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CATCHWORD

Digital Twin: Empowering Enterprises Towards a System-of-Systems Approach

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1 Introduction

It is common knowledge that the management of enterprise assets (e.g. plants, IT systems, staff and machineries) contributes to value creation in today's organizations. Moreover, efficient asset management significantly enhances corporate performance. The Digital Twin (DT) is an asset's virtual counterpart that enables enterprises to digitally mirror and manage an asset along its lifecycle. This asset can be tangible as well as non-tangible – ranging from turbines to services. In order to represent the asset's life and behavior virtually, a DT incorporates all kinds of data related to the asset and continuously provides the enterprise with information on the asset's condition. In fact, in some asset-centric organizations, especially those with critical infrastructures, losses due to significant downtime of the asset (e.g. a power plant) involve risks beyond the company's financials. Here, a DT can play an important role to mitigate or even avoid these risks by comprehensively informing about the real-world asset's status, history and its maintenance needs. Moreover, some DTs even provide a direct interaction with the asset.

Although the first vision of a DT dates back more than a decade (Grieves 2002), it has only recently obtained increased research interest within multiple domains. The main reason for this lies in the fact that central technological enablers, such as the Internet of Things (IoT), have only recently reached the maturity to be deployed profitably in economic environments. Within the different interested communities, the term has evolved leading to at least two different viewpoints of a DT nowadays (Negri et al. 2017). The first defines the DT merely as the simulation of the physical asset itself and is mostly used by engineering scholars. However, beyond the scope of simulation, the second perspective refers to a DT as a model which constitutes the basis for simulations, analyses and the like. The latter perspective is currently the most adopted view on DTs and thus the focused viewpoint of this work.

Besides, a multitude of terms exist describing similar phenomena. For instance, the term "product avatar" emerges from product lifecycle management (PLM) research and refers to a concept which is similar to a DT for a product. However, the focus of these works lies on the availability of user-oriented product information in social networks and web pages (Ríos et al. 2015). Moreover, erroneously, the term "digital shadow" is often used interchangeably with the Digital Twin – despite its mainly referring to a digital footprint.

As DTs allow enterprises to gain an in-depth understanding of their assets, corporate optimization and business transformations can benefit from their unique knowledge. We believe that the DT can contribute to value creation in asset-centric companies due to its power to combine previously separated data from different domains

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along the asset's lifecycle (see Sects. 2, 3). The DT is, in fact, a proactive digital approach introducing a next step in digitalization. Additionally, BISE scholars recently elected the DT as a central and important technological trend for the community (van der Aalst et al. 2018). However, at present, the concept is still in its infancy as various challenges have yet to be mastered (see Sect. 4) in order to put the DT meaningfully into practice. Hence, to provide profound ideas for practical operation, business and information systems engineering (BISE) scholars need not only to consider this paradigm, but also better understand its key components, its underlying mechanisms and the challenges entailed. Thus, this catchword article aims to pave the road for research by defining key characteristics of a DT, presenting the DT as a paradigm enabling a system-of-systems, demonstrating its potential application fields as well as future research challenges. Although the DT paradigm can also be applied in societal and private contexts, the following primarily concentrates on DT potentials in a business-centric view.

2 Key Characteristics of a Digital Twin

To infer the key characteristics of the DT paradigm, a DT's competences are considered. In general, DTs are capable of monitoring, and can be further enhanced with control, over optimization to autonomy capabilities. To enable these competences, DTs require specific building blocks and need to be integrated into corporate environments. Thus, Fig. 1 illustrates the paradigm of a DT. In the following, we first describe the general parts involved in the DT concept. Afterwards, we proceed to explain the building blocks as the inner part of a DT.

