Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online
CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 58-19 (2024) 175–180

Exploring Digital Twin Dynamics: An Analysis of Structure Configurations

Victória Melo *, **José Barbosa** *, **Flávia Pires** *,
Fernando de la Prieta **, **Paulo Leitao** *

* *Research Centre in Digitalization and Intelligent Robotics (CeDRI), Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, 5300-253 Bragança, Portugal*
(e-mail: {victoria, jbarbosa, fpires, pleitao}@ipb.pt)
** *BISITE Digital Innovation Hub, University of Salamanca, Edificio Multiusos I+D+i, 37007, Salamanca, Spain. (e-mail: fer@usal.es)*

Abstract: Digital twin (DT) is an important technology to support the realization of the digital transformation, connecting the physical asset to its virtual copy and fostering real-time monitoring, simulation, and decision-support. However, the benefits of DT depend on its intended purpose and application, which is impacted by the design structure configuration that is used for its implementation. This paper discusses the advantages and challenges of considering different organizational structures for the implementation of DTs, namely centralised, hierarchical and decentralised, complemented with a case study that was used to analyse the implementation of DT focusing on centralised and decentralised approaches. Additionally, the paper includes an analysis of the main aspects of DT structures and their design guidelines, the key enabling technologies and the main challenges of distributing DTs.

Keywords: Digital Twin, Organizational structures, Decentralised configuration.

1. INTRODUCTION

The Digital Twin (DT) represents an essential element of the digital transformation and, therefore, an important concept for smart manufacturing development (Shao, 2021). Coupled with Industry 4.0 technologies, including Internet-of-Things (IoT), Artificial Intelligence (AI), Big Data, and Cyber-Physical Systems (CPS), they promote innovative transformations, enabling increased productivity, efficiency, and competitiveness across various industry sectors, particularly manufacturing (Zhong et al., 2017).

In the most common definitions, DTs are considered the virtual representation of physical assets, capable of modelling, simulating, monitoring, analysing, and continuously optimising the real counterpart, being a major pillar of the industry's digital transformation (Capgemini Research Institute, 2022). The advantages of employing DTs include the real-time monitoring and the decision-support through diagnostics, optimisation, prediction and recommendations based on data analysis and/or what-if simulations (Shao, 2021). In the last few years, the interest in the DT has been growing both in industry and academia, having been listed among the Gartner top ten strategic technology trends for 2019 (Panetta, 2018), with a global market size being expected to grow at a compound annual growth rate (CAGR) of 37.5% from 2023 to 2030 (Grand View Research, 2023).

Usually, the proposed DT applications consider a centralised organisational structure for representing virtually an asset that can be a simple device or an entire process, enabling the virtual model to be fed in real-time to promote monitoring, data analysis, simulation and decision support capabilities. However, when an asset represents complex systems, for example an entire multi-stage production line, the efficiency and responsiveness of a centralised approach decreases since the computation of the virtual model demands high computational resources. Some studies focus on the potential application of other organisational structures, e.g., decentralised, distributed or hierarchical structures, to improve efficiency when considering complex systems, but few apply these to DT systems (Human et al., 2023; Cohen et al., 2021).

The ISO 23247 standard (ISO 23247, 2021) already considers the creation of DT ecosystems by specifying components in the framework that foresee the interconnection between DTs, i.e. the interoperability, peer interface and plug and play modules within the *Resource Access and Interchange sub-entity.* Nevertheless, the selection of the proper organizational structure to implement DTs requires the analysis of their boundaries and applicability guidelines according to certain aspects, namely granularity, scalability, reconfigurability, model design complexity and security.

With this in mind, the main goal of this paper is to provide an analysis of the different organisational structures and their potential application to implement DT systems, discussing their advantages and challenges, focusing on the referred aspects. In order to support the discussion, a case study of a modular conveyor transfer system is presented, where the system's DT was implemented according to the

10.1016/j.ifacol.2024.09.135

centralised and decentralised structures. This enriches the discussion on the design guidelines for the DT structure, as well as the key enabling technologies and the main challenges of distributing DTs.

