The Digital Twin Concept: A Generic Definition of an Industry 4.0 Driving Force

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More than ever, the digital transformation induced by Industry 4.0 is essential for the survival of industrial activity. Digital twins are an effective way for enterprises to face this new challenge as they allow cyber-physical synchronization. Although the concept is not new, there is still no collective agreement on the digital twin definition, which leads to many misconceptions. To clarify the notion once and for all, this article studies and compares recent literature reviews with existing popular definitions and case study papers to pinpoint the fundamental elements of a digital twin. It then groups the identified key characteristics all together to formulate a generic definition that can be used whatever the application area considered and highlights the two major distinctions that exist between digital twins and traditional simulation approaches. This paper thereby addresses a substantial literature gap, allowing future research and case studies on digital twins to be built on common grounds. Finally, to give the reader a complete overview of the digital twin concept, its expected universal benefits are described and application instances in various sectors are presented. Main implementation challenges are also exposed since they are not yet overcome and form therefore an interesting future research question.

Keywords: digital twin; digital transformation; industry 4.0; cyber-physical synchronization.

1. Introduction

More than ever, the digital transition is an essential evolution for the survival of industrial activity (Julien and Martin 2018). According to many authors, the digital twins (DT) concept could help companies to face this challenge. This idea has been confirmed by the worldwide increase in research and industrial interest in the DT area for a few years, revealing the popularization of the concept as a driving force for Industry 4.0 (Ciano et al. 2021; Lattanzi et al. 2021; Savolainen and Knudsen 2022; Wilhelm et al. 2021). Semeraro et al. (2021) especially note that the integration and interaction between physical and virtual spaces are becoming increasingly important, hence the interest in using DTs. The question is: what exactly is a DT? As suggested by the name, a key brick of the DT definition is a digital model representing a physical entity, but it is actually much more than that.

With respect to the birth of the DT concept, most authors claim that it was first introduced by Michael Grieves in 2002 during a special meeting on product life-cycle management (Jones et al. 2020; Julien and Martin 2018; Kritzinger et al. 2018; Rathore et al. 2021; Trauer et al. 2020; Wilhelm et al. 2021). At that time, Grieves defined the digital twin as the combination of three key elements: (1) a virtual replication, (2) a physical entity, and (3) a data flow cycle between both of them (Lattanzi et al. 2021; Rathore et al. 2021; Trauer et al. 2020). However, some authors such as Ciano et al. (2021), Lattanzi et al. (2021) or Mashaly (2021) assert that the twinning concept dates back to the 1960s when NASA decided to create physical replications on earth that mimic their systems in space in the context of the Apollo program. Yet, Grieves remained the first to use a twin which was digital and to introduce the concept in the manufacturing industry by creating virtual replicas of factories to monitor their processes, predict failures, and increase productivity (Mashaly 2021).

Despite the relative importance of DTs in the digitization process of companies and the numerous scientific articles that have been published on the subject since the appearance of the concept, one may note that there is still no collective agreement on the DT definition (Lattanzi et al. 2021). In particular, Lattanzi et al. (2021), Semeraro et al. (2021), and Wilhelm et al. (2021) indicate that the DT concept tends to vary as the context or the application domain changes, leading to many arguments between authors about DTs definition. In addition, according to Kritzinger et al. (2018), many authors conflate the DT concept with the one of digital model/simulation (no real-time data exchange between twins) or with the one of digital shadow (real-time data exchange only from the physical entity to the digital one). Clarifying the concept through the definition of common grounds for varying applications seems, therefore, to be an important area for future research (Ciano et al. 2021). The present article intends to largely contribute to filling this significant literature gap.

Beyond giving some insights into the DT concept and its application areas, the objective of this paper is thus to identify the key features of a DT and to formulate a definition that can be used in any context, building a strong basis for future research and case studies on digital twins. With this aim in mind, the article is structured around four main questions:

- What are the key elements and popular definitions of DTs according to the literature?
- What is the difference between DTs and traditional simulation/modeling exercises?
- What are the expected benefits and main application areas of DTs?
- What about DT implementation challenges?

After having answered each of those questions, some concluding remarks will be made.

