The digital twin concept: A definition attempt

Jenny Tonka[*] , Michaël Schyns[*]

HEC Liège-Management School of the University of Liège, Liège, Belgium

Abstract. Nowadays more than ever, the digital transition is an essential evolution for the survival of industrial activity. Digital twins (DT) are a good way for enterprises to face this new challenge. Although the concept is not new, there is still no general agreement on its definition. Therefore, this paper seeks to identify what are the key elements of DTs and attempts to formulate a definition that group them all together.

Keywords. Digital twin, digital transformation, industry 4.0

1. Introduction

Nowadays more than ever, the digital transition is an essential evolution for the survival of industrial activity (Julien & Martin, 2018). According to many authors, the concept of digital twins (DT) could really help companies to face this challenge. But 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. It is actually much more than that. Semeraro et al. (2021) especially note that the integration and the interaction between physical and virtual spaces is becoming increasingly important, hence the interest of using DTs.

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 & Martin, 2018; Kritzinger et al., 2018; Rathore et al., 2021; Trauer et al., 2020). At that time, Grieves defined the digital twin as the combination of three key elements: (1) a virtual twin, (2) a physical counterpart, and (3) a data flow cycle between the physical and virtual entities (Rathore et al., 2021; Trauer et al., 2020). However, some authors as Mashaly (2021) asserts that the twinning concept dates back to the 1960s when the NASA decided to create physical duplicates on earth that match their systems in space in the context of the Apollo program. However, she maintains that Grieves was the first to introduce the concept in the manufacturing industry by creating virtual replicas of factories to monitor 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 general agreement on the DT definition. In particular, Semeraro et al. (2021) note that there exist 5 clusters of DT definition in the literature (see *literature review* section) and that the DT concept varies as the context of application changes. 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).

* Corresponding authors.

E-mail addresses: M.Schyns@uliege.be (M. Schyns), J.Tonka@uliege.be (J. Tonka).

Beyond giving some insights into the DT concept and its application areas, the goal of this paper is thus to identify the key elements of a DT and to attempt to formulate a definition which gets the job done. With this aim in mind, the article is structured around four main questions:

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

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

2. Literature review and definitions

To identify what are the key elements that should be found in the definition of a digital twin, this note will first analyse and compare the results obtained in two recent literature reviews on the specific topic of DT definition. 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 key elements of a DT identified and will try to formulate a definition that group them all together.

2.1. Key elements

The first literature review dedicated to the DT definition that will be analysed 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 its basic characteristics (all of which should appear in the DT definition):

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

(2) ***Virtual entity***: Computer generated representation of the physical one.

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

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

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

(6) ***State***: Measured values for all parameters corresponding to the physical/virtual entity and its environment.

(7) ***Parameters***: Types of data, information, and processes transferred between entities such as temperature, or production scores.

(8) ***Physical-to-virtual connection***: Means by which the state of the physical entity is transferred to, and realised in, the virtual environment (update of virtual parameters such that they reflect the values of physical parameters). In fact, it consists of a metrology phase, in which the state of the physical entity is captured, and a realisation phase, in which the delta between the physical and digital entities is determined and the virtual entity is updated accordingly.

(9) ***Virtual-to-physical connection***: Means by which an optimal set of parameter values determined by virtual processes is transferred to, and realised in, the physical environment. It consists of a metrology phase, in which those optimal parameters are captured, and a realisation phase, in which the delta between these new values and the existing state of the physical entity is determined, and the physical entity/environment is updated accordingly.

(10) ***Twinning***: Act of synchronising the states of the physical and virtual entities, see ***Figure 1***. Physical and virtual entities are said to be twinned when both states are equal.

(11) ***Physical processes***: Activities being performed by the physical entity in the physical environment (e.g., a manufacturing production line).

(12) ***Virtual processes***: Computational techniques employed within the virtual world (e.g., optimisation, prediction, simulation, analysis …).