The rest of the paper is organised as follows: Section 2 discusses the different types of connections between assets and DTs, as well as the design structures for DTs. Section 3 presents a comparison of centralised and decentralised structures through a case study. Section 4 discusses the advantages and challenges of each configuration, the key technologies, and the challenges of distributing DTs. Finally, Section 5 concludes the paper and identifies areas for future research.

2. DIGITAL TWIN STRUCTURE CONFIGURATIONS

The concept of the DT has been widely used in diverse areas, but its definition, organisational structure, implementation guidelines, and associated components are constantly evolving along with further studies and developments. However, the different connections between the physical asset and its associated DT, and the related granularity, can be further explored, opening up space for analysis of the possible configurations the DTs can assume according to their associations with the assets.

The first analysis explores the relationship between DT and the asset *(Asset-DT)*. The asset class represents the objects of the physical world from which is obtained all the information to feed the digital representation in the DT. The instances of this generic class can be specified in *product* and *resource* (Sakurada et al., 2023), this last one covering, e.g., *personnel*, *material*, *equipment*, *processes*, and even sub-processes that compose a more complex process. The levels of granularity with which they can be represented, i.e. in terms of the individual components defined within the asset, can determine the number of DTs connected with them to provide a complete representation of the system. In this perspective, some works classify DT types from the point of view of the granularity of the asset, namely *Component/Part Twin*, *Asset/Product Twin*, *System Twin* and *Process Twin* (Woods, 2018; Singh et al., 2021). From another perspective, systems and products can have different DTs throughout the stages of their life-cycle, e.g., design, production, and maintenance (Capgemini Research Institute, 2022). Therefore, in terms of the relationship for both classes, it can be defined that one or more assets can be associated with one or more DT.

A second analysis can be conducted focusing on the relationships between DTs *(DT-DT)*, referring to the associations that can involve multiple DT instances. Although these instances are of the same type, each one might perform a specific role, justifying their distinction. The first justification is *collaboration*, in which the DTs operate independently but need to communicate to share information and knowledge, contributing to the overall performance of the system (holistic view of the system). The second is *composition*, in which a DT can be composed of other DTs following the principles of holonic systems in a useful combination when modelling more complex systems. Both associations are presented on the top left of Fig. 1, illustrating that a DT can be composed of other DTs and these DTs may interact to exchange information. In this context, the terms “System of systems” (Dietz and Pernul, 2020), “system of DTs” (Human et al., 2023), “DT of twins” (Redelinghuys et al., 2020) and “Internet of DTs (IoDT)” (Wang et al., 2023) have been used to address these associations.

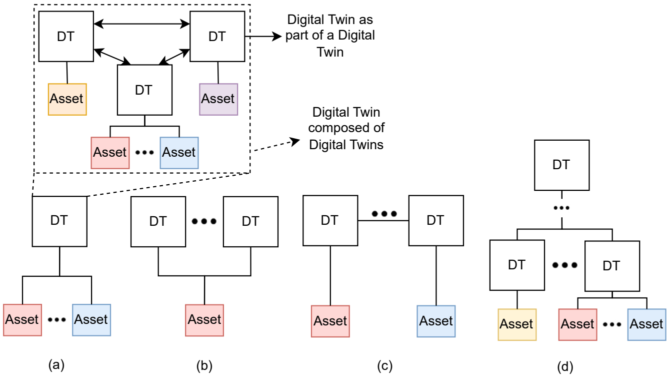

Fig. 1. Digital Twin structure configurations.

These relationships between Asset-DT and DT-DT can be better exploited by analysing the different configurations that a DT structure can assume according to its level of interation with the physical asset and with the other DT instances, as illustrated in Fig. 1. Each configuration, i.e. centralised, hierarchical or decentralised, can offer different advantages according to the overall objective of implementing the DT, as well as, e.g., in terms of flexibility, optimization and security aspects.

The first structure (a) follows a centralised approach and is the most usual when designing a DT. This structure considers that all of the assets (e.g., a sensor, equipment, a system, or the entire process, including all of its sub-processes) have their digital representation in a common DT, designed to cover all the functionalities related to these assets.

The second structure (b) represents that an asset can have multiple associated DTs depending on the retrieved data used to feed its digital representation, e.g., considering different stages of the asset life-cycle. Additionally, it may reflect, the diversity of information needed to be processed and analysed according to the levels of employed roles and hierarchy, where operators, supervisors, and managers need to be informed or have access to distinct data and possess different degrees of authority to act in the process.

