversarial Networks (GANs) solution, simulated defensive and penetration test exercises. Dietz et al. [196] have presented a process-based security framework to integrate DT security simulations in the security operations center. They used DT to simulate a man-in-the-middle attack and assist enterprise security by simulating attacks and analyzing the effect on the virtual counterpart.

Furthermore, there are significant recent research efforts to unlock the potential of cybersecurity in DT environments [154,197–202]. These efforts focus on the design of safety rules at the planning phase, with the aim to predict and manage risks. Nonetheless, there is a need for advanced and standardized approaches that align with international regulations (e.g., NIS/GDPR Compliance), enable continuous cyber risk assessment, allow zero-day simulation and defense, and offer cybersecurity forensics.

6.8. Cultural heritage

Europe's cultural heritage strives to the diversity and rich mosaic of cultural and creative expressions, rooted in its art, architecture, practices, places, objects, artistic expressions, film, values, different types of music, economics, literature, and philosophy. The increasing need for shaping Europe's digital future has fueled the need for the digitalization of our cultural heritage, thanks to the recent technologies such as Big Data, 3D digital acquisition devices, 3D laser scanners, AI, 3D and XR. In the light of these evolving technologies and due to the complexity of the cultural heritage data and of their intrinsic interrelationships, Niccolucci et al. [203] have introduced a Heritage Digital Twin (HDT) to digitalize the Heritage Assets (HA). The authors proposed a novel ontology model in the frame of the Europeana platform to improve the digital transformation of cultural heritage and enhance the design and organization of digital space using DT for cultural heritage that models cultural heritage assets and their digital information. In parallel, Darwish et al. [204] have suggested an Historical BIM (HBIM) powered by Digital Twins for monitoring the deterioration of heritage structures, and blockchain for efficient and effective preventive conservation. Historical BIM creates a comprehensive and efficient data management system that collects data from different IoT sensors to create a high-fidelity physical replica of artworks. Likewise, Massafra et al. [205] have proposed new tools for managing the workflow of HBIM of Italian modern buildings built between the 1920s and 1960s. Their approach carries out information acquisition about the building, measures energy intervention, computes construction costs during building's life cycle in order to predict their thermal demand.

7. Open challenges

The concept of the digital twin is not new. However, despite the benefits in different domains, there are several thriving challenges towards its adoption at scale [206,207]. These challenges should be addressed holistically to realize the significant advantages of their deployments. This section delves into the open issues that slowed down the widespread adoption of digital twin technology.

7.1. Security and vulnerability

Cybersecurity is a significant challenge that faces the extensive adoption of DT [208]. Cyberthreats involving access to confidential data by unauthorized bodies pose a severe risk. In particular, scenarios involving multi-parties, data ownership, and intellectual properties should be considered. Different authorization roles, data accessibility limitations, and responsibilities should be granted to only authorized participating stakeholders. Role-Based Access Control (RBAC) should be implemented in the digital twin to restrict network access based on a person's role [209,210].

Furthermore, security and privacy are the main concerns for sharing IoT data among distributed digital twin infrastructures. In particular, data in the DT network are fed and backed between the physical object and the virtual model, making the virtual model vulnerable to cybersecurity attacks. Such attacks are critical for scenarios like remote robot surgery, intelligent transportation systems, and federated EU airport operations.

Additional risks of data leakage arising from data aggregation, i.e., in some scenarios such as smart cities, future smart fabrics, healthcare, etc., data coming from different involved parties should be merged to improve the decision-making process and achieve connected digital twins. However, a significant risk is that data aggregators could be storing all shared data in one place, which creates a new and the heightened security risk for the digital twin. Besides, as the digital twin needs to synchronize the virtual replicas with the physical, real-world system or entities in real-time, data or a subset of data should be exchanged between both parties to achieve synchronization, which inevitably increases the surface attack and augment the risk of data leakage [10].

7.2. Privacy-preserving

Digital twins and the metaverse are envisioned to advance the future of healthcare and precision medicine [211]. Healthcare data contains sensitive and personal information that could be attractive to many parties. Therefore, healthcare systems require access control models to prevent cyber-attackers from using sensitive data for financial transactions with third-party providers, who may perform data analysis to identify individuals [212].

Digital twins for healthcare should ensure privacy and data integrity to protect the data from unauthorized access attempts from inside the network so that the system grants access to only authorized parties [7]. Conventional cryptographic primitives and access control models that empower traditional IoT communication have reached their limitations and cannot ensure the protection of health data existing in the healthcare industry, specifically when attacks could be intentional.