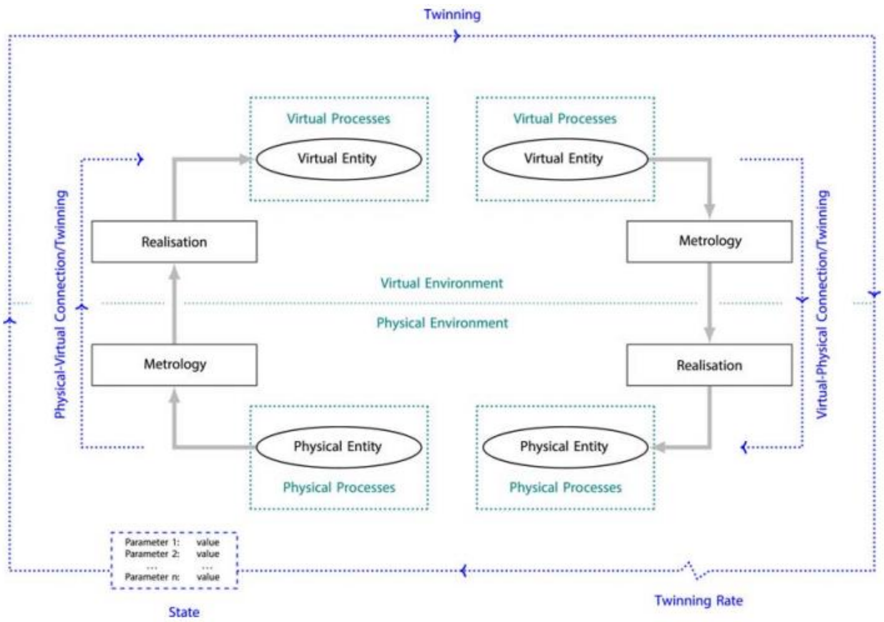

Figure 1 *– The physical-to-virtual and virtual-to-physical twinning process (retrieved from Jones et al. (2020))*

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

(1) ***The ability of 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 & Martin, 2018; Kritzinger et al., 2018; Rathore et al., 2021; Trauer et al., 2020), many of them emphasize the idea that a DT should connect real and virtual spaces over all phases of the product life cycle. According to Semeraro et al. (2021), authors like Glaessgen & Stargel (2012), Grieves (2014), Ríos et al. (2015), Schroeder et al. (2016), Zhang et al. (2017), Schleich et al. (2017), and Söderberg et al. (2017) provide definitions which fall in this category.

(2) ***The synchronization of the cyber system with the physical assets***: For many other authors, the most important thing is that the DT bridges the gap between the physical entity and the virtual one to improve and support the decision making. It is thus the information exchange between both systems that is underlined here. In this definition family, Semeraro et al. (2021) especially cite (Alam & El Saddik, 2017), (Graessler & Poehler, 2017), and (Autiosalo, 2018).

(3) ***The integration of real time data***: Some others, as (Lee et al., 2013), (Brenner & Hummel, 2017), (Schluse et al., 2017), (Stark et al., 2017), (Weber et al., 2017) (Yun et al., 2017), (Lee & Kim, 2018), (Haag & Anderl, 2018) or (Leng et al., 2019) according to Semeraro et al. (2021), claim that the main aspect of DT is the real time data connection between the physical and virtual worlds because it is this feature that will allow the DT to respond to changes over time and consequently to optimize business performance.

(4) ***The behavioural modelling of the physical space***: Still others concentrate on the fact that physical behaviours, properties, and characteristics should be transferred in the virtual space. According to them, the main function of digital twins is to duplicate the current state of the physical system in the virtual world. The definitions provided by (Rosen et al., 2015), (Ciavotta et al., 2017), (Tao et al., 2018), (Liu et al., 2018), (Zhuang et al., 2018), (Bao et al., 2019), and (Nikolakis et al., 2019) are quoted by Semeraro et al. (2021) in this fourth definition cluster.

(5) ***The services provided by the virtual system***: Remaining authors focus on the services that the DT can offer such as the control of the current situation, the prediction of the near future, or the optimisation of the physical twin. It is notably the case of (Tuegel, 2012), (Negri et al., 2017), (Asimov et al., 2018), and (Luo et al., 2018) according to Semeraro et al. (2021).

If we compare the results obtained by both literature reviews, 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). However, Jones et al. (2020) insist more on the twinning process and on 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 but this last one should not necessarily appear in the DT definition as it is more a way to evaluate the DT performance (see *Additional comments* section). On the other hand, Semeraro et al. (2021) add the notion of real time data exchange which is quite 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 the DT definition since it is linked to the specific field of production.