- *Enterprise asset*: An object, subject, system (tangible), or process (non-tangible) relevant to the enterprise, commonly contributing to corporate benefit. Each asset evolves along its lifecycle. A tangible enterprise asset might not physically exist in its first lifecycle phases as well as in the last phase of its lifecycle.
- *Asset lifecycle*: The lifecycle the enterprise asset evolves along. The number of lifecycle phases varies from asset to asset. Thereby, the first phase generally represents the idea of creating the asset and the final phase constitutes the end of its existence. Each lifecycle phase produces relevant information about the asset and therefore, third parties, such as partners, can be involved.
- *Data sources*: The providers of data about the enterprise assets. Data sources can be of any type (e.g. sensors, enterprise systems etc.). Thereby, they can differ between the lifecycle phases, and even belong to an involved third party.

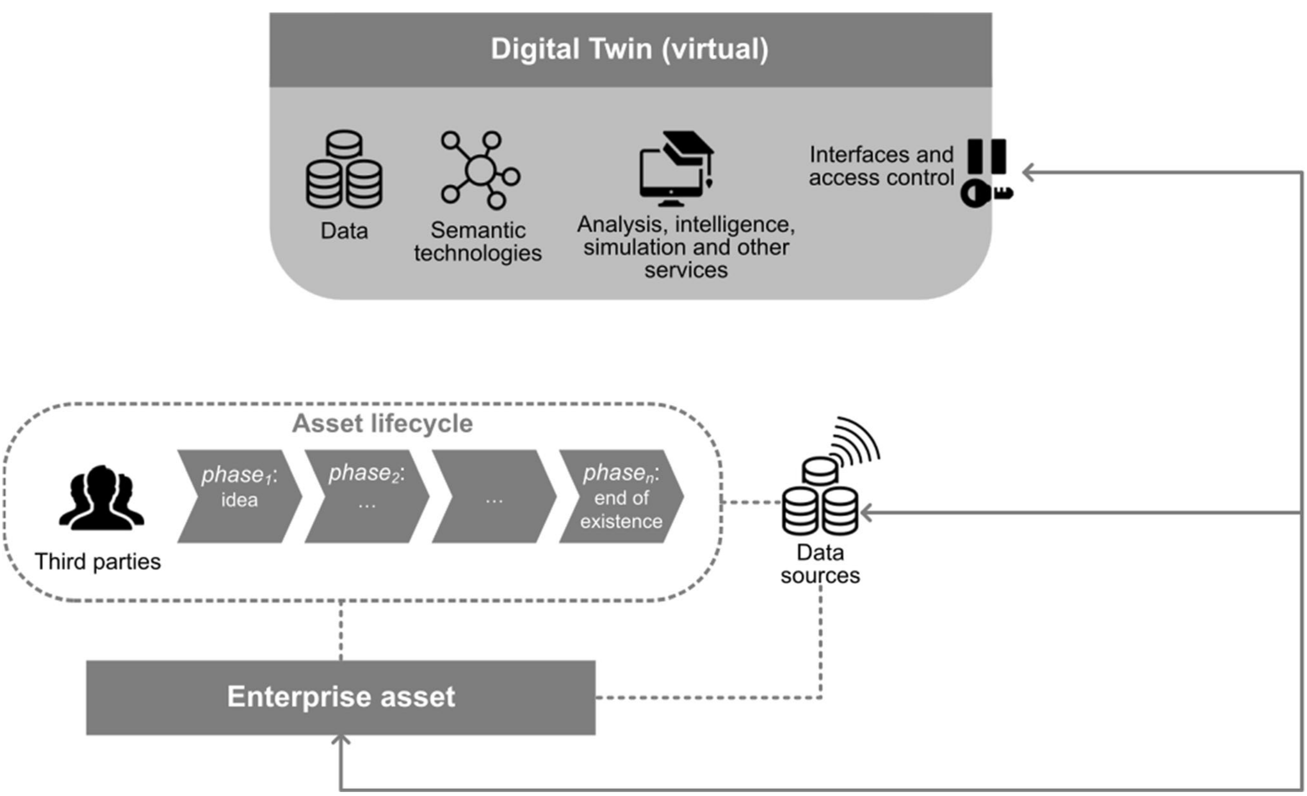

Fig. 1 The Digital Twin paradigm

- *Digital Twin (virtual)*: The virtual counterpart to the specific enterprise asset. The DT might exist even after the asset has ceased to exist for documentation purposes. It enables data integration and sharing across the lifecycle phases, resulting in a continuous learning process. It may even be embedded in the physical asset itself or deployed on the cloud or an edge computer (Boschert et al. 2018).

