Digital Twins' Maturity: The Need for Interoperability

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***Abstract*—Digital twins have gained tremendous momentum since their conceptualization over 20 years ago, as more and more domains discover their value in driving efficiencies and reducing costs, while enabling technologies continue to advance. Originally aimed at product optimization and intelligent manufacturing, the range of applications for digital twins now spans entire complex, often highly interconnected systems such as ports, cities, and supply chains. Despite the increasing demand for sophisticated digital twinning solutions across all domains and scopes, their development is often still constrained by differing definitions, different understandings of their functional scope and design, and a lack of concrete methodology toward implementing a comprehensive digital twinning solution. Although there are already papers that evaluate the capabilities of existing digital twinning solutions on the basis of maturity levels, these usually consider the object to be twinned in isolation and are often domain-specific. With this article we address exactly this gap discussing how interoperability of digital twins can break physical boundaries of an isolated system, enabling system of systems joint optimization. We therefore consider interoperable digital twins to be the most mature twinning platforms, thus, we discuss in detail six digital twin maturity levels, departing from the interrelated contexts of ports, cities, and supply chains. Examples drawn from these domains demonstrate the need for interoperability toward optimizing processes and systems in realistic contexts, rather than in assumed isolation.**

***Index Terms*—Digital twin (DT) maturity, interoperability, smart cities, ports, supply chains.**

I. INTRODUCTION

IT HAS been already more than 20 years since Grieves introduced the concept of the digital twin (DT), as the "conceptual ideal for product lifecycle management" at an industry workshop in 2002 [1]. Even though the realization of DTs did not become a reality until around 2014 due to the infancy of many enabling technologies, the development of DTs has experienced an explosive growth in recent years and has gained momentum in numerous domains [2], [3], [4], [5], [6]. The number of practical applications in various industries has therefore increased rapidly [7].

As they bridge the gap between virtual cyberspace and physical entities, DTs are consequently seen as pillars of Industry 4.0 and the innovation backbone of the future [8]. According to Minerva et al. [9], the most tangible value of a large DT implementation may be the ability to understand real-world interactions and the effects on different objects at a very detailed level, allowing such a DT system to predict and even simulate the behavior of objects under different conditions. In addition, perceived benefits in academia and industry include cost reductions, efficiency gains, safety and reliability, maintenance decision making, and the promotion of innovation [10]. The increasing recognition of the benefits of DTs is in turn driving innovation triggers for emerging technologies that will enable the implementation of more advanced digital twinning solutions [11].

Today, DTs are no longer limited to manufacturing or products, but encompass entire cities, supply chains, or dynamic systems, such as ports [12], [13]. As a result, DT solutions from different application domains increasingly differ in terms of complexity, requirements and architecture, making a general domain-independent characterization and definition of DTs increasingly challenging [14]. Moreover, the growing variety of DT solutions, coupled with the growing supply of providers promising efficiency gains through the introduction of DTs, requires guidelines that help adopting companies to assess the maturity of the DT solutions being offered. Such guidelines are also needed to compare and benchmark the maturity of current and future digital twinning implementations.

Although there already are papers providing characteristics designed to assess the capabilities and the maturity of existing and upcoming digital twinning solutions [15], [16], [17], these assessment frameworks are often strictly domain-specific and view their respective actual products, services or systems in isolation. Consequently, there is a need for domain-independent guidelines that contain a certain level of generality without becoming too vague. Moreover, considering the maturity of individual systems in isolation contradicts new research outlining that DTs should be linked as a large whole to improve the performance of whole systems and beyond [18].

With the increasing interconnection of systems in the context of globalization and efforts to improve system of systems (SoS) performance, the inevitable interconnection of DTs is

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gaining momentum [19]. A system originates if an object is connected with further related objects and thus enhancing their functionality [20]. In addition, the consolidation of multiple, previously unrelated systems provides a SoS approach that offers the opportunity to blur corporate boundaries [21] and promote interconnectedness to enhance the efficiency of each system and their interplays as a SoS as a whole [22]. This process is accelerated by the ever-increasing number of systems with physical and digital connections, which creates scope for an ecosystem of connected DTs and complex cyber-physical systems characterized by automated decision making or decision support based on the collected data [23].

The objective of this article is to provide an assessment framework for the maturity of digital twinning solutions intended to evaluate, in a domain-independent manner, 1) the maturity of the digital twinning solution of a twinned system, as well as 2) the potential of a system's DT to jointly co-operate with other related systems' twinning solutions, toward a system of (twinned) systems. Demonstrating the application of the maturity levels outlined, examples from the port and smart city context are presented for the first five maturity levels reflecting the maturity of the DT solution of the respective system.

In this article, interoperability is discussed as the highest level of maturity in the context of supply chains, which are recognized as systems of systems [24], assuming that the DT of the supply chain consists of a collection of DT systems, such as those of cities and ports, covering the entire multimodal transport chain from origin to destination. The importance of DT interoperability, together with the vision of building a DT ecosystem, has been highlighted in recent research [25], and is promoted in major research and innovation funding programmes, such as the Horizon Europe. In this context, we refer to interoperability as the mutual collaboration of peer DT systems, toward a joint SoS goal, rather than the exchange of needed data across DTs' modules toward achieving a single system's goal.

The rest of this article is organized as follows. Section II begins with a brief characterization of DTs (II-A), followed by a discussion of the necessity of an evaluation framework for assessing and benchmarking current and future digital twinning solutions (II-B) under consideration of previous work regarding digital twinning maturity evaluation (II-C). The proposed maturity framework and its six consecutive maturity levels are presented in Section III. Section IV is dedicated to the application of the maturity levels to the port (IV-A), smart city (IV-B), and supply chain context (IV-C), and their interconnection with each other (IV-D). Section V discusses barriers of interoperability and provides potential solutions. Finally, Section VI concludes this article.

