A New Digital Twin Paradigm: Definition, Framework, and Proposed Architecture

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Abstract: In this paper, the concept of Digital Twins is addressed in the context of Industry 4.0, highlighting its definition, functional components, scope of application, proposed framework, and architecture. A definition is proposed that emphasizes the precise replication of physical reality and the ability to adapt to changes and incoming data. The proposed framework and architecture provide guidance for the effective implementation of Digital Twins, emphasizing the importance of data management and versatile infrastructure. In summary, Digital Twins represent a transformative technology with the potential to improve operational efficiency, drive innovation, and realize the vision of Industry 4.0. Their evolution will continue to require additional research and practical applications to unlock their full potential across various industrial and commercial sectors.

1 INTRODUCTION

The advent of Industry 4.0 implies a marked inclination towards the full automation of manufacturing processes. This trend is supported by the integration of cyber-physical systems, driven by cloud computing and connectivity provided by the Internet of Things (IoT) (Joyanes Aguilar, 2019). The term Digital Twin is closely linked to Industry 4.0. These digital twins create an accurate virtual representation of a physical entity, where its behavior is simulated using data. They are characterized by their real-time synchronization capability, faithful reproduction, and high fidelity through feedback mechanisms between the real and virtual worlds, data fusion analysis, and optimization of iterative decision-making. Their purpose is to foster interaction and integration between the physical world and the world of information, as well as to expand the capabilities of the physical entity (Li, Lei, & Mao, 2022). The Digital Twin provides a digital representation of the physical product. The digital representation is constructed based on the information gathered from various sources (C. S. Durão, Zancul, & Schützer, 2024).

Although the concept of "digital twin" originated in the 1970s, its current popularization is attributed to a presentation by Michael Grieves in 2002. In this presentation, Grieves addressed how the creation of a virtual model of a product could have a significant impact on the management of the product lifecycle (Li, Lei, & Mao, 2022). The application of digital twin technology has expanded into the architectural, engineering, and construction (AEC) field, and numerous studies have been actively conducted over the past decade. However, existing studies are more focused on establishing the framework and possibilities of digital twins, and on proposing specific architectures for certain use cases, making these approaches difficult to generalize (Wook Kang & Mo, 2024).

Various methodologies are employed in the development of a Digital Twin, and each phase of its creation presents different levels of complexity. According to Hyre et al. (Hyre, y otros, 2022), the complexity and capability of the Digital Twin vary depending on the established objectives, categorizing them into four categories, each one more complex than the previous: the representation of the real system, the replication of the real system, the realistic representation of the physical object, and the ability

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to make decisions by integrating elements of artificial intelligence.

In this work, we propose a new definition of Digital Twin that encompasses not only the precise replication of physical reality but also the ability to adapt and evolve as circumstances and available data change. Our approach focuses on flexibility and interoperability, aiming to provide a robust framework that can be applied across a variety of contexts and sectors.

In addition to presenting our definition of Digital Twin, we also outline a proposed framework for its effective implementation. This framework is based on principles of modularity, scalability, and collaboration, with the goal of facilitating the creation and management of complex Digital Twins in dynamic and evolving environments.

Finally, we explore a proposed architecture to support the implementation of Digital Twins across various domains. This architecture is based on a combination of emerging technologies, such as the Internet of Things (IoT), machine learning, and cloud computing, and is designed to provide the necessary infrastructure for collecting, storing, and analyzing data in real-time, as well as for visualizing and simulating virtual environments accurately.

2 APPLICATION SCOPE

The Digital Twins, although emerging, represent a promising innovation in today's technological landscape. While the concept can be traced back to the 1970s, their widespread adoption and practical application in various fields are relatively recent. The rapid evolution of technology in areas such as cloud computing, the Internet of Things (IoT), and artificial intelligence has propelled the development and expansion of Digital Twins, making them an increasingly relevant and powerful tool for enhancing efficiency, productivity, and decision-making across a wide range of industries and sectors.

So far, a formal or widely accepted definition, as well as a unified process for the creation and implementation of the Digital Twin, have not been achieved. Different industries and application fields present diverse perspectives and approaches. A thorough review reveals that the Digital Twin is progressively leaving its initial phase and moving towards a stage of rapid development, where researchers are beginning to explore real industry practices and technologies. Although the original vision of fully understanding and reflecting every aspect of the physical twin is still far from being fully realized, the application fields of the Digital Twin demonstrate great vitality (Liu, Fang, Dong, & Xu, 2021).

This article is part of the doctoral thesis titled "Methodological Proposal for Improving Production and Service Systems in the Waste Industry through the Use of a Digital Twin. Application in High-Population Density Areas. In this study, an updated definition of Digital Twins is presented, which encompasses not only the precise replication of physical reality but also the ability to adapt and evolve dynamically in response to changes in the environment. Furthermore, a proposed conceptual framework and architecture are described to support its effective implementation, with emphasis on modularity, scalability, and integration with emerging technologies such as the Internet of Things (IoT) and cloud computing. These functional components lay the necessary groundwork for fully understanding and harnessing the potential of Digital Twins in improving production and service systems.