2.2. Existing definitions

Knowing the key characteristics of a DT, we can now examine several popular definitions found in the scientific literature to see if they include all those elements and/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 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 behaviour in interaction with its environment in the real world*" as well as the one of Negri et al. (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 behaviour and environment, Negri et al. (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 the fact 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 full cycle of data integrated (see *Introduction* section). For instance, the CIRP Encyclopaedia of Production Engineering definition of the digital twin, which is "*A digital twin is a digital representation of an active unique product or unique product-service system that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple life cycle phases*" (Stark & Damerau, 2019), does not include the virtual-to-physical connection (Jones et al., 2020). Therefore, according to Kritzinger et al. (2018), this definition is not correct as it does not refer to DTs but rather to digital shadows.

In view of the foregoing, we can notice that the different definitions analysed globally agree on the key elements previously pinpointed. It can also be seen that no new characteristics are mentioned. We can thus suppose that the key concepts already identified are the only ones to consider in the DT definition.

2.3. Proposed definition

The various analyses of the literature having been made, we can now move on to the final step of this analysis, the definition formulation but, first, let's list the key concepts underlying DTs:

- There exists a physical entity which performs some activities (physical processes), and which 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 whereas 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 optimisation, prediction, or simulation for instance (virtual processes).

Although all those elements are key 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 DT definition could be the following one:

> *A digital twin is a virtual replication of a physical entity (and its environment) which is completely synchronized with its counterpart thanks to the combination of a physical-to-virtual connection (physical metrology*† *and virtual realisation*‡*) with a virtual-to-physical one (virtual metrology and physical realisation), and which can be used for various purposes as modelling, decision making, monitoring, optimizing, predicting, or even staff training.*

---

† Act of measuring the state of the physical/virtual entity.

‡ Act of changing the state of the physical/virtual entity to equal the one of the virtual/physical entity.

Note that this definition is quite strict because it describes the highest possible maturity of the technology. The fact that a digital twin can supply every required piece of information about the physical system in a real-time manner indeed constitutes the optimal target for digital twins (Mashaly, 2021). In addition, as there exists a broad range of applications for DTs, there is no specific example for them (Trauer et al., 2020). Therefore, we cannot precise more the form or even the goal of the DT in its definition.

3. Digital Twins vs. simulation and modelling

Before going further with DTs benefits and application areas, it is important to understand the difference that exists between DTs and traditional simulation/modelling 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 IoT) 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). Second, DTs benefit from a virtual-to-physical connection which does not exist in traditional modelling methods. This bidirectional relationship between the virtual and the physical allows DTs to hypothesise, and subsequently perform, test, and adjust that hypothesis in a continuous adapting and improving cycle since the loop between hypotheses generated in the virtual environment and the actual consequences realised in the physical environment is closed (Jones et al., 2020).

4. The expected benefits and application areas of DTs

4.1. Applications areas

Now that the notion of digital twins has been clarified, it is interesting to have a quick look at DTs application areas and benefits to better understand how flexible and helpful such a technology can be.

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 as smart cities, education, transportation, or even medicine (Mashaly, 2021; Rathore et al., 2021; Semeraro et al., 2021). In addition, whatever the sector considered, DTs can be used for many different reasons: process modelling, real-time monitoring, deviation alert, deviation prediction, process optimisation, decision-support tool, creation of a virtual reality environment, training support and so on (Julien & Martin, 2018). To illustrate this broad range of applications, the following lines are dedicated to three concrete examples of DTs usage in different fields.

First of all, in the area of product lifecycle management, Tao et al. (2018) detail the various applications of DTs in product design, manufacturing, utilization, and maintenance. Among the numerous illustrations given in their article, a very interesting one is the product maintenance service that could be achieved by a DT. This 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 immediately detected and the maintenance strategy (e.g., position of faulty part, disassembly sequence, part specifications to be replaced …) is provided by the virtual twin (Tao et al., 2018).

Then, when looking at smart cities, we can talk about the 3D graphical digital twin designed by Major et al. (2021) for the municipality of Ålesund in Norway. After having mapped the entire city digitally, they decided to measure and visualise 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 either for the common good or for commercial purposes. For instance, we can easily imagine that a city could use such data for adjusting traffic lights during peaks to smooth the flow of vehicles or for allowing the use of smart street lighting to reduce the 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).

Finally, in the healthcare sector, a possible DT application is the real-time monitoring of old people. Indeed, 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 recommendation for dosage and frequency of medication.