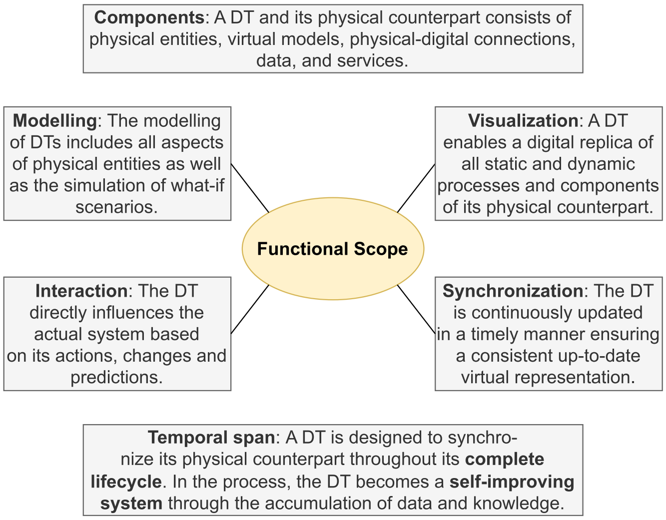
II. LITERATURE REVIEW OF DTs

A. *DT Characteristics*

Twinning of physical assets or processes represents a significant step in the process of digitization and has evolved over the last twenty years along with the technologies that support its realization [e.g., sensor technology, Internet of Things (IoT), cloud computing, Big Data analytics, and artificial intelligence (AI)] [26]. Although there have been numerous, often domain-dependent definitions of DTs since their introduction by Grieves at an industry workshop in 2002 [1] (see [3], [5], [13], [27], [28], and [29] for extensive comparisons), most definitions consider them as a virtual representation (replica) of an actual system (AS) that can be continuously updated with real-time data throughout its lifecycle and can interact with and influence the AS, ideally in an automated way [30].

TABLE I
DT Features, Derived From [31]

Definition: A DT is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.	
DT	**Emphasizess on**
DT systems transform business by accelerating holistic understanding, optimal decision-making, and effective action.	Value
DTs use real-time and historical data to represent the past and present and simulate predicted futures.	Capabilities
DTs are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems.	Specification



Components: A DT and its physical counterpart consists of physical entities, virtual models, physical-digital connections, data, and services.

Modelling: The modelling of DTs includes all aspects of physical entities as well as the simulation of what-if scenarios.

Visualization: A DT enables a digital replica of all static and dynamic processes and components of its physical counterpart.

Interaction: The DT directly influences the actual system based on its actions, changes and predictions.

Synchronization: The DT is continuously updated in a timely manner ensuring a consistent up-to-date virtual representation.

Temporal span: A DT is designed to synchronize its physical counterpart throughout its **complete lifecycle**. In the process, the DT becomes a **self-improving system** through the accumulation of data and knowledge.

Fig. 1. DT characterization derived from [13].

As part of its efforts to counteract domain-specific and thus fragmented development of DTs, the DT Consortium has created a cross-domain DT definition [31], which is reflected in Table I. Table I reveals that DTs are characterized by three foundational elements: the virtual representation enabling a comprehensive situational awareness, the real-world entities and processes it represents that are further analysed within its models, and the constant bidirectional data exchange through which the virtual and the real-world entities are synchronized and in constant interaction [31]. Following Botín-Sanabria et al. [32] in this article, a digital shadow exists if the latter is absent and thus only unidirectional automatic information flow from the physical world to the virtual world is integrated, and a digital model exists if no automatic information flow is integrated.

Drawing on the extensive reviews of DT characteristics by Jiang et al. [8] and Klar et al. [13], Fig. 1 attempts to illustrate the core characteristics of DTs. It comprises the components of a DT, its functional scope, especially modeling, visualization, interaction and synchronization, and the temporal span of a DT, which is characterized by the goal of synchronizing its AS throughout its life cycle, resulting in continuous self-improvement due to the continuous accumulation of data and knowledge.

Despite varying domain-specific objectives, DTs generally aim to produce actionable information, feed verifiable AI systems, and are used to improve strategic, design, operational, and maintenance decisions of both real and virtual systems [33]. Moreover, although DTs are the subject of study and a tool applied in various disciplines that practitioners understand from their own professional perspectives, most recent research on DTs focuses on dynamics, learning, and development, rather than just connecting DTs (in real-time) with its real-world entities, as in the context of digital shadows [14].

Although recent research in the field of DTs has primarily focused on DTs at the product, process, or system level, the concept of connected DTs has gained momentum in recent years as the increasing number of systems with physical and digital connections offers potential to view processes and systems not in isolation, but in their interplay as part of a larger whole [23]. Connected DTs can therefore be regarded as tools used to understand the complexity and interplay of interconnected systems. Consequently, connected DTs enable better understanding of SoS performance, improved predictive maintenance, and better decision-making capabilities, especially in multistakeholder environments. In this context, the importance of interoperability is particularly emphasized, as its absence can at the very least contribute to greater barriers, risks, inefficiencies, and even outright failure [34] Consequently, ensuring the interoperability of systems and their respective DTs is essential to unlocking their greater potential with lower implementation costs, reduced risk of failure, and less complexity at scale [25], [33].

B. (Im)Maturity of DTs

Although the concept of DTs has largely evolved since its coining in 2002 [1], along with its enabling technologies, there is still a lack of standardization, methodologies, and tools for the development and implementation of more sophisticated DTs [7]. Moreover, the concept and content of DTs do not have a precise, uniform definition or even description [35]. The resulting lack of consistency and consensus on the definition of DTs can lead to different expectations, culminating in conflicts in the provision of DTs in practice [36].

Furthermore, it is common practice that different DT models are created separately by different stakeholders of a complex system, corresponding to different subsystems or components throughout the lifecycle [37]. These existing DT models must be properly integrated and orchestrated into the DT architecture to prevent interoperability issues at the data level, but also for the interconnection of DTs at the system level.

An example cause of the immaturity of many existing DTs from the port domain that is transferable to many other domains is that the various port actors involved typically maintain a wide range of, practically, vertical information systems (i.e., with limited or no actual connectivity between them), due to the large number of actors in port processes and the isolated procurement of digitization projects that have provided these systems [38].