7.3. Ethics

Responsibility, ethics, decency, and morality are essential pillars to enhance its innovation in digital twin [213]. Therefore, Simone et al. [214] discussed the ethics of digital twins in smart agriculture and highlighted the need for data sovereignty regarding data aggregation and data analytics on framing data. Similarly, in light of the ethical concerns in the healthcare domain, Derrick et al. [215] discussed the ethical considerations of psychological effects of the digital twin in the healthcare domain. Popa et al. [216] anticipated privacy and socio-ethical issues, especially when there is a digital twin connection between the patient and the model is established. Braun et al. [217] defined conditions that should be met for digital twins to take on an ethically justifiable form of representation, not only for improving diagnosis and therapy but also for providing future states of health and illness. Braun et al. [218] have elaborated a concise reflection on the ethical challenges of DT in healthcare and medicine. The authors suggest that patients should have control over their simulated and virtual representation and highlight the ambivalence in representation between enabling new modes of freedom and endangering through the predictive mode of digital twins.

Another vital aspect in ensuring ethical digital twins is achieving data transparency and avoiding data bias while providing seamless data integration and making predictions. For example, historical data used to build virtual models in digital twins should not imply discrimination between target freedom rights, especially when human behavioral manipulation is involved [215]. Besides, even though digital twins create replicated copies of the human body, it should not conflict with human dignity, i.e., treating patients as a thing or robots is considered highly inappropriate and unethical. Hence, digital twins should not be used to amplify inequality, shorten the lives of some people for the benefit of others.

7.4. Scalability and complexity

With the increasing adoption of the digital twin in large-scale projects like building construction, healthcare, automotive, aerospace, railcar design, military, and defense, etc., digital twin networks become significantly complex as they need sophisticated data acquisition and storage [219] to design and build relevant models for these industries. Both the software and hardware components required to build the DT systems become more constrained and complex, e.g., they involve advanced techniques such as AR/VR and metaverse. Although significant efforts are to build scalable DT solutions [220,221], they tend to implement specific scenarios in controllable areas such as labs and small factories. Therefore, we need efficient and cost-effective tools and software models that fit the requirements of different DT domains, ensure higher scalability and deal with big data analytics and massive network data processing to achieve more accurate models and higher performance in large-scale distributed DT scenarios.

7.5. Real-time properties

A digital twin is envisioned to replicate physical entities to their virtual entities and enable synchronization between them to achieve real-time replication. To this end, data should be exchanged among potentially wireless and wired network infrastructure, potentially, each has its own routing and forwarding protocols, such as wireless cellular networks, Wi-Fi, optical metropolitan Ethernet, etc., which should be able to provide the right data at the right place and time. These networks, however, offer different Quality of Service (QoS) settings, which may impact the service level agreement (SLA), i.e., model simulation data could encounter higher latency (around 100 ms) and lower bandwidth, which will impact the delivery of real-time information and therefore influence the real-time synchronization between the real world and the DT system.

Additionally, the emergence of new IoT services and applications, such as remote robot-assisted surgery [222] pose strict real-time QoS requirements on the underlying network. However, given the distributed nature of the digital twin systems and the variation of the network delay (e.g., queuing and propagation delays), it becomes challenging to keep network digital twins in sync or auto-sync between the physical network and digital twin network. Reflecting the changes in the physical entities to their virtual replicas in real-time can be even more challenging. Similarly, Digital Twins require continuous interaction between real-world objects and their virtual representation in real-time and reliable two-way communications. However, due to the dynamic behavior and the frequent changing in the network environment, it becomes challenging to ensure strict reliability, low latency, and real-time requirements over the future wireless broadband 5G/6G network.

To achieve this goal, it is necessary to provide an efficient network architecture that aids in developing many scalable, interoperable and predictable IoT applications. This network architecture must be flexible enough to be reprogrammed following any change in the digital object. Additionally, we need to simplify the design of network digital twins as much as possible, describe and specify QoS and real-time requirements of different DT applications, and achieve automated resource allocation and orchestration to fulfill the requirements of these applications.

7.6. Interoperability and standardization

There are several research projects to achieve the different visions, perhaps diverging designs, developments, and implementations of a digital twin. As described in Section 3, multiple parties have been involved in the standardization and design of diverse digital twin architectures. Most of them lack consensus when implementing DT systems. Hence, digital twins are harmed by fragmentation and heterogeneity since each model is developed from scratch, no common methods, models, or mechanisms are considered. There are no open and standardized open interfaces to meet the requirements of all digital twin stakeholders, which makes it difficult and even impossible to ensure interoperability among different DT implementations. However, providing common data standards and interoperability can ensure the widespread adoption of DT technologies in various domains. Therefore, there is a need to develop novel modeling tools to build models for digital twins that draw on several industry schemas.