4.2. Some 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 "general" benefits that DTs can deliver whatever the sector of activity considered. In that category, a first major asset of the DT is that its implementation makes it possible to create a continuous cycle of optimisation (Rathore et al., 2021): The bidirectional data flow between the physical and virtual worlds allows to perform a virtual optimisation process based on the current state of the physical entity and to realise this optimal set of virtual parameters in the physical twin. This last one then responds to the change and the loop cycles to update the virtual entity with the new measured physical state. Finally, the delta between the actual and predicted states can be compared and the optimisation process re-run with the updated information (Jones et al., 2020). Furthermore, since DTs offer the opportunity to simulate the physical entity, it is possible to test various scenarios and to experiment different solutions without affecting the physical environment. That way, the best result can be chosen and deployed in order to increase the overall efficiency of the physical system (Julien & Martin, 2018; Mashaly, 2021). Another advantage of DTs that should be underlined is the fact 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 data at hand (Rathore et al., 2021). This collection of data also allows to make faster, better-informed and, consequently, more efficient business decisions (Mashaly, 2021). A last serious advantage of DTs is that, when combined with machine learning techniques, they are one of the most powerful technology for predictive analytics and health monitoring of physical components (Mashaly, 2021; Rathore et al., 2021).

5. DT implementation

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

First, regarding DTs implementation, multiple technologies may be required: Internet of Things (IoT) to harvest big data from the physical environment, AI-ML model to create a digital copy of the physical entity and to take optimisation decisions, sensors and actuators to bridge the physical and virtual twins (Rathore et al., 2021)**.** The challenge here is that every technological component can be implemented with a variety of tools, therefore it is essential to choose the ones that fit the best the needs and the context of the company considered. Then, since IoT data is big in nature, data collection and data storage may be challenging too (Mashaly, 2021; Rathore et al., 2021). In addition, as the connection between digital and physical twins requires real-time data transfer for keeping them always synchronized, latency avoidance is also something to which enterprises should give careful consideration (Mashaly, 2021).

Second, with respect to DTs evaluation, the main aspect considered is fidelity: the higher the fidelity, the closer the virtual and physical twins and thus the more accurate the simulation, modelling, and optimisation will be (Jones et al., 2020). However, a very high-fidelity DT would cause problems in terms of network speeds and computational processing, reason why such DTs are not currently achievable (Jones et al., 2020). Consequently, Rathore et al. (2021) add processing time and efficiency constraints for the evaluation of the digital twinning. The challenge is thus to find the fidelity level that maximises DT performance[§] while minimising expense and technical difficulty of implementation (Jones et al., 2020).

Thirdly, a focus should be put on the interaction between humans and DTs. As already mentioned in this article, DTs can be used for a training purpose. Indeed, virtual and/or augmented reality technologies can be integrated in DTs to create interactive and immersive environments that allow workers training (Semeraro et al., 2021). For instance, Mashaly (2021) presents the possibility to use DTs simulating the function of human body to train young surgeons. The challenge comes when humans should be an integral part of the DT since, in that case, workers must learn how to operate smoothly with the technology. For instance, if the virtual twin is used to monitor the health of a particular component using a predictive model, and that it sends a mechanic to replace that component, the mechanic will perform the realisation process of the virtual-to-physical twinning which is an essential element of a DT (Jones et al., 2020).

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 rather recent. Therefore, there remain some unknowns, starting with the definition of the concept itself and going to the way to implement and to evaluate such a technology.

In order to clarify a little bit those questions, this article gives a general definition of digital twins that can be used whatever the application area considered. It also approaches DTs common benefits and details how they could be used in different fields. Lastly, it briefly states challenges faced by companies in the implementation and the evaluation of DTs.

Regarding future work, we should underline the fact that, although DTs have multiple applications in various domains, many research still need to be done in the specific field of logistics. We thus intend to find out which added value digital twins could have for this area and, in particular, we plan to work in partnership with ASL Airlines Belgium, Liège airport and Orange telecom to develop a DT for

§ Performance improvement of the corresponding physical system that is attributed to its digital twin (Rathore et al., 2021).

ground operations management in the air cargo industry. Results of those research will be available in further articles.

Acknowledgements

The work reported in this paper has been undertaken as part of the project “Digital Twin Academy” supported by the European Regional Development Fund (Interreg EMR).

Bibliography

Glaessgen, E., & Stargel, D. (2012). The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2012-1818

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), *Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches* (pp. 85-113). Springer International Publishing. https://doi.org/10.1007/978-3-319-38756-7_4

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, *29*, 36-52. https://doi.org/10.1016/j.cirpj.2020.02.002

Julien, N., & Martin, E. (2018). *L’usine du futur : Stratégies et déploiement*. Dunod.