Recent studies from the supply chain context also reveal that while companies are striving for openness and standardization of their information technologies, there is a significant need to overcome the technical, organizational, and commercial barriers to managing the large amounts of data that DTs require and generate to optimize the supply chain as a whole across organizational boundaries [39].

In addition, many complex systems, such as ports and cities, differ significantly in terms of size, geographic characteristics, governance and institutional frameworks, functionality, and specialization [40], which poses an additional challenge to a unified one-size-fits-all DT solution for complex systems.

Recent DT survey papers further demonstrate that there is a need for more sophisticated technological solutions to manage the multitude of input parameters and data in complex systems [13], and several issues related to data (trust, privacy, cybersecurity, convergence and governance, acquisition, and large-scale analysis) [41], [42].

Once overcoming these issues and evolving into mature versions, DTs are more than platforms of structured information collection and visualization. They can then serve as an information resource that enhances the design of new infrastructure and the understanding of the condition of existing facilities, such as in the case of the Köhlbrandbrücke in Hamburg [49], verify the as-built condition, perform "what-if" simulations and scenarios, enhance collaboration, or provide a digital snapshot for future works [17], [38]. Consequently, a fully developed DT is expected to have elements of self-adaptation combined with machine learning, simulation, and data processing to enable accurate prediction of specific characteristics related to performance [30], integrating all processes in conjunction to optimize the system as a whole and beyond [13].

C. Previous Work on DT Maturity

Instead of looking at DTs solely in their futuristic and fully implemented version, it is necessary to focus on their purpose, distributing their realization over realistic milestones, understanding the benefits of each milestone, and observing how their value increases as they reach higher levels of maturity. A first attempt to create such an approach comprises the five maturity levels (plus level 0) of Evans et al. [17], that propose a maturity spectrum of six levels (inluding level 6), with an emphasis on the built environment. Since then, there have been several attempts to define milestones for the development status of DTs in the form of maturity levels (or capability levels in some papers).

Attempts to create maturity levels to assess and guide the development of more sophisticated digital twinning solutions already exist for several domains, including built environment [17], manufacturing [18], ports [38], and (wind) energy systems [16], [47]. A comprehensive overview of the core contributions regarding DT maturity assessment, including a brief summary and a description of a DT with full maturity, and their respective domain context, is illustrated in Table II.

TABLE II
COMPARISON OF DT MATURITY ASSESSMENT APPROACHES

Contribution	Brief description of the DT maturity assessment	Domain context
Evans et al. [17]	**Summary:** The authors propose a model consisting of six maturity levels: (0) Reality capture (for existing physical assets), (1) 2D map/systems or 3D model (object-based only), (2) Connected to persistent (static) data, metadata, and BIM Stage 2, (3) Enrich with real-time (dynamic) data, (4) Two-way integration and interaction, and (5) Autonomous operations and maintenance. An increase in each level leads to increases in complexity and connectivity, and subsequently value. **Description of a high-level DT:** "In the future it is not hard to imagine that the DT learns and evolves as a living repository for institutional knowledge, absorbing enough experience about the behavior of the physical asset that it could become completely autonomous in its operations, able to react to anomalies and upsets and can take the necessary corrective action with little or no human interaction" [15]. **Comment:** In this article, [32], Botín-Sanabria et al. applied this maturity model to further domains, including smart cities, medicine, manufacturing, and automotive. The maturity levels are further applied to assess urban DTs by the authors in this article, [43].	Built environment
Singh et al. [44]	**Summary:** The maturity of DTs is divided into four levels, a pre-DT, DT, adaptive DT, and intelligent DT. For each maturity level, the corresponding level is referred to specific characteristics, namely life-cycle stage, PT-DT (physical twin-DT) connectivity, application scenarios and model improvement characteristics. The authors further provide guidelines towards achieving mature DT implementations by highlighting tools and methods of DT creation and simulation. model **Description of a high-level DT:** "A level four DT translates the optimization scenarios developed in the DT directly into control strategies for the PT. Connectivity at level four is extended continuously, including a growing number of contextual data sources" [44].	Battery system in a robotic minicar
Medina et al. [45]	**Summary**: The authors provide a matuirty model with four levels that rely on the following ten dimensions: 1) analytical capability, 2) model update frequency, 3) data collection frequency, 4) modeling scope, 5) decision implementation, 6) lifecycle integration, 7) level of DT individualization, 8) business level affected, 9) operational data accessibility, and 10) stage of implementation. **Description of a high-level DT:** A DT with full maturity (level 4) provides prescription on how to make things happen, provides regular model updates while collecting data in real time, models the complete product environment, has a (fully) automated connection to its physical twin, is fully integrated along the whole lifecycle of the physical twin, and is fully deployed.	Commercial Aerospace OEM Industry
Chen et al. [46]	**Summary**: The authors propose a model that is based on Gemini Principles to form a systematic view of DT development and implementation. Within this maturity model, three main dimensions consisting of nine subdimensions have been defined. Based on the determination of a score with respect to the fulfillment of the subdimensions, one of the following six maturity levels is determined: 1) unaware, 2) identifiable, 3) aware, 4) communicative, 5) interactive, and 6) instructive and intelligent. **Description of a high-level DT:** At the highest maturity level (Level 6: Instructive and Intelligent), the DT enables "Semi-automatic/automatic managing asset, intelligent decision-making support on its own and instigating actions" [46].	Asset management
San et al. [47]	**Summary**: The authors propose six DT capability levels ranging from 0 to 1 : 0) standalone, 1) descrptive, 2) diagnostic, 3) predictive, 4) prescriptive, and 5) autonomous. **Wind Description of a high-level DT**: "Can replace the user by closing the control loop to make decisions and execute control actions on the system autonomously" [47]. **Comment**: In a follow-up paper, Stadtman et al. [16] applied these DT capability levels to wind farms in greater detail.	Wind energy industry
Uhlenkamp et al. [48]	**Summary:** The maturity of DTs is based on seven categories: context, model, computing capabilities, data, control, integration and human—machine—interaction and provide a maturity score based on the fulfillment of these seven categories. **Description of a high-level DT:** Not directly applicable here as the maturity of a DT is determined by a score between 0 and 1 taking the 7 categories and their respective dimensions and attributes into account.	Application examples within multiple domains
Klar et al. [38]	**Summary:** The authors propose a model consisting of five maturity levels: (1) Replication of assets, (2) Connection, (3) Synchronization, (4) Interaction, and (5) Automation. **Description of a high-level DT:** In the highest maturity level, DTs encompass transparent explainable systems with broad control potential, enabling autonomous operations optimization and self-maintenance.	Port and terminal operations
Reiche et al. [18]	**Summary:** The authors propose a model consisting of four maturity levels reflecting the provided scope of information and abilities and the intensity of interaction of the DT and its environment. **Description of a high-level DT:** The DT is active by requesting environmental information. It evaluates this information and infers deterministic decision and reactions. Its interaction with the environment and inference are based on learning behavior influenced by machine learning algorithms. Thus, the DT is able to develop over lifetime.	Manufacturing and Production Systems
Hu et al. [15]	**Summary**: The authors propose a model consisting of six maturity levels, including the basic level (Level 1), the connection level (Level 2), the integration level (Level 3), the perception level (Level 4), the interaction level (Level 5), and the autonomy level (Level 6). The authors further provide a comparison and assessment of three dimensions and 27 rubrics for different DTs of high-end equipment based on a qualitative analysis of DT maturity. **High-Description of a high-level DT**: At the highest level (Level 6: Autonomy Level), "the DT of high-end equipment should carry out automatic prediction and operation under different unknown working conditions. The DT of high-end equipment can autonomously make decisions to robustly maintain the safety of high-end equipment [15]."	High-end equipment, such as underground engineering equipment