2. Literature review

To identify the key elements that should be found in the definition of a digital twin, this paper will first analyze and compare the results obtained in recent literature reviews on the specific topic of DT definitions. It will then look at several popular definitions that can be found in the scientific literature and examine the key components they contain. A third and final section will summarize all the identified fundamental elements of a DT and will formulate a definition that groups them all together, allowing the clarification of the term for both research and business communities.

2.1. DTs key features

The first literature review dedicated to the DT definition that will be analyzed is the one of Jones et al. (2020). After examining 92 papers ranging from 2009 to 2018, they came to the conclusion that DTs are composed of 12 key concepts that form their basic characteristics (all of which should appear in the DT definition):

(1) Physical entity: Real-world element such as a vehicle, a product, or a system.

(2) Virtual entity: Computer-generated duplication of the physical entity.

(3) Physical environment: Measurable environment within which the physical entity lies.

(4) Virtual environment: Environment within which the virtual entity lies, replication of the physical one.

(5) Fidelity: Number and accuracy of parameters that are transferred between physical and virtual entities.

(6) State: Measured values of physical/virtual entity and environment parameters.

(7) Parameters: Types of data/information transferred between entities such as temperature, machine speed, or production scores.

(8) Physical-to-virtual connection: Means by which virtual parameters are updated such that they reflect the state of the physical entity (physical metrology[1] followed by a virtual realization[2] phase).

(9) Virtual-to-physical connection: Means by which the state of the physical entity/environment is updated such that it equals an optimal set of parameter

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[1] Act of measuring the state of an entity.

[2] Act of updating the parameters of an entity and its environment to equal the state of its corresponding twin.

values determined by virtual processes (virtual metrology followed by a physical realization phase).

(10) Twinning: Physical and virtual states synchronization through a bidirectional data flow as presented in Figure 1. Physical and virtual entities are said to be twinned when both states are equal (i.e., when virtual and physical parameters are set to the same value).

(11) Physical processes: Activities and processes performed by the physical entity in its environment.

(12) Virtual processes: Computational technique(s) employed by the virtual entity (e.g., information display, monitoring, optimization, prediction, validation, prognostic and diagnostic, decision-making).

[Figure 1 near here]

A second literature review of interest is the one of Semeraro et al. (2021), which analyzed not less than 150 papers. The results show that 5 clusters of DT definitions exist, each placing a different concept at the core point of the definition. These are:

(1) The simulation along product life cycle: As most authors agree on the fact that the DT concept was first introduced during a special meeting on product life-cycle management (Jones et al. 2020; Julien and Martin 2018; Kritzinger et al. 2018; Rathore et al. 2021; Trauer et al. 2020; Wilhelm et al. 2021), many of them emphasize the idea that a DT should connect real and virtual spaces over all phases of the product life cycle. This is also outlined in the keywords cluster analysis performed by Ciano et al. (2021) since DTs can be used in all product design, manufacturing, and service phases.

(2) The cyber-physical synchronization: For many other authors, the most important thing is that the DT bridges the gap between the physical and virtual entities to improve and support decision-making. It is thus the information exchange between both systems that is underlined here.

(3) The real-time data integration: Some others claim that the central aspect of DT is the real-time data connection between the physical and virtual worlds. In fact, it is the real-time feature that allows the DT to update itself, respond instantly to changes over time, and subsequently optimize business performance.

(4) The replication of the physical space: Others concentrate on the fact that physical behaviors, properties, and characteristics should be transferred into the virtual space. According to them, the primary function of digital twins is to duplicate the current state of the physical system in the virtual world.

(5) The virtual processes: Remaining authors focus on the services that DTs can offer, such as the control of the current situation, the prediction of the near future, or the optimization of the physical twin.

Comparing the results obtained by both literature reviews, as shown in Figure 2, we can notice that most of the key elements presented by Jones et al. (2020) are also present in the results presented by Semeraro et al. (2021): physical/virtual entities and environments, state and parameters, physical-to-virtual connection, physical and virtual processes. Nevertheless, Jones et al. (2020) insist more on the twinning process and the importance of the virtual-to-physical connection, which is one DT feature that cannot be omitted. They also approach the specific topic of fidelity; however, this last one should not necessarily appear in the DT definition as it is more a way to evaluate the DT performance (see Section 5). On the other hand, Semeraro et al. (2021) add the notion of real-time data exchange, which is somewhat implicit in the analysis of Jones et al. (2020).