The third structure (c) presents a completely distributed structure, considering that each asset possesses its own dedicated DT. This kind of decentralised approach requires interoperability mechanisms to enable the interaction and communication when exchanging information among the DTs, which is crucial when their functionalities contribute to the collective performance of the overall process, extending beyond specific asset monitoring. This type of structure is suitable for analysis that covers the lifecycle of a product or the different stages that a product can go through in complex or multi-stage processes.

The structure presented in (d) addresses an aggregation structure in which the individual DTs can send data to a central DT containing knowledge about the entire system, in addition to exchanging data between themselves, contributing to the distribution of the system and bringing benefits in terms of processing, optimisation, and overall view of the system. This representation shows that the DTs at the lowest level of the hierarchy can assume centralised or decentralised configurations according to implementation needs, combining these structures. Several studies have focused on the hierarchical DT aggregation, e.g., (Redelinghuys et al., 2020; Villalonga et al., 2021; Human et al., 2023; San et al., 2023), presenting various methodologies and models that address this through federated learning principles and collaboration models.

3. CASE STUDY IMPLEMENTATION

This section presents an in-depth analysis of DTs structure configurations, using a case study based on the monitoring conditions of a conveyor transfer system, testing the centralisation and decentralisation approaches of the DTs.

3.1 Case Study Description and DT Implementations

The system under study is composed of cyber-physical components. The physical part comprises a conveyor belt, two photoelectric sensors for input and output detection of parts, vibration and current sensors, and a DC motor to operate the belt. The sensors enable the collection of data to be used in the DT functionalities as parameters for monitoring the system's health condition. The cyber part comprises a Raspberry Pi platform, in which the agents were deployed for the control of the system. This system transports parts from a starting point (entrance to the first conveyor) to an endpoint (exit from the last conveyor) using self-organisation mechanisms performed by the use of Multi-agent systems (MAS), providing scalability and dynamic system reconfiguration, allowing to remove, add or modify the position of the modules on-the-fly.

The design of a DT for this system enables its operation monitoring and early fault detection. The observed parameters are related to the system's operational data, i.e. the states of motors and sensors (activate or deactivate), the motor operating time, the battery level, the current drawn by the motor's operation, vibration, the time needed to transport a piece, the number of pieces transported and the position of each module in the sequence. More details about the system digitalisation, i.e. the monitored parameters and data acquisition, storage, analysis and visualisation can be found in (Pires et al., 2020).

Implementing one DT for each module and one DT for the entire system enables the comparison of the characteristics of each type of structure, the evaluation of the key advantages and challenges encountered, and the assessment of their performance in terms of the functionalities provided. Fig. 2 illustrates both approaches, presenting the configurations tested and the components involved.

The DT configuration proposed in (a) addresses the centralised approach, in which the data collected from each asset related to the operational parameters described previously converges to a single common point. In this DT implementation, a unified virtual model of the entire process is created, and a connection to a database is established, enabling the storage of these parameters. Regarding the functionalities provided by this DT, the real-time monitoring is performed by presenting the virtual model data directly on a dashboard, allowing users to access this information in real-time for the simultaneous monitoring of the process. The stored data is used to perform the process analysis, aiming to evaluate the system performance and to enable the early detection of abnormal situations. These analysis create alerts regarding the system's operation, shown on the visualisation panel, allowing users to access the information and perform the system maintenance. The access control of the exchanged information can be carried out using certificates and user authentications.

The decentralised approach considers each module as an asset possessing its own DT. The components of these DTs are similar to those described in the previous approach with an individual perspective as each DT encompasses a digital representation and mechanisms for storing, monitoring, and analysing data from a single conveyor. In this configuration, it is also necessary to consider the mechanism for exchanging information between the DTs, represented by the interoperability component in the architecture, enabling each DT to be aware of the operation of its associated assets and the general information about the other assets involved in the process. The DTs of each conveyor communicate via MQTT protocol and exchange messages about their position in the sequence, the motor's operating time, the number of pieces transported, and the alert if an overtime to transport the piece is detected.