TABLE III
MATURITY LEVELS FOR DTs, ADAPTED FROM [17]

Level	State	Requirement	Enabled potential
1	Replication of assets	Digitization of physical assets and their state at moment of capture (e.g. 2D maps or 3D models)	Awareness of assets, rudimentary decision support
2	Connection	Connect processes and models to static data and metadata of level 1	Realistic simulations and asset planning
3	Synchronization	Enrich with timely data (sensors and other IoT technologies)	Real-time situational awareness and immersive environments
4	Interaction	Two-way data communication and interaction	Remote control of physical assets and processes
5	Automation	Transparent explainable systems with broad control potential	Autonomous operations optimization and self-maintenance
6	Interoperability	Highly linkable systems characterized by a high level of standardization, ontology definition, and semantic modelling	Joint decision-making among various systems, enhanced system of systems performance

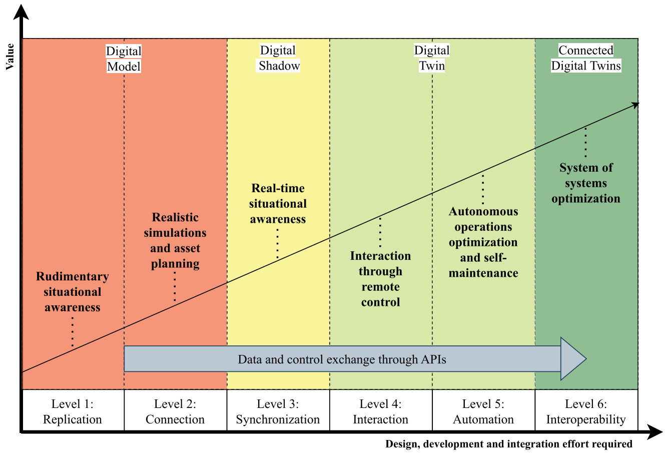


Fig. 2. Overview of the maturity levels and their added value.

Although these papers significantly contributed to maturity assessment frameworks in their respective domain, we argue that these frameworks are often either very domain-specific and often view the respective system or asset to be twinned in isolation. To the best of authors knowledge, this article emphasize on autonomous operations as the highest maturity level. However, we claim that within the SoS paradigm, the highest level of maturity should emphasize on DTs that act autonomously, while being in constant interaction with other DTs to improve the SoS performance, thus requiring a high level of interoperability.

III. DT MATURITY ASSESSMENT

Drawing on the initial maturity guidelines for the built environment proposed by Evans et al. [17], and an adapted version by Klar et al. [38] in the context of ports, we synthesize the two initial levels of basic digitization proposed by Evans et al. [17], assuming that each system or asset to be twinned already has a high level of data acquisition and thus an enhanced understanding of the object to be twinned in digital form. We further add a new sixth level: interoperability, to address the paradigm of connected DTs [50] and thus facilitates the contribution of DTs to improve the SoS performance [21]. The resulting six maturity levels are presented in Fig. 2. It demonstrates that with increasing effort and time, along with higher levels of integration, a higher value is achieved. The figure further highlights the key milestones for achieving each level and aligns the six maturity levels into different DT constructs. An overview of the six maturity levels along with their requirements and potential is presented in Table III.

A. Level 1: Replication of Assets

The first maturity level provides an exact replication of the physical object to be twinned in digital form. This includes the exact digital replication of all static processes as well as the state of all dynamic processes at their moment of capture. This enables rudimentary situational awareness through the miorroring of all static processes by the DT.

B. Level 2: Connection of Models and Systems

The second maturity level extends the digital replication obtained toward acquiring the first maturity level by attaching models of physical or business processes relevant to the assets and their life-cycle, enabling the DT to capture and estimates the effects of real-world events using historical data.

C. Level 3: Synchronization of Data and Processes

The third maturity level enriches the models of the DT obtained in maturity level two by real-time data, collected by sensor networks, enabling a timely connection and mapping from the physical world to the digital world. Therefore, the integration of both static and dynamic data enables real-time situational awareness by providing knowledge about both less time-sensitive real-world events and more time-sensitive events. Upon reaching the fulfillment of the third maturity level, the respective DT covers the aspects of modeling, visualization, and synchronization, as presented within the functional scope of Fig. 1.