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC PapersOnLine*, *51*(11), 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Liu, Y., Zhang, L., Yang, Y., Zhou, L., Ren, L., Wang, F., Liu, R., Pang, Z., & Deen, M. J. (2019). A novel cloud-based framework for the elderly healthcare services using digital twin. *IEEE Access*, *7*, 49088-49101. https://doi.org/10.1109/ACCESS.2019.2909828

Major, P., Li, G., Hildre, H. P., & Zhang, H. (2021). The use of a data-driven digital twin of a smart city: A case study of Ålesund, Norway. *IEEE Instrumentation and Measurement Magazine*, *24*(7), 39-49. https://doi.org/10.1109/MIM.2021.9549127

Mashaly, M. (2021). Connecting the Twins: A Review on Digital Twin Technology & its Networking Requirements. *Procedia Computer Science*, *184*, 299-305. https://doi.org/10.1016/j.procs.2021.03.039

Negri, E., Fumagalli, L., & Macchi, M. (2017). A Review of the roles of digital twin in CPS-based production systems. *Procedia Manufacturing*, *11*, 939-948. https://doi.org/10.1016/j.promfg.2017.07.198

Rathore, M. M., Shah, S. A., Shukla, D., Bentafat, E., & Bakiras, S. (2021). The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and Opportunities. *IEEE Access*, *9*, 32030-32052. https://doi.org/10.1109/ACCESS.2021.3060863

Rosen, R., von Wichert, G., Lo, G., & Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *IFAC-PapersOnLine*, *48*(3), 567-572. https://doi.org/10.1016/j.ifacol.2015.06.141

Schleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin for design and production engineering. *CIRP Annals*, *66*(1), 141-144. https://doi.org/10.1016/j.cirp.2017.04.040

Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. *Computers in Industry*, *130*, 103469. https://doi.org/10.1016/j.compind.2021.103469

Stark, R., & Damerau, T. (2019). CIRP Encyclopedia of Production Engineering. In S. Chatti & T. Tolio (Eds.), *The International Academy for Production Engineering* (pp. 1-8). Springer. https://doi.org/10.1007/978-3-642-35950-7_16870-1

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*, *94*(9-12), 3563-3576. https://doi.org/10.1007/s00170-017-0233-1

Trauer, J., Schweigert-Recksiek, S., Engel, C., Spreitzer, K., & Zimmermann, M. (2020). What is a digital twin? – Definitions and insights from an industrial case study in technical product development. *Proceedings of the Design Society: DESIGN Conference*, *1*, 757-766. https://doi.org/10.1017/dsd.2020.15

Bibliographic complements

Alam, K. M., & El Saddik, A. (2017). C2PS: A Digital Twin Architecture reference model for the cloud-based cyber-physical systems. *IEEE Access*, *5*, 2050-2062. https://doi.org/10.1109/ACCESS.2017.2657006

Asimov, R., Chernoshey, S., Kruse, I., & Asipovich, V. (2018). *Digital twin in the analysis of big data*.

Autiosalo, J. (2018). Platform for industrial internet and digital twin focused education, research, and innovation: Ilmatar the overhead crane. *IEEE 4th World Forum on Internet of Things (WF-IoT)*, 241-244. https://doi.org/10.1109/WF-IoT.2018.8355217

Bao, J., Guo, D., Li, J., & Zhang, J. (2019). The modelling and operations for the digital twin in the context of manufacturing. *Enterprise Information Systems*, *13*(4), 534-556. https://doi.org/10.1080/17517575.2018.1526324

Brenner, B., & Hummel, V. (2017). Digital twin as enabler for an innovative digital shopfloor management system in the ESB logistics learning factory at Reutlingen university. *Procedia Manufacturing*, *9*, 198-205. https://doi.org/10.1016/j.promfg.2017.04.039

Ciavotta, M., Alge, M., Menato, S., Rovere, D., & Pedrazzoli, P. (2017). A microservice-based middleware for the digital factory. *Procedia Manufacturing*, *11*, 931-938. https://doi.org/10.1016/j.promfg.2017.07.197

Graessler, I., & Poehler, A. (2017). Integration of a digital twin as human representation in a scheduling procedure of a cyber-physical production system. *IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 289-293. https://doi.org/10.1109/IEEM.2017.828989

Grieves, M., 2014. Digital twin: Manufacturing excellence through virtual factory replication. *White paper*, *1*, 1-7.