They also introduce the consideration of product lifecycle phases, but it seems that this notion should not be included in a general DT definition since it is linked to the specific field of production.

[Figure 2 near here]

2.2. DTs popular definitions

Knowing the key characteristics of a DT, we can now examine several definitions that are often referred to in the scientific literature to see if they include all those elements or if they add new ones.

First, according to Grieves and Vickers (2017), the digital twin is ‘a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level’. Although very common because of the renown of its first author, this definition concentrates a lot on product lifecycle management which has been identified as not relevant in the context of a general DT definition. Therefore, many authors, as well as NASA, prefer to refer to Glaessgen and Stargel (2012), who define the DT as ‘an integrated multi-physics, multi-scale, probabilistic simulation of a complex system that uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin’. In addition to being much more general, this definition better introduces the notion of virtual replication.

Then, still among frequently used DT definitions, we can highlight the one of Rosen et al. (2015), where a DT is described as ‘a very realistic model of the current state of a process and of its behavior in interaction with its environment in the real world’ as well as the one of Negri, Fumagalli, and Macchi (2017) which says that ‘a digital twin is a virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field'. Whereas Rosen et al. (2015) focus on the digital imitation of the physical system behavior and environment, Negri, Fumagalli, and Macchi (2017) underline the real-time synchronization of both entities and the diversified virtual processes that could be used.

Finally, the definitions given by Schleich et al. (2017) and Kritzinger et al. (2018) are also very present in the literature. Both emphasize that what underlies the concept of DT is the bidirectional data flow between the physical and virtual entities (i.e., their synchronization). Kritzinger et al. (2018) especially insist on the fact that DTs should not be confused with digital models or digital shadows, which do not have the entire cycle of data integrated. Indeed, many authors tend to group these two notions with the one of DTs by mistake, simply noticing that the integration level can vary.

In view of the foregoing, we can notice that the different popular definitions analyzed globally agree on the key elements previously pinpointed. It can also be seen that no new characteristics are mentioned. Note, however, that none manages to group the various DTs key elements identified by Jones et al. (2020) and Semeraro et al. (2021) all together, contrary to the general DT definition formulated later in this article. Besides, when reading papers related to specific DTs applications, the same fundamental concepts seem to appear (especially the virtual replication of the physical entity, the bidirectional data flow, and the real-time synchronization of both entities) whereas various virtual processes are mentioned. Some authors still add other characteristics to the DT definition as the interaction between historical and real-time data (Aivaliotis, Georgoulias, and Chryssolouris 2019) or the need for a human-machine communication interface (Wilhelm et al. 2021), but these are very specific to the application domain presented in the concerned article and therefore do not appear relevant for a general DT definition. We can thus suppose that the key concepts already identified are the only ones to consider in the DT generic definition.

2.3. Generic definition formulation

The various analyses of the literature having been made, we can now move on to the final step of this analysis, the definition formulation. For doing so, let us begin by listing the key concepts underlying DTs whose graphical synthesis is shown in Figure 3:

- There exists a physical entity that performs some activities (physical processes) and that is influenced by the parameter values of its physical environment.
- There exists a virtual entity and a virtual environment that replicate the state of the physical ones.
- A physical-to-virtual connection allows real-time data transfer from the physical entity to the virtual one. In contrast, a virtual-to-physical connection allows the virtual entity to change parameter values in the physical entity/environment. This bidirectional data flow between the physical and virtual worlds enables the synchronization (twinning) of both entities.
- Depending on why the DT is used, different computational techniques can be employed within the virtual world, such as optimization, prediction, or simulation for instance (virtual processes).

[Figure 3 near here]

Although all those elements are critical characteristics of the DT, not all of them should explicitly appear in its definition as far as they can be understood implicitly. Consequently, based on previous information, a possible generic DT definition could be the following one:

> A digital twin is a virtual replication of a physical entity (and its environment) that is entirely synchronized with its counterpart thanks to the combination of a physical-to-virtual connection[3] with a virtual-to-physical one[4], and which can be used for various purposes as monitoring, optimizing, predicting, or decision-making support.