D. Level 4: Interaction Between the DT and the Asset

The fourth maturity level builds upon the collected operational data and its processing in the DT's models, resulting in detailed real-time simulations of the processes of the object to be twinned and enabling a bidirectional exchange of information

TABLE IV
DT MATURITY LEVELS OF COMPLEX SYSTEMS IN ACTION

Domain	Example DT	Level	Justification	Path ahead
Ports	The Port of Rotterdam's digital platform termed Portmaster provides precise information, including the arrival and departure times of ships. Quays, berths and other port infrastructure can be digitally mapped in Portmaster and linked to information about accessibility and availability [52]. The DT further uses IoT sensors to enable advanced intelligence by simulating the physical characteristics of the port so that multiple variables can be changed and effectively tested. As a result, the DT models are able to make accurate real-time predictions of arrivals and departures, reducing waiting times and costs [52], [53].	Level 3	The DT of the port of Rotterdam encompasses a digital replication of a port that is enriched by models with distinct simulation capabilities that are updated in a timely manner. It thus enables realistic simulations and facilitates to real-time situational awareness.	(1) Remote control of port equipment, processes, and facilities (2) Full automation and self-maintenance with full transparency (3) Joint decision-making with other DTs, such as those of ships, supply chains, and cities
	The Mawan Smart Port can access historical operation data to create a historical operation review and to identify the causes of operational bottlenecks, helping to provide solutions to avoid them in the future. In addition, current operating conditions are improved based on insights from historical operating data [54]. Mawan Smart Port's fleet management system can further monitor the status of partially unmanned vehicles in real time, provide optimal routing and scheduling, and support mixed operations of multiple unmanned trailers [55].	Level 4	Mawan Smart Port's DT is capable of providing decision-support in real-time. It further provides real-time situational awareness and limited interaction with the ports' semi-automated vehicles.	
Smart City	The New South Wales government is currently developing a DT-based open-source interactive platform to capture and display 3D and 4D data about the urban environment in real time [56]. It enables real-time spatial data sharing and collaboration to help policy planners and project developers better design and manage the future of cities [54]. It also includes intelligent infrastructure that provides access to real-time data on electric vehicle charging station locations.	Level 3	The DT provides a dynamic digital replication of the city and its processes in realtime. It thus contributes to real-time situational awareness and forsters collaboration among stakeholders.	(1) Simulation of what-if scenarios (2) (Automated) remote control of infrastructure, charging stations, and measures against urban heat islands (3) Interaction with DTs representing other urban processes
	The Virtual Singapore digital twin platform provides a dynamic 3-D representation of the city [57]. It integrates data regarding ambient temperature and sunlight exposure throughout the day to visualize the heat island effect in urban areas as well as the effects of any potential measures taken in response [54].	Level 3	The DT provides a dynamic digital replication of the city. It is capable of real-time visualization and simulating certain effects in real-time.	
Supply Chain	The DT-based supply chain platform "Logistics Mirror" developed by JD Logistics is capable of increasing supply chain efficiency and to reduce costs. First deployed in JD's Beijing Asia No.1 logistics park, the platform covers over 8,000 transportation routes that are constantly mirrored across JD's own logistics and warehousing network, providing accurate capacity forecasts and alerts for sales peaks [58], [59].	Level 3	The DT is capable of realtime monitoring and thus contributes to enhanced situational awareness throughout the supply chain. It further provides simulation capabilities.	(1) Automatic rerouting of trucks based on real-time disruptions, (2) Joint decision-making across different stages of the supply chain

that allows the user to issue control commands remotely. The fourth maturity level thus embeds the bidirectional nature of the DT enabling the DT to interact with its physical twin.

E. Level 5: Automation of Processes

In the fifth maturity level, the DT is capable of taking autonomous decisions about operations and maintenance based on real-time and historical data and their further processing in its models. The DT is thus fully automated to reduce the risk of human errors while providing full transparency to provide diagnostic tools for troubleshooting in case of undesired results. The DT is further capable of learning from the consequences of previous decisions, resulting in the DT to become a self-adapting system.

F. Level 6: Interoperability Across DTs

In the sixth maturity level, the DT is capable of optimizing its broader system beyond its asset's physical boundaries by exchanging information with other, interconnected systems, thus allowing decisions to be taken jointly with the respective DTs of these interconnected systems, leading to enhanced SoS performance through joint optimization.

IV. MATURITY LEVELS IN APPLICATION

The comparison of different approaches to assessing DT maturity among different domains, including manufacturing, aerospace, and the built environment, presented in Table II, demonstrates the need for a domain-independent framework for assessing DT maturity. Interoperability, in the sense of data and control exchange across systems within a DT, is already recognized as a fundamental requirement in many domains and projects, such as the Destination Earth project [51]. However, this is not yet the case in all domains. In multistakeholder environments, especially in transportation, the interoperability of multiple, potentially antagonizing DT systems is not yet recognized due to lack of actors' coordination and collaboration, reluctance to change traditional processes, high implementation costs and risks, lack of capacity for change, lack of stakeholder support, and lack of trust among stakeholders and in DTs (see Section V for a more thorough discussion) [13].

The six DT maturity levels presented in table III are discussed in depth in this section from the viewpoint of ports (IV-A), supply chains (IV-B), and smart cities (IV-C), since these represent a class of domains with massive potential gains from DTs interoperability of their multiple stakeholders, without limiting the scope of our presentation. Table IV expands the corresponding subsections by presenting current DT examples from the three domains and assigns them to one of the six levels. It reveals that most existing digital twinning instances have reached upon level 3: Synchronization, while some of the examples from the port domain, representing innovation-leading ports, are already on their way to the fourth level. Following our detailed discussion of the maturity required to meet the DT requirements in the context of the three respective domains within the framework of the maturity levels presented, we will then discuss in Section IV-D the scenario, in which different DTs interact to improve the SoS performance, with a particular focus on the aspect of interoperability.

A. *Port DT Maturity*

Ports are characterized by their complex interplay of numerous actors linked by cargo and information flows, resulting in a plethora of closely intertwined port processes [40]. In a recent paper, Klar et al. [13] identified 1) situational awareness, 2) data analytics capabilities for intelligent decision making, and 3) fostering multistakeholder governance and collaboration as the three key requirements for DTs in ports.