DTs are no monolithic data models, but include different aspects of digital representations, functionalities and even interfaces. The following four building blocks make up a DT (see Fig. 1):

- *Data*: Data in various forms (static, dynamic, functional, behavioral, environmental, sensor-based, from handbooks/manuals etc.) relevant to virtually represent the asset.
- *Semantic technologies* (Schroeder et al. 2016; Boschert et al. 2018): Technologies describing the relations between data elements to infer their context, unerstand their meaning and thus, derive utility for later analyses.
- *Analysis, intelligence, simulation and other services* (Ríos et al. 2015; Boschert et al. 2018): Software enabling search, supporting different analyses, intelligence and other services ranging from simple monitoring to autonomy. Thereby, the extent of the functionalities varies. For monitoring purposes, 3D models (e.g. CAD models) are commonly incorporated and sensor data is often visualized in dashboards for control of the real-world asset. Analyses of past situations, simulations[1] of possible alternatives and further predictive maintenance techniques offer asset optimization. Sometimes self-healing mechanisms are instituted that operate autonomously.
- *Interfaces and access control* (Schroeder et al. 2016; Boschert et al. 2018): Mechanisms to mediate between the virtual and the real world, enable data sharing and synchronization. Especially the bi-directional connection between the real-world asset and its twin provides a novel opportunity not only to report real-world data to the twin, but to send commands from the twin towards its real-world counterpart for its optimization.

However, there are also other perspectives on the paradigm's characteristics. For instance, in the manufacturing area Tao et al. (2018) suggest a DT to be a combination of the product (physical asset), its virtual counterpart and the connected data. In contrast, Uhlemann et al. (2017) see the DT as an enabler to realize Cyber Physical System (CPS) that is divided into system layer, data layer, and information and optimization layer. The latter points towards another characterization of the concept that focuses on the data lifecycle: In DTs data is mostly gathered by sensors and the assets they describe (e.g. production systems with CPSs). It is then commonly transferred via IoT technologies and processed by fine-granular and real-time capable simulations, data analytics and the like (Uhlemann et al. 2017). As the DT is an asset-centric concept, the described key characteristics put the emphasis on its representational character, and considering this view, we derived the building blocks as given in Fig. 1.

To conclude, the term "Digital Twin" may be conflictual. According to the Oxford dictionary the term "twin" refers to "Something containing or consisting of two matching or corresponding parts" (Oxford University Press 2019). While it fits in terms of the DT being the corresponding virtual counterpart to the real-world asset, the digital part may nevertheless exist after the end of existence of the real-world part and of course, be of different capabilities and granularity by contrast with its real-world counterpart. Therefore, the term "twin" might on the one hand be useful to catch this phenomenon in a metaphorical way. On the other hand, it can be quite misleading as one might expect twins to be rather identical.