There are several research efforts to build a generalized library to create an interoperable implementation of the IoT digital twin. For example, Picone et al. [74,101] introduced WLDT (White Label Digital Twins), a general-purpose library for developing different modular DT systems for IoT. Similarly, several other solutions [48,55,56,102,116,223] have been explored to provide a framework to enable modular, adaptable, and interoperable software agents for sharing data across the different lifecycle phases; however, they tend to provide implementations for specific use cases or DT domains.

Furthermore, despite the recent efforts achieved by Microsoft towards providing a standardized definition language for describing models, devices, entities, objects, etc. in digital twin [86], helping to implement vertical use cases and complex modeling relationships, however, more efforts are required to develop open vendor-neutral DTDL to achieve an accurate representation of the physical environment. Such a DTDL should ensure the consistency of DT technical implementations and support the heterogeneity of devices and vendors that adopt the DT technology. Hence, an open and unified digital twin network system and abstract interfaces are required to keep all the expected common functionalities and components to enable cross-industry implementations of DT systems and ensure compatibility and interoperability.

7.7. High-fidelity data modeling difficulties

As many industrial sectors are turning to digital twins to improve the operational efficiency and enhance the workflow and life cycle of their products, digital twin data modeling should not only focus on the accuracy of model functions but also should consider flexibility and the expendability of the model to compose and extend future requirements to support large-scale and multipurpose applications [17,224]. Furthermore, digital twins can contain different representation models, such as statistical, machine learning, geometrical and material, mixed-reality, and virtual-augmented reality augmented with physics/data-oriented models, which makes it hard to keep data consistent. Digitalized data in DT should be updated in real-time to track every change in the physical system, i.e., metamodels involving data about the scheme of the system, measured data values and data structure at runtime should be consistent.

In this context, Wilking et al. [225] proposed a SysML approach for improving digital twin data modeling by creating DT behavior using SysML diagrams and generating usable code to speed up the implementation of DT applications. The authors proposed extending the SysML model with a new XMI file to enable universal utilization of all SysML diagrams in DT modeling. Nevertheless, the solution proposes some extensions to SysML diagrams. Still, more investigation is needed to ensure the feasibility of integrating system models into more generalized "*SysML4DigitalTwins*" to lower the obstacles of Digital Twin design. Hence, we need to rethink how many diagrams should be considered to describe fully and model DT systems (i.e., similar to the improvements made to UML diagrams) towards providing autonomous digital twins with a consistent control loop. UML is also expected to support model-driven engineering (MDE) for simplifying the connection between DT and the physical world [226,227], as it enables a bidirectional relationship between the UML models of the digital twin [228].

There are diverse research directions that attempt to provide the data model for digital twin, based on Automation Markup Language (AutomationML) [229] to model DT attributes using machine learning methods [230], using stacked auto-encoder (SAE) based model [231], by leveraging the open manufacturing platform [232], and many other approaches involving hierarchical functional data models.

Therefore, we need a more generic modeling model, aka meta-data model, that covers the digital twin applications. We can rethink abstracted metamodels similar to those the W3C provides for web services. Offering an abstracted level of models helps DT capture the system's salient features, improve its performance, refine the granularity configuration, and reduce the need for high-demand computational resources.

7.8. Data coherence and model revision

Data coherence and model revision are key challenging issues to ensuring the high fidelity of data in digital twins. Indeed, since DT uses a huge volume of data, e.g., historical data, versioning and archiving those data, recent approaches [233,234] suggest integrating blockchain InterPlanetary File System (IPFS) for data distribution. Such an approach could also be used to power MLOps (Machine Learning Operations) algorithms to alternate between previous decision-making protocols, compile historical data to forecast future possible states of the systems, and thereby adapt MLOps to anticipate future decision-making algorithms. Indeed, machine learning models usually degrade in production, i.e., concept drift occurs when changes in the relationship between input and output data give rise to deterioration in prediction accuracy and provoke unforeseen changes in the predicted statistical properties of the digital twin. Digital twin require closed-loop data wrangling and cleaning at scale using Automated Machine Learning (AutoML), which in turn will help digital twin to support drift monitoring to continuously track the ML model's performance in production and adapt both models and decision-making algorithms according AutoML.