Following the maturity levels presented in Table III and approaching the realization of a rudimentary version of 1), a digital replica of the port including all its assets and facilities (such as berths, quay cranes, and storage yard) has to be created. To approach 2), the digital replication of level 1 must be enriched with meaningful models, for example, for estimating ship and truck arrival and departure times, ship and truck turnaround times, or unloading duration and equipment demand [60] to enable the port operator to run realistic simulations and facilitate asset planning

In order to develop more realistic and dynamic situational awareness in accordance with 1) and to promote a timely exchange of data and information between the various port actors in the context of 3), real-time data collection compliant with level 3 is required. For example, the port of Rotterdam is equipped with sensors in all docks that collect real-time data on environmental and water conditions in addition to operational data to ensure smooth operation [42]. Thus, level 3 compliance enables ports to perform real-time vehicle routing and dispatching [61] and to perform intelligent storage space assignments to reduce the cycle time of storage space operations [62], which is highly dependent on the availability and quality of arrival and departure times for handled import, export, and transshipment containers.

Recent research assessing the maturity of existing DTs in ports [38] indicates that most ports have reached at most maturity level 3, with the exception of a few innovation-leading ports. In such ports, direct interaction between the DT and the port (level 4) is achieved using bidirectional data exchange. Such interactions could be as follows:

1) the remote control of quay cranes in case of alarming operational patterns [63];
2) issuing instructions to ships based on their position and the progress of port processes required to serve the ship [13];
3) the remote interaction with the trucks, which may be needed whenever schedule adjustments needs to be made.

The transition from manual remote control to automated control by the DT leads to the achievement of the fifth level. Level 5 thus enables DTs to make a significant contribution to terminal automation. Despite numerous recognized benefits, such as efficient operations, environmental, cost and energy savings, social security, and resilience, less than 3% of ports can be considered having level 5 [64].

The interaction of a port DT with those of other related systems regardless of their maturity level to the best of the authors knowledge is still not realized. This is an obvious mismatch of reflection of the real world onto the cyber one, since the port actually interacts with related physical systems, such as supply chains and cities. This comes despite the recent observation that facilitating the coordination of such interactions can be one of the major DT requirements in the port context [13] and several recent papers recognizing the importance of standardization for the fusion of data from operators, equipment, and the environment into the virtual space of a DT-based system (e.g., see [65] and the references therein). Thus, there is an urgent need for achieving the 6th level enabling the interoperability of different DTs with that of the port.

B. *Urban DT Maturity*

DTs are recognized as a means to achieve smart city goals, such as facilitating better governance through better-informed decision-making, improving citizen well-being, reducing operational costs, providing disaster management and protection, and supporting development and business uptake [14]. DTs are thus becoming increasingly important for the realization of the smart city, as DTs in the urban context allow the integration of urban planning and management in a single tool, promote urban management as they can reflect the exact state of the city in real time (Level 3: Synchronization), and enable faster response times as they can actuate autonomously (Level 5: Automation) [66].

Four key requirements for urban DTs are identified in [36]. The first entails the provision of 3-D city models with geometric and semantic information. Following the maturity levels outlined in Table III, the first level must be fulfilled for this requirement, as its compliance leads to a complete digital replication of the physical urban infrastructure in the form of a 3-D city model.

The second requirement, the provision of near real-time data, requires the urban DT to achieve the third level. This allows the city's DT to continuously collect data on various processes, such as traffic [12], energy [67], and the environment [68], and to map all processes in real time, promoting a high level of situational awareness. This enables, for example, monitoring of the wear and tear of bridges, roads and other urban infrastructure to ensure timely maintenance and extension of service life [69]. The comprehensive maturity evaluation of Botín-Sanabria et al. [32], following the maturity levels presented by Evans et al. [17], reveals that most urban DTs have reached at most level three.

The third requirement, enabling a variety of operations, e.g., analysis, simulation, and prediction, requires the DT to realistically mimic urban processes within the framework of level 2 by complementing its digital replication with simulation models. Such models may encompass urban mobility simulations [12], disaster management [14], urban energy modeling [14], airflow simulations [66], or water supply management [70]. However, to fully comply with the third requirement, the fourth level is required as it allows the results of the various simulations of the urban DT from level 2, which have been upgraded with a real-time component in level 3, to be applied to the real world by remotely regulating the processes based on the outcome of the simulations. Level 4 can be exemplified by an application example by Fuertes et al. [70], which describes the use of a DT to optimize Valencia's water supply network, the control of which will be enabled remotely by the DT in the future. Further examples include controlling traffic systems and dynamic road and congestion charging, and managing energy consumption in cities based on real-time updated traffic and energy data [67].

The fourth requirement, which addresses the social and economic functions of the built environment, such as enabling participatory processes that involve humans as sensors, requires level 5. Since the complexity of the smart city exceeds that of conventional DT applications, such as manufacturing, by several dimensions [14], a high degree of automation is required to enable a higher response time and direct interaction without human intervention.

The lack of interoperability between the different DTs composing the urban DT is identified as the biggest issue in the current development of DTs in the urban context by Ferré-Bigorra et al. [66], as a lack of interoperability reduces their efficiency and data exploitation capabilities. The authors further identify four different types of interoperability, including datasets, semantics, scales, and tools. The great significance of interoperability of DTs in the urban context can also be derived from their definitions. DTs in the urban context are commonly circumscribed as *a container for models, data, and simulations* [12], or even further as *a system of interconnected DTs representing certain aspects of the functioning and development of the urban environment* [69], or *an ecosystem of connected DTs to foster better outcomes from our built environment* [14].

These definitions show that a maturity assessment of a single DT in isolation, as presented in most cases in Table II, is not sufficient. Therefore, in order to enable interaction between the DTs representing different aspects of the urban environment and to efficiently optimize the various smart city processes in conjunction in a SoS manner, a high degree of interoperability is required as outlined in level six.