3 With Digital Twins Towards a System-of-Systems Approach

As stated above, DTs may have different dimensions depending on their context of application. Therefore, they can be divided into multiple perspectives. Note that this does not contradict the universal principle of having only one digital counterpart per asset. At first, a DT exhibiting the characteristics shown in Fig. 1 can be referred to as *basic DT*. *Complex DTs* embed sub-DTs and thus represent a composition consisting of basic DTs or other complex DTs. For instance, consider a simple conveyor belt (*complex DT*) that consists of smaller components (e.g. motor, PLC) that themselves are represented by *basic* or *complex DTs*. Furthermore, DTs may be categorized into different types, i.e. "moving", "outdoor", "engine" (*typed DT*). In doing so, a DT referring to a human is referred to as a special type, the *personal DT*. Every *typed* DT can thereby either be a *complex* or *basic* DT. Likewise, similar DT instances might be derived from a *reference*-DT (fleet management[2]). An example is a wind park consisting of

[1] To impart a common understanding, a DT can include emulation and simulation functions. For instance, the DT in the work of Eckhart and Ekelhart (2018) emulates a real-world counterpart and provides a simulation environment for testing safety and security rules of the real-world counterpart.

[2] Considering that the asset can carry the digital representation of its type, the establishment of suitable reference systems (models) in which important types are described would be beneficial.

multiple, similar windmills. Here, each windmill produces its own data and thus needs to be monitored by its own DT. However, a *reference*-DT that describes a windmill in general (blueprint) might exist, from which each windmill instance is derived. Expanding beyond a single company's scope towards a notion of a network of companies, the foundation for autonomously *cooperating DT*s that originate from different home domains is laid.

Generally, by connecting an object with further related objects, their functionality is enhanced and a system originates (Wortmann and Flüchter 2015). Furthermore, the consolidation of multiple, previously discontiguous systems offers a system-of-systems approach, which provides the opportunity to fade out company boundaries and promote networking, in order to overthrow competitive dynamics (Porter and Heppelmann 2014). By linking corporate DTs, systems emerge which in turn can be linked to establish a system-of-systems approach. Figure 2 illustrates this idea exemplarily. In this example we consider the system of a power plant, which includes various *complex* DTs (e.g. windmills) and their sub-DTs (e.g. wind turbines). Moreover, this system is connected to other systems, such as to the supply chain system delivering materials and the like, or to the power distribution system, containing assets like transmission towers. By combing these systems through their DTs, a system-of-systems approach is realized. On a more detailed level, DTs or their sub-DTs can be connected in a spatio-temporal manner (Canedo 2016) to indicate a real-world connection. For instance, consider a car being filled up at a gas station, where the DT of the car is virtually connected with the fuel dispenser of the gas station. As soon as the car is filled up, the relation disappears. In a nutshell, DTs manage assets along their lifecycle and thus support the management of the system-of-systems containing these. It is further vital to highlight the relations between the assets, which boost efficiency as optimization can be performed globally at a system-of-systems level. Thus, the DT constitutes more than just a novel technology – it may become a real game changer.

Certainly, the DT paradigm applies in multiple domains. The industrial domain, including Industrial IoT, smart factories and Industry 4.0, is not only a very suitable area for the DT concept, but also the most advanced domain regarding its realization. For instance, General Electric (GE) already counts about 551,000 DTs referring to products, part of products, processes and systems in late 2017 (Saracco 2018). It also offers the "world's first digital wind farm"[3] including DT technology. Another industrial example is Tesla, which applies the DT paradigm to its cars: every car reports its experience on a daily basis, which further serves simulation in the DT to detect anomalies and propose corrective measures (Saracco 2018). Also, commerce is an area where DTs can achieve efficiency gains. The digitalization of a shop floor, for example, allows the enterprise to manage sub-parts (e.g. shelves) in correspondence with the global system of the shop floor and even the interdependence to other systems such as the supply chain. Moreover, the real-world counterpart must not necessarily be tangible, also processes can be assets monitored by DTs such as shown in Meroni and Plebani (2018). Furthermore, DT implementation can foster social and governance areas equipped with IoT, such as smart cities (Saracco 2018). Besides, DTs can also support individuals (*personal* DT). For instance, the trend "quantified self"[4] refers to individuals gathering as much quantitative information about themselves and their daily lives as possible – mostly with the help of technology. A real-world example is the "most connected human on earth"[5], for whom up to 700 sensors daily gather his physical condition, activities etc. A DT could combine these data sources and manage the physical condition virtually. This leads also towards medical healthcare, where currently a lot of effort is put into DTs. For instance, a major German engineering company established a blueprint of a DT representing a human heart by using MR, ECG measures and massive data sets next to complex algorithms to enable planning, prediction of recovery of medical procedures.[6] In the future, the creation of an individual's own digital heart could be based upon that blueprint. Moreover, in the long-term view, the complete human body with its organs, its inner cellular constitution etc. will be represented by a DT. Hereby, again *reference*-DTs can deliver the general structure of the organs, from where the individual's organs are derived, enhanced with data of the individual (e.g. ECG, medication plan, diseases) and further customized. In addition to the representation of individuals, DTs can also support the optimization of medical and organizational workflows, or even entire hospitals. Combining these two applications towards a system-of-systems approach, a variety of scenarios can be simulated and their effects on process efficiency can be presented without great expense. Especially the U.S. market is adopting the technology, e.g. through introduction of DT technology in a new facility at the Medical University of South Carolina (MUSC) Shawn Jenkins Children's Hospital and at the Pearl Tourville Women's Pavilion to predict workflows, propose optimizations, to forecast the impact of changes and health