We can rethink of Explainable Artificial Intelligence (XAI) [235] as a tool for providing explanations for digital twin models. Recent approaches have shown that XAI can be a powerful tool for creating trustworthy, intelligent digital twins in healthcare [236], in maintenance, repair, and operations [237], as well as for predicting lane changes for vehicles [238] and distributed autonomous mobile robots and Human-in-the-loop data integration [239]. In the light of those contributions, we argue that explaining predictions, recommendations, and other AI output to users is critical for building trust in digital twins [240]. We believe user-level explainability can help to find and detect potential issues of DT in production, e.g., global explainability, can help to spot how small features in a model can contribute to predicting the overall model [241].

7.9. Unclear access to quality data

A digital twin is built upon data, giving insight into the system's past, present, and future status, as well as model knowledge and algorithms, to make some facts about the DT systems. All these data and models should fit the purpose for which they have been collected or designed to ensure that DT applications continue to work correctly and update and upgrade to meet the needs they are used for. While recent advances in machine learning and artificial intelligence, in general, have provided new solutions for data filtering and quality insurance and help to evaluate the fitness of DT. For example, AI algorithms usually need cleaned and labeled data to predict the future states of physical entities and assets. However, AI solutions have limitations that can further complicate the business goals, as they have low interpretability and explainability and require additional time to learn patterns. Indeed, given the variability and heterogeneity of data that feed the digital twin in different manufacturing domains, data modeling poses a significant burden in providing consistent models to empower the DT system. Hence, data quality is paramount to prediction accuracy [242].

8. Trends and key research directions in digital twins

A digital twin is a The wireless research landscape is rapidly evolving to address emerging Internet of Everything (IoE) applications such as extended reality flying vehicles, brain–computer interaction, etc. In this new context, DT has to address new requirements such as self-sustaining wireless systems, proactive online learning-based systems, isolation between twins-based services (microservices architecture), device mobility Management and DT forensic. In this section, we highlight diverse DT trends and research directions.

8.1. Composable digital twins

Digital twins are envisioned to assemble complex systems such as turbines, wind farms, power grids, and energy businesses, which creates additional complexity beyond the physical models to support future capabilities such as data services (i.e., including data integration, aggregation, and management), semantic labels, trustworthiness, user interfaces, intelligence, etc. Hence, new approaches for composing digital and physical elements into larger assemblies and models can simplify the design, control, management, and operation of the DT [45]. Therefore, composability is key to scaling DTs, delivering high-value business capabilities, and providing reusable, interoperable, and composable enterprise business. The Digital Twin Consortium recently released the Capabilities Periodic Table (CPT) framework [51] to provide an architecture- and technology-agnostic solutions for Composable Digital Twins (CDT). The CDT framework should be able to deliver service-based orchestration by developing modular packaged business capabilities that can develop and adapt the digital application to business needs and support large-scale, complex environments [243]. Therefore, we should identify composability gaps that should be addressed and focus on delivering DT capabilities in a model-based approach. Additionally, we should envisage a composable- and capability-driven architecture that facilitates the composability of DT models and ensure the interoperability among modules, thereby driving innovative business future in the next 10 years.

8.2. Cell-based microservice

Current DT software implementations like Eclipse Ditto [66] use different microservice layers (e.g., policies, connectivity, gateway, things, concierge, etc.) using Kubernetes-like (e.g., Helm, Docker, OpenShift, etc.) microservices through an Infrastructure as Code (IaC) model. While these microservices offer a global security approach chained as a single service to mitigate attacks, enable modular architecture, and improve network efficiency, they are associated with the complexities of the distributed system and a higher chance of failure during communication. Cell-Based Microservices [244] are recently envisioned as a promising approach to building independently deployable components that can be loaded from multiple network locations and repositories at runtime. Unifying and harmonizing these components will enable horizontal and vertical scalability and deployment independence. Thus, multiple federated IoT application components can run independently and be redeployed without restarting IoT applications or interrupting IoT services.

Therefore, we need to rethink how to develop distributed Cell-Based microservices to ensure deployment independence and promise flexibility and autonomy. The sought-after goal guarantees modularity and cooperation among distributed federated DT networks.

8.3. Standardization

We discussed in Section 3 diverse standardization efforts to implement an architecture for DT. We also highlighted in Section 7.6 the challenging interoperability issues that stem from the diversity of DT architectures. Indeed, recently, there have been some trends, such as Change2Twin project [245], towards providing a common framework that could fit most DT use cases. For example, the DT consortium is collaborating with the Industrial Internet Consortium (IIC) to concentrate, combine and standardize a single platform and framework that fits most DT systems.