C. Digital Supply Chain Twin Maturity

DTs have been suggested to improve supply chains [59], [71], [72], [73], by providing enhanced visibility, traceability, and authentication [74], as a decision support system for risk management [73], a way to improve resilience [75], improve robustness and include multimodal options [71], and improving integration [59]. It is also important to mention the difference between other Supply Chain Management digital solutions, such as online freight exchange platforms. Busse et al. [71] suggested three areas where these systems fall short in comparison to a DT: update frequency, advanced analytical capabilities, and simulation capabilities.

Drawing on the applications of the digital supply chain twin presented above and the requirements for a smart supply chain by Wang et al. [59], these can be summarized into five core requirements: connectivity, visibility, agility, integration, and intelligence. Both connectivity and visibility require the fulfillment of level 3 to provide comprehensive timely information exchange between the different actors and to to keep track of the flow of materials, finances, and information throughout the supply chain [71].

Agility implies the ability to analyze opportunities and threats, make optimal decisions, and implement those decisions [59]. Agility therefore requires two-way data communication and interaction, first to identify threats and simulate potential solutions, and then to remotely adjust supply chain processes to address those threats. If the handling of these threats must take place in a timely manner, level 5 is required to make decisions automatically without human interaction.

Full integration, joint decision-making across different stages of the supply chain, requires full maturity (Level 6: Interoperability), as analyzing structured and unstructured data from internal and external sources to provide deeper supply chain insight requires consolidating all data streams to create a single source of truth [76].

In contrast to agility, intelligence requires making large-scale decisions that optimize the entire supply chain and protect it against future risks [59]. These large-scale decisions require full maturity, as optimizing the whole supply chain requires consolidating all data streams and thus the integration of all DTs encompassing the supply chain DT.

Although some papers consider a single DT to manage the entire supply chain, for example see [72] and the references therein, we argue here that the complexity of supply chains surpasses the capabilities of a single DT. The distinction of application areas by the same authors into network level (covering network management and transportation), and site level (encompassing cargo handling, manufacturing, and warehousing) refutes this view, as each of these application areas is highly complex and considered by their respective domain as an independent DT application (see [13] for cargo handling in ports, [77] for manufacturing, [78] for warehousing). This inevitably leads to the integration of multiple DTs to optimize the supply chain, which is itself composed of multiple systems, as a whole. For such a composition of different DTs that are integrated into the digital twinning process of the entire supply chain, it is vital that each twin provides a high level of interoperability and thus reaches maturity level 6.

D. Interconnecting Related DT Systems

An overview of the identified six maturity levels and its application to the supply chain context considering their interactions with cities and ports is illustrated in Fig. 3. It reflects a digital supply chain twin, which is composed of the integration of several relevant DTs involved in the freight and information flows of the supply chain. Thereby, the different actors involved

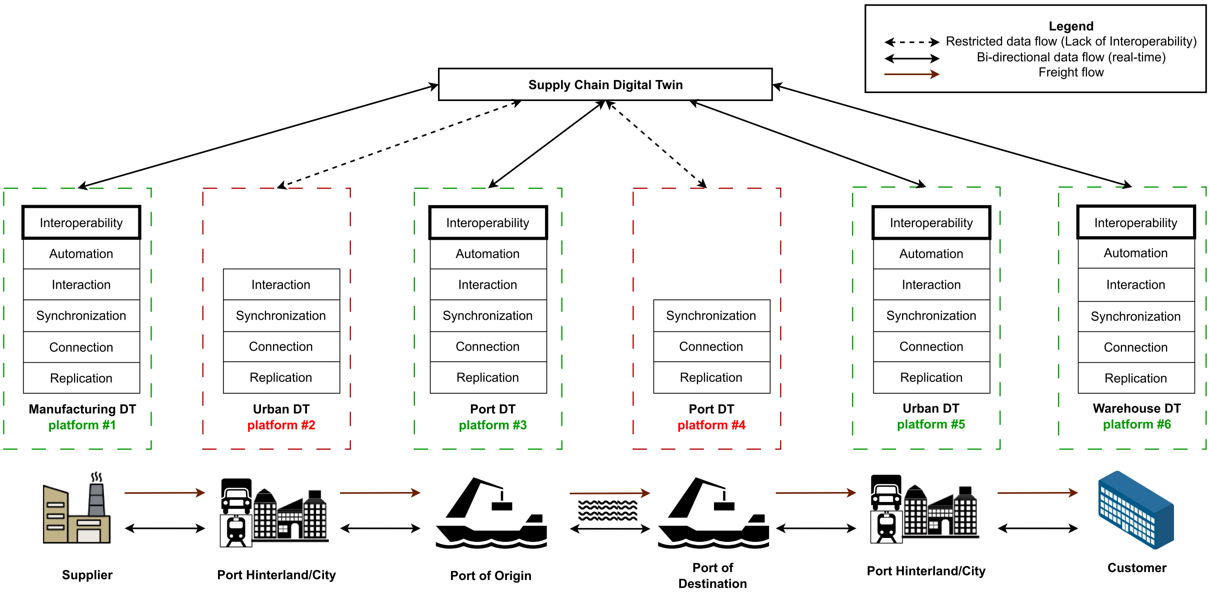


Fig. 3. Illustration of the six maturity levels applied to the supply chain domain under consideration of its interaction with ports and cities. DT platforms highlighted in red represent potential bottlenecks for SoS performance.

can optimize both common interests together, such as the smooth flow of transshipment operations at the port, or conflicting goals, such as the supply chain's ambition to deliver efficient flows of goods through the city while the city aims to reduce emissions. The figure thus demonstrates that constant interaction and exchange of information (such as estimated time of arrival, congestion, or disruptions) leads to improved SoS performance. If there is a lack of interoperability, as is the case with platform 2 or platform 4, the agility of the supply chain is severely impaired and the respective systems are not able to react to bottlenecks taking the supply chain into consideration. Ideally, however, a high degree of interoperability between the DTs of all supply chain actors involved can ensure a smooth flow of goods from production to final storage, with goods flowing smoothly and with low emissions through urban infrastructure and seamless transshipment and (un)loading operations at ports.