[3] https://www.ge.com/renewableenergy/wind-energy/technology/digital-wind-farm.

[4] http://www.quantifiedself.com/.

[5] http://www.chrisdancy.com.

[6] https://www.siemens-healthineers.com/de/press-room/press-videos/im-20181204001shs.html.

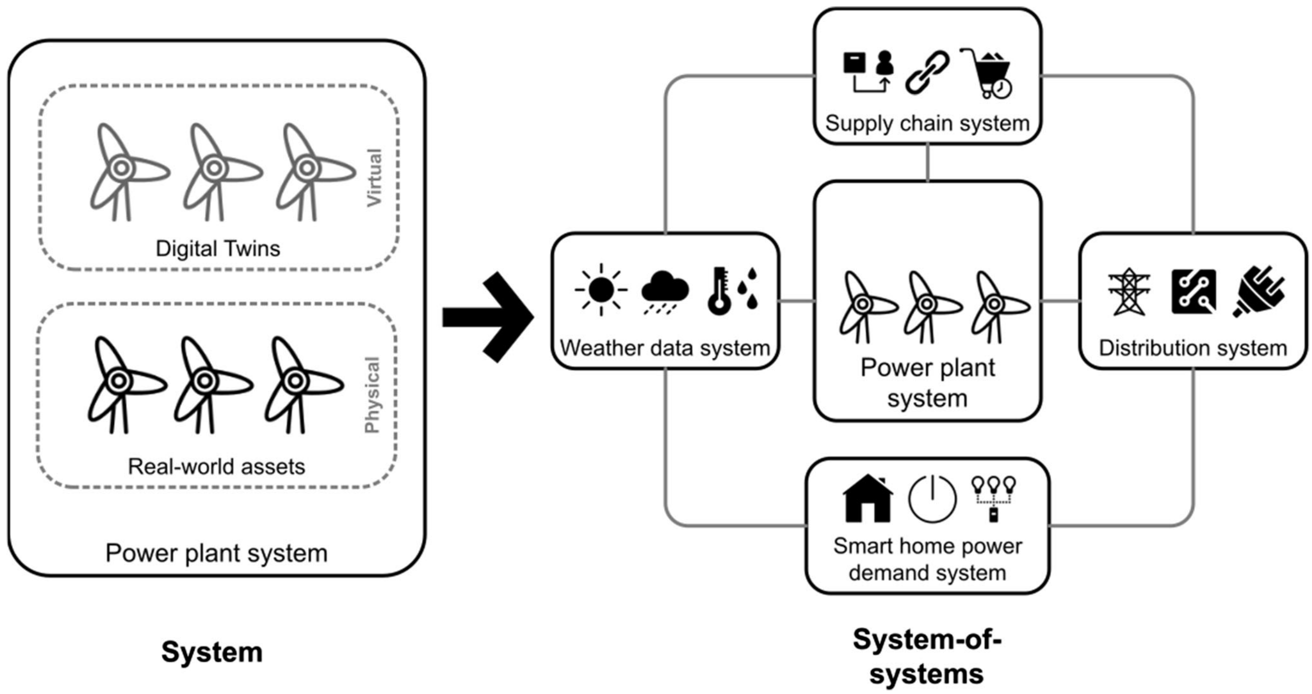

Fig. 2 A system-of-systems approach by networking systems and their DTs (based on Porter and Heppelmann 2014)

innovations.[7] Clearly, domains of all verticals and among different use cases can benefit from the DT.

4 Challenges and Future Directions

DTs create substantial economic and organizational power for firms. However, while the paradigm broadens its application domains in the business world, challenges from technical as well as business perspective emerge. The following illustration of challenges will hopefully initiate fruitful discussions among BISE researchers in order to solve some fundamental problems in the area of DTs. Thereby, the issues are categorized in technical and corporate challenges. Finally, prospective research areas are listed.

DTs require substantial *technical efforts* from firms. Especially the incorporation of heterogeneous data requires further progress. For instance, the standardization in data acquisition needs to be accelerated (Uhlemann et al. 2017). Also, issues with real-time data have to be focused on. For instance, the manual acquisition of real-time data has to be automated to enable the collection of full historical data instead of snapshots (Uhlemann et al. 2017). Another great technical burden is the current decentralization. Interfaces, connections and the like need to be developed to enable a more holistic approach. Moreover, security concerns have to be addressed. This includes version management and compatibility checks of the DT versions to ensure data integrity as well as access management to allow third parties to access (parts of) the virtual twin.

At different levels, *corporate challenges* remain. While operational challenges mostly overlap with the technical challenges, the DT potentially implies major economic and organizational transformations at a strategic level. The strategic decision of DT implementation focuses on but is not limited to the degree of asset-centralization of an organization. The study of Klostermeier et al. (2018) shows that the DT paradigm qualifies for