Note that this definition is quite rigorous because it describes the highest possible maturity of the technology. The fact that a digital twin can supply in real-time every required piece of information about the physical entity indeed constitutes the optimal target for digital twins (Mashaly 2021). Moreover, since there exists a broad range of application areas and purposes for DTs, we cannot better precise the form or even the goal of a DT in this generic definition (Trauer et al. 2020). Be that as it may, this definition definitely clarifies the notion and specifies the key features a DT should have, no matter the application domain considered.

3. Digital twins vs. traditional simulations

Before going further with DTs expected benefits and application areas, it is important to understand the differences that exist between DTs and traditional simulation/modeling exercises. Indeed, these two notions are often inadvertently confused with each other. However, DTs could be seen as an evolution of such conventional approaches.

In particular, Jones et al. (2020) highlight two major differentiators. First, in DTs, there exists a continuous physical-to-virtual connection (thanks to technologies such as the Internet of Things) between the two entities allowing for the monitoring of every state change in the physical environment, whereas, in traditional simulations, analysis is frequently performed "off-line" (Jones et al. 2020). Here, the simulation concept is

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[3] Physical metrology and virtual realization.

[4] Virtual metrology and physical realization.

therefore extended by the real-time connection that exists between virtual and physical entities, allowing DTs to concentrate on what is currently happening in the physical world (Franceschi et al. 2022). Second, DTs benefit from a virtual-to-physical connection which does not exist in traditional modeling methods. This bidirectional relationship between the virtual and the physical allows DTs to hypothesize and subsequently test different scenarios until reaching the expected result and transferring it into the physical entity (Jones et al. 2020). Results collected in the real world then allow DTs to adjust the selected hypothesis and enter a continuous adapting and improving cycle (Jones et al. 2020). In short, the second main distinction between DTs and traditional approaches comes from the twinning process closing 'the loop between hypotheses generated in the virtual environment and the actual consequences realized in the physical environment' (Jones et al. 2020).

4. DTs application areas and expected benefits

Now that the digital twin concept has been correctly defined, it is interesting to have a quick look at DTs application areas and expected benefits to understand better how flexible and helpful such a technology can be, and therefore why they are becoming so popular in many different fields.

4.1. Application areas

One may know that DTs can be used in any domain (Rathore et al. 2021). Indeed, beyond manufacturing, which is the dominant field for digital twinning, the literature cites DTs applications in many other areas such as aerospace, smart cities, education, transportation, and even medicine (Mashaly 2021; Rathore et al. 2021; Semeraro et al. 2021; Wilhelm et al. 2021). In addition, whatever the sector considered, DTs can be used for many different reasons: process modeling, real-time monitoring, deviation alert, deviation prediction, process optimization, decision-support tool, creation of a virtual reality environment, training support, and so on (Julien and Martin 2018). To illustrate this broad range of applications, the following lines are dedicated to concrete examples of DTs usage in different fields.

First of all, let us give some instances related to the manufacturing sector since it is the main DTs application domain for now (Lattanzi et al. 2021; Savolainen and Knudsen 2022; Wong, Mo, and So 2021). In fact, due to mass customization, uncertainties in the market, and increasing requirements, especially regarding lead times, factories must ensure a proper system behavior under different conditions to be able to react quickly to any unexpected events (Alexopoulos, Nikolakis, and Chryssolouris 2020; Ciano et al. 2021). It is therefore essential for industrial companies to increase their flexibility, that is, to have easily reconfigurable production lines, to remain competitive in the marketplace even when disruptions occur (Alexopoulos, Nikolakis, and Chryssolouris 2020; Ciano et al. 2021). In this context, adopting new production technologies becomes imperative, extending the attractiveness of DTs for the field and reinforcing its relevance for Industry 4.0 (Alexopoulos, Nikolakis, and Chryssolouris 2020; Ciano et al. 2021; Lattanzi et al. 2021). Note, however, that, beyond bringing the flexibility the sector asks for, DTs are considered for improving various other aspects of manufacturing (Franceschi et al. 2022). The most cited ones being: The increase in productivity and efficiency; The gathering and displaying of useful real-time information (potentially using augmented or virtual reality) leading to an impressive real-time operations/performances monitoring and subsequently allowing quick response in case of failures or unexpected changes; The improvement of predictive analyses and especially of predictive maintenance; The enhancement of decision-making support through virtual validations/verifications and improved feedbacks and diagnostics; And the cost reduction