3.2 Analysis of Experimental Results

Both implemented configurations allow the analysis of the main advantages and challenges identified by using one DT for the entire system or one DT for each asset. Regarding the DT development, the first point that can be discussed is the design of the digital representation. The development considering the entire system is more complex and lacks flexibility since the data from all the conveyors and their correlations need to be represented within a single model, which affects the synchronization of this model with its physical object and increases the challenge of having a model that accurately represents all aspects of the system. Developing a DT for each conveyor simplifies the digital representation and allows for more details about their individuality since it does not need to focus on the correlations involved in the process.

Furthermore, the model designed for one conveyor can be reused and replicated for the others as they are similar assets, making the development even easier and adding scalability and flexibility to the solution. The system reconfigurability is better exploited with the decentralised approach, allowing, e.g., an easier management of the DT if a conveyor needs maintenance or removal, which can also be removed without affecting the dynamics of the system.

Regarding the DT functionalities, the analytics services differ in both approaches, in the centralised approach, the parameters are analysed in the same application, enabling a global view of the system operation. In the decentralised approach, the analysis is performed individually, which affects the degree of myopia since the DT only knows what is happening with its respective module. In this case, the interoperability between DTs becomes a key aspect since

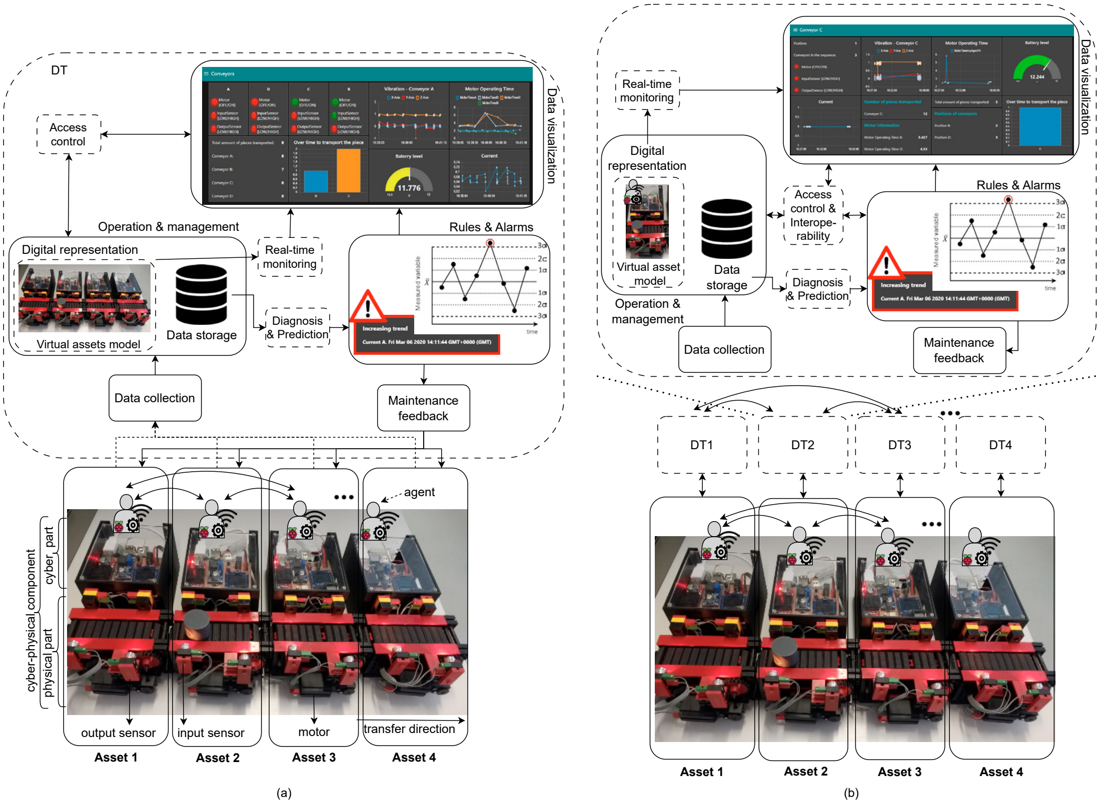

Fig. 2. Digital Twin for monitoring the operating conditions of a conveyor transfer system considering the centralised (a) and the decentralised (b) configurations.

it is essential to communicate and exchange information about data analysis and process monitoring in the overall process. In this scenario, the DTs receive the alerts triggered by the others, allowing a self-analyse whether they have the same problem or if it was an individual detection. In this sense, the centralised approach allows a dynamic view of the system, while the individual models need to receive information from the others to obtain a view of the whole process. While in the centralised approach all messages arrive directly, in the decentralised approach, each DT needs to know the information relating to its associated conveyor and then transmit it to the others.