3 FUNCTIONAL COMPONENTS OF DIGITAL TWINS

In the Functional Components section of Digital Twins, we will delve into a proposed definition of these innovative systems, as well as the conceptual framework and architecture designed to support their effective implementation. Firstly, we will introduce an definition of Digital Twins, which encompasses not only the precise replication of physical entities in virtual environments but also their ability to adapt and evolve dynamically in response to changes in the environment. Subsequently, we will examine the proposed framework, which provides a structured guide for the design and implementation of Digital Twins in various industrial and service contexts. Finally, we will explore in detail the architecture designed to support the functionality and operability of Digital Twins, emphasizing their modularity, scalability, and integration capabilities with emerging technologies such as the Internet of Things (IoT) and cloud computing. These functional components provide the necessary foundation for fully understanding and harnessing the potential of Digital Twins in improving production and service systems.

3.1 Proposed Definition

In the realm of Digital Twins, they have been proposed as a practical option for real-time interaction. Based on this, some general characteristics have been established (Ogunsakin, Mehandjiev, & Marin, 2023).

- Digital Twins must accurately represent both the structure and the state of their physical system, and data transfer must occur in real-time with said physical system (Ogunsakin, Mehandjiev, & Marin, 2023).
- Digital Twins should enhance designs and processes of the physical system even when the physical system undergoes changes (online or in real-time) (Ogunsakin, Mehandjiev, & Marin, 2023).
- Since physical systems are dynamic and changing over time, the Digital Twins representing them must also be able to change their states in real-time (Singh, y otros, 2021).
- A Digital Twin evolves alongside its physical counterpart throughout its lifecycle. Any changes in either twin, whether physical or digital, are reflected in the other, creating a closed feedback loop. A Digital Twin must be self-adaptive and self-optimizing with the help of data collected by its physical twin in real-time, thus maturing along with its physical counterpart throughout its entire lifespan (Singh, y otros, 2021).
- The Digital Twin, being a virtual replica of its physical counterpart, needs to incorporate the properties of the latter across multiple scales or levels. This means that the virtual model of the Digital Twin is based on both the macroscopic and microscopic geometric properties of the physical twin, as well as its physical properties such as structural dynamics models, thermodynamics, stress analysis, fatigue damage, and material properties, including stiffness, strength, hardness, and fatigue resistance, among others. Therefore, the Digital Twin is multi-physical, as it considers both the geometric and physical properties of the physical twin (Singh, y otros, 2021).
- Industry 4.0 encompasses various areas of knowledge, and the Digital Twin is essential for its operation as it integrates disciplines such as computer science, information technology, communications, mechanical engineering, electrical engineering, electronics, mechatronics, automation, industrial engineering, and systems integration physics, among others (Singh, y otros, 2021).

Given the characteristics of Digital Twins, we propose a conceptualization that encompasses their ability to dynamically and in real-time represent physical systems, integrating multidisciplinary data and models to accurately reflect both the structure and behavior of their physical counterparts. This approach would allow for the synchronous evolution of Digital Twins with their associated physical systems, facilitating continuous adaptation and optimization in response to changes and events in the real environment. Furthermore, Digital Twins would provide a platform for simulation, analysis, and prediction of operational scenarios, significantly contributing to improving efficiency, productivity, and quality across a wide range of industrial and commercial applications.

A Digital Twin is an active representation technique of a real system with continuous feedback, which, using tools such as autonomous learning, Data Mining, and sensors among other integrated tools in Industry 4.0, generates active and predictive information of systems in the virtual space. Depending on the level of implementation and the objectives set in its creation, the Digital Twin can be used as a tool for short, medium, and long-term decision-making, as an evaluation and training tool, or as a key tool for improving production systems. Figure 1 shows a proposed schematic definition of Digital Twins.

The development of a Digital Twin must be planned following some key concepts and practices of project management. Just like in discrete event simulation, Digital Twins should not be applied indiscriminately, but rather a decision should be made based on considerations about the system under study and the relevance of the problem to be solved with this tool.

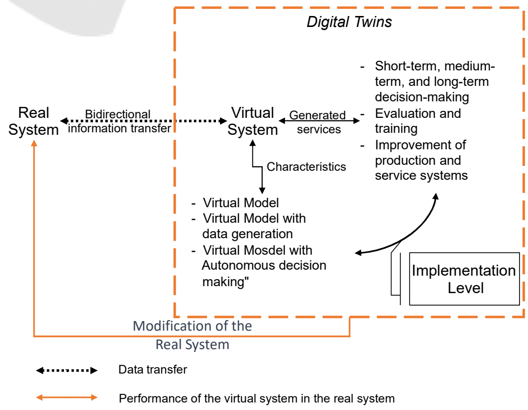

Figure 1: Proposed Definition of Digital Twin.