(Alexopoulos, Nikolakis, and Chryssolouris 2020; Ciano et al. 2021; Damjanovic-Behrendt and Behrendt 2019; Franceschi et al. 2022; Lattanzi et al. 2021; Savolainen and Knudsen 2022). This explains the enthusiasm of the field for DTs and the vast number of case studies presented in the scientific literature. In particular, Aivaliotis, Georgoulias, and Chryssolouris (2019) present a DT able to estimate the RUL (remaining useful life) of industrial machine's components thanks to data coming from both the physical entity and the simulation of digital models. The idea is to recalibrate the modeling parameters as soon as a deviation is detected between the actual machine's component behavior and the predicted one such that obtained results are sufficiently accurate for the correct scheduling of maintenance activities (Aivaliotis, Georgoulias, and Chryssolouris 2019). Such a solution allows moving from fail-and-fix practices to a more proactive strategy (predictive maintenance) in which factories can prevent production line stoppages/failures and corresponding expenses from happening, therefore reducing their maintenance costs (Aivaliotis, Georgoulias, and Chryssolouris 2019). Of course, DTs can be used for various other applications than predictions. Tao et al. (2018) especially detail the various applications of DTs in product design and manufacturing machine maintenance. Among the numerous illustrations given in their article, a very interesting one is the maintenance service a DT could achieve. This one involves creating a high-fidelity virtual model that reflects the mechanical structure of the different product parts and collecting their real-time state (thanks to sensors in the physical twin). Thereby, when a fault occurs, the faulty part is detected immediately and the maintenance strategy (e.g., position of the faulty part, disassembly sequence …) is provided by the virtual twin (Tao et al. 2018).

Second, it is essential to mention the aerospace industry, this field being one of the first to have studied the power of DTs. Indeed, the huge expenses generated by undesired system behavior in this sector have raised a great interest in virtual aircraft replications, especially for design and maintenance (Ciano et al. 2021). Nowadays, air transportation has become a major actor in e-commerce whose volume of activity increases year after year and has known a real explosion in 2020 when the covid-19 crisis emerged (Statista 2022). In quantitative terms, millions of tons of cargo are transported worldwide each year. This creates many logistical challenges that still need to be overcome, all the more so as customers are always more demanding in terms of delivery time. Reason why DTs are starting to gain interest in the logistics field and especially in the air cargo ground operations area where activities must flow smoothly. A good example here is the DT introduced by Wong, Mo, and So (2021), which assists planners in determining the optimal loading plan of cargo aircraft based on ULDs information, cargo destinations, and dangerous goods segregation. It also allows close monitoring of the physical operations, detecting and optimally reacting to any deviations from the plan (Wong, Mo, and So 2021). This shortens the physical validation process and results in better cargo loading time, safety, and profitability for several stakeholders (Wong, Mo, and So 2021). In the same line of thought, we are currently analysing which added value digital twins could have for the air cargo global ground logistics. We are creating a fully connected and synchronized digital copy of a cargo airport that enhances the coordination of ground service vehicles to optimize ground operations, as it is a common bottleneck in the air cargo industry. Two dashboards, a conventional web-based one and a fully interactive virtual reality (VR) environment, are connected in real-time to the physical world through classical information systems and Internet of Things (IoT) devices, allowing for constant operations monitoring and deviation alerts when activities move away from the norm defined by an optimal operational model we have conceived. Beyond allowing for a better understanding of current processes, those dashboards will support decision-making by giving insights into what happened in the past, what is currently happening, and what will happen soon following machine learning prediction models. Digital entities will also suggest optimal corrective procedures to human operators to ease and speed up their work in case of disruptions. While the focus is here on global logistics, the problem shares many similarities with problems encountered in manufacturing. Therefore, the lessons learned can clearly be shared between the fields. Indeed, the main goals, based on real-time monitoring, are the same, whereas defining the correct expected underlying process and acquiring all the required data through sensors remain the main challenges. The VR environment offers extra possibilities, including operators training in safe conditions, new processes testing and evaluation (without requiring getting access to the actual airport), and 3D simulation of various scenarios (e.g., emergency situation) without hindering the physical airport activity. This use case is built in partnership with ASL Airlines Belgium, Liège airport[5], and Orange Telecom.