The data processing is influenced by the approach, as in the centralised approach, the diagnosis and prediction analyses are performed in the same place for all conveyors, requiring more time and computing power than in the decentralised approach, in which each DT analyses the data from a single conveyor. This factor can have a major impact on more complex applications.

4. DISCUSSION

This section explores the main factors that might influence the different DT configurations, outlining their advantages, alongside with an overview of the main technologies supporting the DT distribution and related challenges.

4.1 Main Aspects of DTs Structures

Considering the lessons learned from the works available in the literature and the results obtained with the implementation of centralised and decentralised approaches for the proposed case study, it is possible to evaluate the DT structures according to aspects that most influence their choice based on the value they can add to the proposed solutions, as listed in Table 1.

In centralised approaches of DT, the granularity of individual asset components is reduced since the digital model must encompass the entire system. In contrast, decentralised approaches allow to focus on the details as each asset is represented individually in the digital model. For the same reason, the digital representation in centralised structures is more complex as it should encompass the correlations linked to the interconnections of the assets related to the overall system functioning and should have a high level of abstraction, representing the essential interactions and functionalities. In decentralised structures, it is simplified, presents a higher level of detail, is flexible, and can be replicated for similar assets. In terms of the digital model complexity, the centralised structure is mainly based on the data collected from the assets and the functionalities provided by DT. The decentralised structure needs to aggregate the interoperability capacity and requires the development of collaboration models for the information exchange, increasing the complexity level.

In terms of scalability and reconfigurability, in centralised structures, changes made at the asset level, e.g. adding, removing, replacing or changing the order in which they are interrelated in a process, require adjustments to the current model. Decentralised models are modular and flexible to these changes since they are independent models, but the need for coordination between these models must be considered. Furthermore, while decentralised models

Table 1. Main aspects of DTs structures.

Key aspects	**Centralised**	**Decentralised**
Granularity	- Lower level as the model represents the whole	- Higher level in terms of asset components
Digital representation	- Complex and focused on the interconnections between the assets	- Simplified - Higher level of detail of the assets - Flexible, allowing replicas for similar assets
Model design/ Complexity	-Based on the collected information from the assets	- Needs interoperability capacity - Definition of collaboration models
Scalability & Reconfigurability	- Requires adjustments to the current model	- Flexible and modular - Needs coordination between the models
Reusability	- The model fits only the current configuration	- The model can be reused by similar assets
Robustness	- Presents a single point of failure	- Increases system resilience - Need synchronisation between Asset-DT and DT-DT
Myopia	- Holistic view of the system	- Individual view - Needs interoperability for the overall view
Data processing & Execution time	- Slower data processing - Complex models can be time-consuming to be analysed and simulated	- Distribution of data to be analysed can reduce the processing time - Needs to consider the time to exchange messages between the DTs
Security	- Enable data privacy - Single point of vulnerabilities	- Higher risk in terms of data privacy

can be reused for similar assets, centralised models are very specific for the current configuration. As for robustness, decentralised structures are more resilient to failures, but it is necessary to ensure synchronisation between Asset-DT and DT-DT to avoid inconsistencies in the decision-making process, while in centralised structures, a single point of failure can affect the entire operation of the system. For the myopia aspect, centralisation offers a system-wide view, while decentralised DTs focus on individual asset functions and are limited by system context.

The data processing time and computational costs are reduced in decentralised systems since the analytics services for the assets are distributed. However, the communication time necessary between the distributed DTs for the decision-making process involving the system as a whole needs to be considered. Also, analysing and simulating complex models in centralised approaches can be time-consuming. The security aspects in centralised structures present a single point of vulnerability in which an attack or failure could cause the entire system to fail. Nevertheless, it guarantees greater data privacy since exchanging information is unnecessary. The same is not observed in decentralised structures since they present distributed information that needs to be exchanged, and there is no single point of failure.