Haag, S., & Anderl, R. (2018). Digital twin – Proof of concept. *Manufacturing Letters*, *15*, 64-66. https://doi.org/10.1016/j.mfglet.2018.02.006

Lee, H., & Kim, T. (2018). Smart factory use case model based on digital twin. *ICIC Express Letters*, *9*(9), 931-936. https://doi.org/10.24507/icicelb.09.09

Lee, J., Lapira, E., Yang, S., & Kao, A. (2013). Predictive manufacturing system: Trends of next-generation production systems. *IFAC Proceedings Volumes*, *46*(7), 150-156. https://doi.org/10.3182/20130522-3-BR-4036.00107

Leng, J., Zhang, H., Yan, D., Liu, Q., Chen, X., & Zhang, D. (2019). Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop. *Journal of Ambient Intelligence and Humanized Computing*, *10*(3), 1155-1166. https://doi.org/10.1007/s12652-018-0881-5

Liu, Z., Meyendorf, N., & Mrad, N. (2018). The role of data fusion in predictive maintenance using digital twin. *AIP Conference Proceedings*, *1949*(1), 020023. https://doi.org/10.1063/1.5031520

Luo, W., Hu, T., Zhu, W., & Tao, F. (2018). Digital twin modeling method for CNC machine tool. *IEEE 15th International Conference on Networking, Sensing and Control (ICNSC)*, 1-4. https://doi.org/10.1109/ICNSC.2018.8361285

Nikolakis, N., Alexopoulos, K., Xanthakis, E., & Chryssolouris, G. (2019). The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor. *International Journal of Computer Integrated Manufacturing*, *32*(1), 1-12. https://doi.org/10.1080/0951192X.2018.1529430

Ríos, J., Hernández, J. C., Oliva, M., & Mas, F. (2015). Product avatar as digital counterpart of a physical individual product: Literature review and implications in an aircraft. *Transdisciplinary Lifecycle Analysis of Systems*, 657-666. https://doi.org/10.3233/978-1-61499-544-9-657

Schluse, M., Atorf, L., & Rossmann, J. (2017). Experimentable digital twins for model-based systems engineering and simulation-based development. *Annual IEEE International Systems Conference (SysCon)*, 1-8. https://doi.org/10.1109/SYSCON.2017.7934796

Schroeder, G. N., Steinmetz, C., Pereira, C. E., & Espindola, D. B. (2016). Digital twin data modeling with automationML and a communication methodology for data exchange. *IFAC-PapersOnLine*, *49*(30), 12-17. https://doi.org/10.1016/j.ifacol.2016.11.115

Söderberg, R., Wärmefjord, K., Carlson, J. S., & Lindkvist, L. (2017). Toward a digital twin for real-time geometry assurance in individualized production. *CIRP Annals*, *66*(1), 137-140. https://doi.org/10.1016/j.cirp.2017.04.038

Stark, R., Kind, S., & Neumeyer, S. (2017). Innovations in digital modelling for next generation manufacturing system design. *CIRP Annals*, *66*(1), 169-172. https://doi.org/10.1016/j.cirp.2017.04.045

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S.C.-Y., & Nee, A.Y.C. (2018). Digital twin-driven product design framework. *International Journal of Production Research*, 1–19.

Tuegel, E. (2012). The airframe digital twin: Some challenges to realization. In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2012-1812

Weber, C., Königsberger, J., Kassner, L., & Mitschang, B. (2017). M2DDM – A maturity model for data-driven manufacturing. *Procedia CIRP*, *63*, 173-178. https://doi.org/10.1016/j.procir.2017.03.309

Yun, S., Park, J.-H., & Kim, W.-T. (2017). Data-centric middleware based digital twin platform for dependable cyber-physical systems. *Ninth International Conference on Ubiquitous and Future Networks (ICUFN)*, 922-926. https://doi.org/10.1109/ICUFN.2017.7993933

Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J. (2017). A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. *IEEE Access*, *5*, 26901-26911. https://doi.org/10.1109/ACCESS.2017.2766453

Zhuang, C., Liu, J., & Xiong, H. (2018). Digital twin-based smart production management and control framework for the complex product assembly shopfloor. *The International Journal of Advanced Manufacturing Technology*, *96*(1-4), 1149-1163. https://doi.org/10.1007/s00170-018-1617-6