Finally, when looking at other DT application areas, we can first talk about smart cities. In this domain, Major et al. (2021) have designed a 3D graphical digital twin for the municipality of Ålesund in Norway. After mapping the entire city digitally, they decided to measure and visualize the flow of persons and vehicles in the city to understand the mobility patterns of the urban district. To do so, they collected IoT data from inductive coils installed under the roads as well as cellular data from a mobile phone company. Such a system allowed them to know the hourly average number of vehicles (and their speed) going in both directions on given roads. Even if their case study stops after data collection, Major et al. (2021) note that insights given by 3D graphical DTs could be used

[5] Liège airport is Europe's 5th largest cargo airport and belongs to the world's top 20, holding both FedEx and Alibaba European hubs.

either for the common good or commercial purposes. For instance, we can easily imagine that a city could use such data to adjust traffic lights during peaks to smooth the flow of vehicles or to allow the use of intelligent street lighting to reduce overall energy consumption (common good). On the other hand, municipalities could also decide to sell some information to advertising agencies so that these last ones know where to place their billboards to reach as many people as possible (commercial purpose). Then, another sector where DTs have great potential is the healthcare sphere. A possible DT application here would be the real-time monitoring of older people. In fact, according to Liu et al. (2019), by collecting real-time physiological data of the elderly through wearable smart devices (such as connected wristbands or portable electrocardiograms for instance), DTs could allow personalized recommendations for dosage and frequency of medication. Another application could be the design of a DT for bed planning and work allocation in a hospital (Lattanzi et al. 2021). To finish, note that the literature also mentions many other possible application domains for DTs, among which we can find transportation, education, construction, electronics, and sports for instance.

4.2.Expected benefits

When looking at the reasons for using such a technology, it appears that DTs have many potential advantages. Indeed, beyond all industry-specific ones, there exists a range of universal benefits that DTs can deliver whatever the sector of activity considered. In that category, the first major asset of DTs is that their implementation makes it possible to create a continuous cycle of optimization (Jones et al. 2020; Rathore et al. 2021): The bidirectional data flow between the physical and virtual worlds allows to perform a virtual optimization process based on the current state of the physical entity and to realize this optimal set of virtual parameters in the physical twin. This last one then responds to the change and the virtual entity is updated with the new measured physical state. Finally, the divergence between actual and predicted states can be compared such that the optimization process can be re-run with the latest data (Jones et al. 2020). Furthermore, since DTs offer the opportunity to simulate the physical entity, it is possible to test various scenarios and experiment different solutions without affecting the physical environment (Lattanzi et al. 2021). That way, the best result can be chosen and deployed at low risk to increase the physical system's overall efficiency while avoiding computational-intensive mathematical methods (Julien and Martin 2018; Lattanzi et al. 2021; Mashaly 2021). Another advantage of DTs that should be underlined is that they gather real-time information on the state of the physical entity. Physical processes can therefore be perfectly monitored, whereas both diagnosis and predictions can be made based on the latest data at hand (Rathore et al. 2021). This real-time data collection also allows faster, better-informed, and, consequently, more efficient business decisions (Mashaly 2021). A last serious benefit of DTs is that, when combined with machine learning techniques, they are one of the most powerful technologies for predictive maintenance and analysis (Mashaly 2021; Rathore et al. 2021). In fact, when enriched with artificial intelligence, DTs develop autonomy and adaptability capabilities; they are called intelligent DTs (Lattanzi et al. 2021). In addition, according to Alexopoulos, Nikolakis, and Chryssolouris (2020), DTs are facilitators for the implementation of machine learning (ML) approaches: ML models require the availability of a considerable quantity of quality datasets to be trained, but data gathering/cleaning is time-intensive and prone to errors when done manually whereas DTs can easily generate a massive amount of realistic virtual datasets thanks to their high-fidelity replication of the physical entity. These datasets can be further enriched or cross-validated with data collected in the real world through sensors to improve again the accuracy of ML models (Alexopoulos, Nikolakis, and Chryssolouris 2020).