In this sense, both structures bring different advantages and challenges for the DT applications and need to be selected according to the expected efficiency of the solution. Generally, centralised structures are usually suitable for simpler systems with few interconnected assets, static properties, well-defined structure and scenarios where are not expected reconfigurability and scalability. Decentralised structures are ideal for dynamic and complex systems involving a large number of assets and requiring flexibility to adapt to changes. Hybrid structures, e.g., aggregation, although not studied further in the case study, can also be considered, offering an adjustment between the high level of details from the asset and general system perception and giving local autonomy and global supervision.

4.2 Key Technologies Supporting Distribution

Although the selected structure, e.g., centralised or decentralised, significantly influences the choice of specific technologies for their respective developments, some technologies can be considered generically as the basis for the DT development, regardless of the adopted structure. This group can include sensors, supervisory systems, or IoT technologies enabling the asset's data acquisition. Some AI mechanisms, e.g., Machine Learning algorithms or other data analysis techniques, can be deployed to enable the decision-support process. Simulation can be experiment scenarios, e.g., considering hypothetical situations (what-if scenarios). For data processing, cloud-based, edge-based, or a hybrid solution can be selected according to the specific needs of the applications and services.

However, when considering decentralised structures, it is necessary to provide the needed infrastructure to ensure the interoperability of the different components. In this scenario, IoT technologies (including their associated communication and protocols) can be considered tools for the collection of data and transmission of commands to assets and for providing information exchange between the various DTs involved in the system. Some IoT platforms, e.g., Azure DT, AWS IoT TwinMaker and Siemens MindSphere, can be highlighted in this regard, facilitating the data management between Asset-DT and DT-DT. The deployment of MAS within this type of structure promotes the necessary infrastructure for collaboration among DT models by leveraging their features that facilitate agent interaction (Reinpold et al., 2024). Microservice structures can be explored to encapsulate the DT functionalities, ensuring compatibility between the provided services.

4.3 Main Challenges of Distributing DTs

One of the biggest challenges related to DT distribution is ensuring the interoperability between the different models that need to communicate and exchange information. Standardising the data exchange, for instance, improves comprehension across multiple components. The Asset Administration Shell (AAS) (Plattform-I4.0, 2022) fulfils this requirement, acting as a standardised communication interface for linking physical assets to their digital representation regarding the Asset-DT interaction. Extending to the DT-DT interaction, the DT should be developed following standards or reference architectures, such as ISO 23247 or RAMI 4.0 (DIN-91345, 2016), to ensure terminology consistency and information sharing across the system.

Another aspect that should be considered is the design of high-fidelity models for the digital representation of the assets for the DT. The model's accuracy ensures synchronisation between the asset and the DT, consequently enabling synchronisation among the DTs. This aspect has a direct impact on the decision-making capacity of the DT system, as each DT requires precise and consistent information to make autonomous decisions that contribute to improving the system's performance. The complexity of the interaction between different DTs must also be considered, requiring the development of coordinating strategies and defining communication models between the DTs, contributing to the collaborative decision-making process.

Security mechanisms should also be implemented in this development, for example, in terms of authentication and authorisation, to guarantee data integrity and privacy and manage information access. Blockchain technology is emerging as a viable option, offering a secure method for recording data exchanges between different DTs while maintaining data integrity and traceability.

5. CONCLUSION

This work discussed the relationships between Asset-DT and DT-DT, analysing the different structure configurations that a DT architecture can assume according to its iteration level with the asset and with other DTs. In this sense, centralised, hierarchical and decentralised structures were assessed in terms of the main advantages and challenges offered. A case study based on a modular conveyor transfer system was used, allowing an in-depth analysis of centralised and decentralised DT configurations, with the first considering a unique DT for the entire system and the second considering a DT for each asset, highlighting the main experimental results in terms of the values aggregated to the DTs functionalities. From this analysis, it was possible to identify some of the main aspects that influence the decision on selecting DT structures, being granularity, model complexity, scalability, reconfigurability, reusability, myopia, execution time, data processing and security. To conclude, the key technologies and the main challenges of distributing DT were discussed. Future work includes the design principles to specify DT structures considering the life-cycle perspective.