We argue that we need to rethink the design of new abstracted programming interfaces that provide standard ways to communicate with, and control, equipment made by different manufacturers. Some enterprises started implementing such an API, e.g., *mapped*, the data infrastructure platform maker, has recently launched a new service built on top of the open-source Brick Schema for describing physical, logical and virtual assets, similarly to Qualcomm's Smart Cities Consortium and Zyter, the IoT provider, has recently partnered to develop and standardize interfaces to enable DTs for diverse domains such as healthcare and smart cities. We believe that we will see, shortly, a wave of consortium partnership agreements to find new ways to improve efficiency and build better interoperable and standardized DT interfaces.

8.4. Dataverse

DT can work with metaverse to enable the future Industrie 5.0, including the manufacturing industry (e.g., creating virtual copies of entire factories and plants to ensure transparent production processes), automobile sector (e.g., creating a virtual model of a physically connected vehicle), healthcare (e.g., surgery training), etc. The union of both technologies will lead to the creation of the *dataverse*, which will build the data infrastructure to support the next generation of DT use cases.

We claim that traditional hierarchical DT asset structures will disappear and new graph-based solutions, such as those modeled with the DTDL approach [86] will appear to facilitate the integration of DT assets and better describe their relationships. We also believe that dataverse will offer a unique opportunity to build interoperable and high-fidelity DTs that relate all data in the virtual world, entities, and objects, thus unfolding in the future.

8.5. Security

We highlighted in Section 7.1 how security and vulnerability pose a significant challenge to the large-scale adoption of DTs by major industry sectors. Meanwhile, DT bodies such as the Industry IoT Consortium (IIC) are working to offer new models and trustworthiness framework that reinforces the security and privacy of DTs. Furthermore, the recent advances in blockchain consensus algorithms [22,192,246] such as the Proof of Authority (PoA), Proof of Ownership (PoO), and the merging of the Ethereum blockchain to support the Proof of Stack (PoS), which will drive the advances towards providing more secure and inviolable digital infrastructure [234].

We claim that the increased development of edge AI, TinyML, and local machine learning models and algorithms and the advances in federated machine learning will foster the development of DT security solutions and increase the awareness of DT security across the DT lifecycle. We believe that the aforementioned distributed intelligence approaches will foster the development of new models or prototypes that target competitive intelligence attacks. We argue that future DT systems will support fully operational competitive intelligence that allows them to preserve their trustworthiness and integrity.

9. Conclusion

In this paper, we have surveyed a wide range of recent and state-of-the-art projects, software implementations, and standardization efforts in the realm of digital twins. This effort stemmed from the needs of the research community, where we found that most researchers call for current digital architectures that need additional research efforts to provide a unified framework that can ensure interoperability between different industrial applications, allow diverse domains that can benefit from DT and ensure secure data dissemination at scale among potentially distributed industrial IoT systems. To address the challenge of integrating heterogeneous DT systems, researchers have started to focus on redesigning the current DT architecture by breaking the tight integration of its capabilities towards integrating various methods, models, and processes to simplify data collection, formatting, and transmission. As a result, major research projects focus on designing DT applications to support specific use cases and applications. However, the next generation of DT will benefit not only from the simplicity of the implementation but also from the benefits of composability, distributed and federated intelligence, security by design frameworks, network slicing, and common standardization, which will have the potential to simplify its integration into various industrial use cases. Unfortunately, we did not find any comprehensive study of existing techniques, research projects, and tools summarized in a single study.

To that end, we provide a taxonomy of the key challenges and opportunities in a number of different areas, including architectural models, security and vulnerability, ethics and data sovereignty, scalability, real-time properties, interoperability with heterogeneous connectivity protocols, as well as high-fidelity data modeling. We showed that both academia and industry are involved in the development of digital twins; however, most of the investigations continue to focus on very specific scenarios involving the optimization of that product's lifecycle.

We argue that these studies are important, but they should only be done in the context of open, standardized APIs that can predict future use cases like the metaverse and holographic mixed reality, cellular-connected drones, autonomous supply chains, and massive twinning. Although several commercial and open-source implementations of DT software exist, they also pose a set of challenges that should be addressed, which will require coordinated attention. From the research community's success and wide acceptance, our goal was to present these challenges and present current standardization efforts. By no means have we presented an exhaustive list of opportunities. We believe there are additional challenges and opportunities. Research exists along a broad spectrum, ranging from composable DT solutions to be used in the upcoming 5G network and beyond, to high-fidelity formal data modeling, knowledge data mapping, and blockchain-based security models to improve the trustworthiness of the DT-based solutions. The aim of this paper is to put forth these challenges, leading to many more research efforts.

CRediT authorship contribution statement

Akram Hakiri: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Aniruddha Gokhale:**

Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sadok Ben Yahia:** Conceptualization, Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nedra Mellouli:** Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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