different enterprises in multiple application scenarios to various implementation degrees. Hence, the degree of reflecting the real-world asset varies depending on the use case. Consequently, this poses yet another corporate challenge in terms of depth of detail and granularity. Moreover, the study indicates that at present, the term "Digital Twin" can be misleading as it is applied for slightly different phenomena in different areas (Klostermeier et al. 2018). Entangled with the complexity of DTs, a further strategic decision bases on the tradeoff between the cost of an asset versus the cost of the DT and its data granularity (e.g. by including sensors). However, with the general decrease in storage and sensor cost, the implementation of DTs tends to become more attractive. Moreover, the emergence of novel business models, including such where the organization does not possess the asset but provides the service of

[7] https://www.wallstreet-online.de/nachricht/10822802-musc-and-siemens-healthineers-form-strategic-partnership-to-disrupt-and-reshape-health-care-delivery/all.

establishing a DT, will entail major privacy issues – including the question of ownership of the virtual counterpart.

Although first assumptions about the effects of DTs exist, *future research* should analyze the concrete technical and corporate implications. One impact of DTs concerns the improvement in interconnectivity, especially within supply chains, where research should not be limited to a single firm's perspective but rather take a system-of-systems approach. Another potential for enterprises is the closure of feedback loops along and the coherent linkage between the lifecycle phases of the asset. Here, the gain of new insights can lead to a win-win situation among the involved parties. Currently, very little is known about potential data-driven business models, their power of digital disruptiveness and pricing strategies for DT services. Research can contribute by identifying the strategic role of DTs for firms and its position in digital transformation, not only from the perspectives of companies owning the DTs but also from third parties contributing to the resources. Nevertheless, first evidence indicates that DTs can give a cutting edge for next-generation virtual asset management.

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