ACKNOWLEDGEMENTS

This work was partially supported by the HORIZON-CL4-2021-TWIN-TRANSITION-01 openZDM project under Grant Agreement No. 101058673. This work was supported by national funds through FCT/MCTES (PIDDAC): CeDRI, UIDB/05757/2020 (DOI: 10.54499/UIDB/05757/2020) and UIDP/05757/2020 (DOI: 10.54499/UIDP/05757/2020); and SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/P/0007/2020). Victória Melo and Flávia Pires thank FCT for the PhD Grant 2022.13868.BD and SFRH/BD/143243/2019.

REFERENCES

Capgemini Research Institute (2022). Digital twins: Adding intelligence to the real world.

Cohen, Y., Pilati, F., and Faccio, M. (2021). Digitization of assembly line for complex products – the digital nursery of workpiece digital twins. 54(1), 158–162. 17th IFAC Symposium INCOM.

Dietz, M. and Pernul, G. (2020). Digital twin: Empowering enterprises towards a system-of-systems approach. *Business and Inf. Syst. Eng.*, 62, 179–184.

DIN-91345 (2016). DIN SPEC 91345: Reference Architecture Model Industrie 4.0 (RAMI4.0). *Deutsches Institut für Normung (DIN).*

Grand View Research (2023). Digital twin market size, share trends analysis report by solution (component, process), by deployment (cloud, on-premise), by enterprise size, by application, by end-use, by region, and segment forecasts, 2023 - 2030.

Human, C., Basson, A., and Kruger, K. (2023). A design framework for a system of digital twins and services. *Computers in Industry*, 144, 103796.

ISO 23247 (2021). Automation systems and integration - Digital twin framework for manufacturing.

Panetta, K. (2018). Gartner Top 10 Strategic Technology Trends for 2019.

Pires, F., Melo, V., Almeida, J., and Leitão, P. (2020). Digital twin experiments focusing virtualisation, connectivity and real-time monitoring. In *IEEE ICPS*, volume 1, 309–314.

Plattform-I4.0 (2022). Details of the Asset Administration Shell Part 1 - The exchange of information between partners in the value chain of Industrie 4.0.

Redelinghuys, A.J.H., Kruger, K., and Basson, A. (2020). A six-layer architecture for digital twins with aggregation. In *Service Oriented, Holonic and Multi-agent Manuf. Syst. for Industry of the Future*, 171–182. Springer International Publishing, Cham.

Reinpold, L.M., Wagner, L.P., Gehlhoff, F., Ramonat, M., Kilthau, M., Gill, M.S., Reif, J.T., Henkel, V., Scholz, L., and Fay, A. (2024). Systematic comparison of software agents and digital twins: differences, similarities, and synergies in industrial production. *J. of Intell. Manuf.*

Sakurada, L., Prieta, F.D.L., and Leitao, P. (2023). A methodology for integrating asset administration shells and multi-agent systems. In *IEEE 32nd ISIE.*

San, O., Pawar, S., and Rasheed, A. (2023). Decentralized digital twins of complex dynamical systems.

Shao, G. (2021). Use Case Scenarios for Digital Twin Implementation Based on ISO 23247.

Singh, M., Fuenmayor, E., Hinchy, E.P., Qiao, Y., Murray, N., and Devine, D. (2021). Digital twin: Origin to future. *Appl. Syst. Innov.*, 4(2).

Villalonga, A., Negri, E., Biscardo, G., Castano, F., Haber, R.E., Fumagalli, L., and Macchi, M. (2021). A decision-making framework for dynamic scheduling of cyber-physical production systems based on digital twins. *Annu. Rev. in Control*, 51, 357–373.

Wang, Y., Su, Z., Guo, S., Dai, M., Luan, T.H., and Liu, Y. (2023). A survey on digital twins: Architecture, enabling technologies, security and privacy, and future prospects. *IEEE Internet of Things J.*, 10(17), 14965–14987.

Woods, D. (2018). Why Digital Twins Should Be The CEO's Best Friend.

Zhong, R.Y., Xu, X., Klotz, E., and Newman, S.T. (2017). Intelligent manufacturing in the context of industry 4.0: A review. *Eng.*, 3(5), 616–630.