V. BARRIERS TO INTEROPERABILITY AND PATHWAYS TO SOLUTIONS

Despite the numerous benefits DTs offer to their respective actors, a lack of trust is one of the biggest barriers to their adoption and maturation [13]. This lack of trust encompasses both difficulties in setting realistic expectations and trust toward DTs [7], but also toward other related actors, as sharing data are often perceived with a loss of competitive advantages [79]. Consequently, the lack of data sharing is caused by corporate policies aiming at securing competitive advantages, and thus requires dealing with people's and society's reservations about data sharing and ownership, which constrains DTs in ways that go beyond the complexity of technology and engineering [42]. The resulting lack of appropriate policies for sharing data internally (within the company) or externally (stakeholders throughout the supply chain) can lead to data silos in the different departments of a company, which can have a detrimental effect on the value chain, as data silos lead to inconsistencies and synchronization problems [76]. Therefore, it is not enough to simply provide the technological framework for data exchange; rather, specific standards and procedures must be created.

Despite reservations about data sharing, recent research indicates that the value of data increases when it is shared and reused, and thus data sharing is increasingly recognized as an important driver in the digital economy [80]. A major contribution facilitating data exchange and usage is the Findable, accessible, interoperable, and reusable (FAIR) principles [81], according to which data should be FAIR throughout the data lifecycle, which are intended to serve as a guide for those seeking to improve the capacity of computational systems to find, access, interoperate, and reuse data with none or minimal human intervention [82]. The FAIR principles can thus help to establish and maintain trust among DTs by ensuring the security, integrity, transparency, and traceability of the data they share. For example, by using persistent identifiers, DTs can locate and access data from other sources.

Another possible solution to address trust is to use a trust framework, which is a set of agreements among participants that define the roles, responsibilities, rules, policies, standards, and practices for data sharing. A trust framework can help to create a common understanding and expectation among actors on how data will be shared, used, protected, and governed. "A European Strategy for data" [83] is a policy initiative to create a single market for data within the EU, which includes the Data Governance Act that can be considered a trust framework for data in the EU. The common European real-time linked data spaces suggested, includes sectors, such as industrial, mobility, energy, and public administration [84].

To further entrust data sharing, data security, and intellectual property rights of stakeholders need to be ensured [79]. This relates in particular to concerns about insufficient data sovereignty. To ensure data sovereignty, there is growing interest in international data spaces [13]. These describe a software architecture for enforcing data sovereignty in enterprise ecosystems and value networks [85]. GAIA-X is such an European initiative that aims to develop an open, transparent digital ecosystem where data and services can be made available, aggregated and shared in a trusted environment that is regulated by its members [51].

To further address the challenges of data sharing, Reim et al. [86] proposed four strategies based on transparency, incentive models, servitization, and control. The problem is exacerbated in an environment where there are multiple DTs at different hierarchical levels as each DT consumes and generates a different type of data and relies on the other DTs, which can lead to a complicated relationship between data sets resulting in data interoperability issues [42]. A list of technical solutions for enabling interoperability, classified into edge-based solutions and server-based solutions, can be found in a recent paper by Naderi et al. and Shojaei [87]. In a recent paper, Blair [88] also highlighted the importance of open data in addressing challenges related to integration and interoperability.

Initial solutions to specifically address DT interoperability challenges are being proposed by the DT Consortium, even if they are primarily aimed at manufacturing. Their DT system interoperability framework is based on seven interoperability concepts as follows:

1) system-centric design;
2) model-based approach;
3) holistic information flow;
4) state-based interactions;
5) federated repositories;
6) actionable information;
7) scalable mechanisms [33].

Further solutions and initiatives to tackle interoperability challenges are as follows.

1) The ISO 23247 DT framework for manufacturing [89].
2) The UK's information management framework for seamless data exchange within the national DT—an ecosystem of connected DTs [90].
3) The ongoing work of the European Telecommunications Standards Institute that aims to develop requirements and guidelines for a horizontal, cross-cutting interoperability and standards framework for DTs [91].

An introductory work toward DT interoperability and standards can be also found in [92].

VI. DISCUSSION AND CONCLUSION

This article critically assesses the maturity of DTs, taking into account previous domain-specific maturity frameworks while focusing on DTs of complex systems. As a result, six domain-independent consecutive maturity levels are presented, enabling a maturity assessment of the system to be twinned both in isolation and in conjunction with interconnected systems.

The application of the proposed maturity levels to complex systems such as ports, cities or supply chains demonstrates that a maturity assessment of a DT in isolation is not sufficient, as it only reaches its full potential through interaction with its environment. Recent research in the supply chain domain has demonstrated that optimizing individual supply chain components does not always lead to an optimization of the supply chain as a whole, as the value of the supply chain is greater than the simple sum of the value of each component [93], and the same applies to DTs of complex systems.

As more and more systems are interconnected as a result of the fourth industrial revolution and as the consistency of data and the exchange of information are fundamental prerequisites for DTs, particular emphasis was placed on the aspect of interoperability. The application of the presented maturity levels to three complex systems—port, city, and supply chain—demonstrates that DTs are still far from reaching their full potential and that there are only a few DTs scratching the surface of level 4.

As discussed in Section V, this can be explained, among other things, by the lack of standards and interoperability, which is common in reality and a significant limitation, as only a small number of DTs can exchange data with other DTs and their respective systems. A current large-scale project, in which interoperability plays a central role and whose findings could benefit other projects, is Destination Earth [51], the creation of a digital ecosystem consisting of several DTs. Discussing the Destination Earth project, Nativi et al. [51] proposed four solutions (unifying data and model standards, sharing data and models, innovating services, creating fora to exchange views and knowledge) and a set of good practices, including a data value-chain ecosystem model, or using innovative paradigms for information processing while maintaining technology neutrality.

Another significant barrier is trust. This includes trust required to entrust DTs with control of the system (Level 5: Automation), but also to distribute data across institutional boundaries while ensuring privacy, ownership, and security, and to ensure shared use of data between different DT systems (Level 6: Interoperability). However, Section V also demonstrates that there are multiple efforts underway to address standardization, trust and related interoperability issues.

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