5. DTs implementation challenges

Before concluding this article, it is essential to make some remarks about DTs implementation. In fact, since DTs are only in their introduction phase in the business world, many challenges still need to be overcome.

First, regarding DTs technical implementation, multiple technologies may be required: Internet of Things (IoT) to harvest big data from the physical environment, artificial intelligence and machine learning models to create the digital replication and to take optimization decisions, sensors and actuators to bridge the physical and virtual twins (Rathore et al. 2021). The challenge here is that every technological element can be implemented with a variety of tools and that there does not exist a one-size-fits-all solution, it is, therefore, essential to invest in the functionalities that fit the best the needs and the context of the company considered (Savolainen and Knudsen 2022). Then, it is essential that the data collected matches the data needs of the DT and, therefore, to equip the physical entity with adequate data-gathering devices (Savolainen and Knudsen 2022). Yet, since IoT data is big in nature, data collection and storage may be challenging too (Mashaly 2021; Rathore et al. 2021). Damjanovic-Behrendt and Behrendt (2019) especially suggest establishing governance mechanisms to identify the right volume, level of details, and periodicity of data to collect and process. They also remind, as Lattanzi et al. (2021), that another main challenge is finding a way to integrate information coming from heterogeneous systems and technologies. In addition, since synchronization and coordinated actions between digital and physical twins require real-time data transfer, latency avoidance is also something to which enterprises should give careful consideration (Damjanovic-Behrendt and Behrendt 2019; Mashaly 2021; Savolainen and Knudsen 2022). In this regard, Damjanovic-Behrendt and Behrendt (2019) and Lattanzi et al. (2021) state that research is needed to find a mechanism that permits a completely automated synchronization between the physical and digital entities. To finish, Damjanovic-Behrendt and Behrendt (2019) mention that, as for many other modern technologies, data security and cyber-security remain critical aspects to focus on.

Second, with respect to DTs evaluation, the main aspect considered is fidelity: the higher the fidelity, the more similar the virtual and physical twins will be, and thus the more accurate the virtual processes will be (Jones et al. 2020). However, a very high-fidelity DT would cause problems in terms of network speeds and computational processing time and power, reason why such DTs are not currently achievable (Jones et al. 2020). Consequently, Rathore et al. (2021) add processing time and efficiency constraints for evaluating digital twinning. The challenge is thus to find the fidelity level that maximizes DT performance[6] while minimizing implementation's expense and technical complexity (Jones et al. 2020). In this regard, it is essential to keep in mind that although the potential future returns of DTs are very high, companies must continuously invest in data collection and management without necessarily receiving immediate payback (Savolainen and Knudsen 2022).

Thirdly, a focus should be put on the interaction between humans and DTs. As already mentioned in this article, DTs can be used for training purposes. Indeed, virtual and augmented reality technologies can be integrated into DTs to create interactive and immersive environments that allow workers' training (Semeraro et al. 2021). For instance, Mashaly (2021) presents the possibility of using DTs simulating the function of the human body to train young surgeons. The challenge comes when humans should be an integral part of the DT. In fact, in that case, workers must first be incorporated into the digital replication as any other components of the physical entity, and second, they must

[6] Performance improvement of the physical entity ascribed to its digital twin (Rathore et al. 2021).

learn how to operate smoothly with the technology (Franceschi et al. 2022). For instance, if the virtual entity uses a predictive model to do preventive maintenance actions, then when a mechanic is sent to replace a machine component, the human operator completes the realization stage of the virtual-to-physical connection, which is an essential part of the twinning process (Jones et al. 2020). Nonetheless, Wilhelm et al. (2021) underline that DTs are now sometimes proposed as a way to improve human-machine interactions. They specifically spot four possible DT-human interactions characterized by different decision authority level of the human operator: information (data gathering and representation to assist the worker in its tasks), support (data analysis and optimization to give insights and assist decision-making), decide (data analysis, optimization, and determination of the optimal strategy to implement which should be verified by a human operator), implementation (physical execution of tasks chosen and verified by the DT itself). For this last category, we can easily imagine a DT-driven collision detection tool that automatically disrupts the control of a human operator to take it over and avoid a collision as soon as a danger to worker safety is detected (Wilhelm et al. 2021). With respect to the third DT-human interaction possibility (decide), Franceschi et al. (2022) state that a proper interaction of that type has the power to allow fast process supervision. Indeed, in these circumstances, any errors detected by the DT will be instantaneously notified to the workers, who will be directly provided with all the necessary information as the reason and the location of the issue such that the problem can be rapidly corrected (Franceschi et al. 2022). Further developments like the possibility to teleoperate a system through its DT could even lead to the remote management of process interruption, increasing productivity (Franceschi et al. 2022; Wilhelm et al. 2021).

6. Conclusion and future work

Finally, it is possible to conclude that, even if the concept of DTs is not new, its application in businesses is relatively recent. Therefore, some unknowns remain, starting with the definition of the concept itself and going to the way to implement such a technology. Indeed, although DTs seem to be essential for the digital transition induced by Industry 4.0, there does not exist a collective agreement on a standard definition of the term. Instead, the concept tends to change depending on the context or the application domain considered. This leads to many arguments between authors and wrong word associations. Kritzinger et al. (2018) especially emphasize that DTs should not be confused with digital models or digital shadows, which do not have the entire data flow cycle integrated.

Therefore, it appeared relevant to construct a general definition of digital twins that can be used whatever the application area considered and that can serve as a common basis for future case studies, preventing concept misconceptions. To fill this important research gap, the present article studies and compares the results obtained in recent DT definition literature reviews with existing popular definitions and case study papers to pinpoint what are the fundamental elements of a digital twin. From this analysis, it appears that DTs' main characteristics were the co-existence of a physical entity and its virtual replication, the presence of a bidirectional data flow allowing real-time physical-virtual synchronization, and the use of different computational techniques within the virtual world. Based on those key concepts, Section 2.3. introduces a generic definition for digital twins that builds the required common grounds for future research and case studies. Still with the objective of clarifying the notion of digital twins, this paper highlights the two major distinctions that exist between DTs and traditional simulation approaches, namely (1) the continuous and real-time physical-to-virtual connection and

(2) the existence of a virtual-to-physical connection. Then, Section 4 provides several examples showing how DTs can be used in many different fields and for many different reasons. It primarily focuses on manufacturing which is the current dominant area for DTs applications but also gives instances in other sectors such as smart cities, healthcare, aerospace, and logistics to reveal how flexible DTs can be. DTs expected universal benefits are also approached in that section, we specifically underline their ability to conduct a continuous cycle of optimization, to test various scenarios without affecting the physical world, to monitor an entity in real-time and subsequently improve the decision-making, and to facilitate the implementation of machine learning models. To finish, the last part of this paper briefly states the DT implementation challenges companies face as many still need to be overcome: multiple technologies integration, big data collection and storage, latency avoidance, cyber-security, DT evaluation, human interaction …

Regarding future work, now that a complete and non-contextual DT definition has been produced, it sounds that two main gaps still need to be filled: (1) implementation solutions as many challenges still need to be overcome here, and (2) DTs potential in other areas than the manufacturing one. In this regard and as previously mentioned, we intend to find out which added value digital twins could have for the logistics field through the development of a DT for ground operations management in the air cargo industry. Results of this research will be available in further articles.

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from Eindhoven in the north all the way down to the border of Luxemburg. Over 5.5 million people live in this cross-border region, where the best of three countries merges into a truly European culture. With the investment of EU funds in Interreg projects, the European Union directly invests in the economic development, innovation, territorial development and social inclusion and education of this region.

Disclosure statement

The authors report there are no competing interests to declare.

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Figure captions

Figure 1. The bidirectional data flow of the twinning process.

Figure 2. DTs definition fundamental elements according to Jones et al. (2020) and Semeraro et al. (2021).

Figure 3. DTs key concepts graphical synthesis.