Given the preceding discussion, it becomes apparent that every real-world system has the potential to be mirrored in the virtual realm, facilitated by unidirectional data transfer in its primary stage or bidirectional communication in its more sophisticated form. In this context, the virtual counterpart, or Digital Twin, encompasses a spectrum of characteristics and functionalities tailored to the level of implementation, ranging from a rudimentary virtual replica to an intelligent decision-making entity driven by the constant generation and acquisition of data. The depth of implementation is intricately tied to the predefined objectives established during the methodological deployment of the Digital Twin.

In broad terms, the primary objectives of implementing a Digital Twin could be to obtain a resource that facilitates: (1) enhanced real-time remote control, maintenance, and optimization; (2) heightened safety concerning both material and human factors; (3) enhanced understanding and awareness of dynamic processes (Føre, y otros, 2024).

At an advanced stage of Digital Twin evolution, it gains the capability to actively influence and adapt the behavior of the real-world system, thus fostering a feedback loop of predictive analytics and continuous enhancement for the systems under study. The extent to which this influence is exerted, and the effectiveness of the feedback loop are contingent upon both the level of implementation and the specific objectives delineated for the Digital Twin's development.

3.2 Proposed Architecture

Arise during the interaction between the physical twin and its virtual counterpart, it is imperative to establish a series of mechanisms that facilitate the efficient management of this data. The inherent complexity of this interaction demands a robust and versatile architecture capable of encompassing a wide variety of tools, processes, models, and mechanisms. In this regard, the proposed architecture stands as a dynamic and adaptable framework responsible for orchestrating all these elements to effectively carry out the task of data management. Its comprehensive design aims not only to optimize the collection, storage, and processing of information but also to ensure its integrity, security, and availability always. This holistic approach to data management within the framework of digital twins is essential to ensure their effective operation and their ability to support informed decision-making processes in various industrial and commercial contexts.

The proposed architecture consists of three fundamental layers: one dedicated to the physical environment, another to the virtual environment, and a third layer for communication and data transfer. Both the layer of the physical environment and the layer of the virtual environment have structural and functional elements that describe the process, collect data, and act based on the data processed and collected by the communication layer. These elements can be defined as follows:

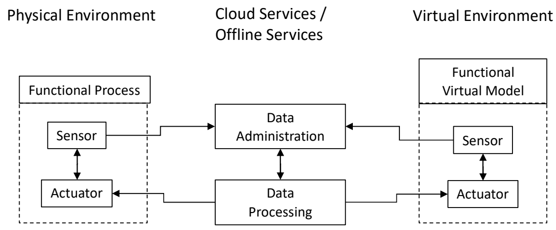

Figure 2: Proposed Architecture

3.2.1 The Physical Environment

In the context of the Digital Twin, the functional process refers to the system under study that will have its digital counterpart, with clearly defined boundaries. This process should incorporate sensors and actuators according to the desired level of application and automation, with these aspects established in the implementation objectives. Sensors are information-capturing devices that detect changes in the system and generate data related to these changes. On the other hand, actuators are devices responsible for executing predefined actions in a process in response to the information captured by the sensors.

3.2.2 Cloud Services/Offline Services

Data management encompasses the collection, maintenance, and secure, efficient, and cost-effective use of data. Authors such as Munappy define data management as a process that includes data collection, analysis, validation, protection, and monitoring to ensure data consistency, accuracy, and reliability (Munappy, Bosch, Olsson, Arpteg, & Brinne, 2022). On the other hand, data processing and analysis refer to the transformation of data into knowledge (value), aiming for these processes to occur within a reasonable timeframe. This can be achieved through batch processing, where data is collected over a specified time interval and transformations are executed as scheduled, or through real-time processing, which involves executing transformations as data is collected.

3.2.3 The Virtual Environment

In the context of Digital Twins, the virtual environment consists of several key components. Firstly, the functional virtual model, analogous to the functional process described in the physical environment, possesses identical functional and operational characteristics but exists within the virtual space. Additionally, virtual sensors, mirroring their counterparts in the physical space, perform the same function of data capture but within the virtual environment. Similarly, virtual actuators, akin to physical actuators, operate within virtual environments, executing actions based on the data received. These components collectively form an essential part of the digital replication process, enabling real-time monitoring, analysis, and simulation in virtual settings.

3.3 Proposed Framework

This text presents a framework designed to address a specific issue in the application of Digital Twins. This conceptual framework is based on a combination of existing theories and practices, highlighting specific needs in the implementation of digital twins for improving production and service systems. The aim of this framework is to provide a solid and coherent structure for understanding and solving the problem effectively and sustainably. Throughout this text, the key components of the framework are described, along with how they interact to achieve its goal. Figure 3 illustrates the framework, which is described below.

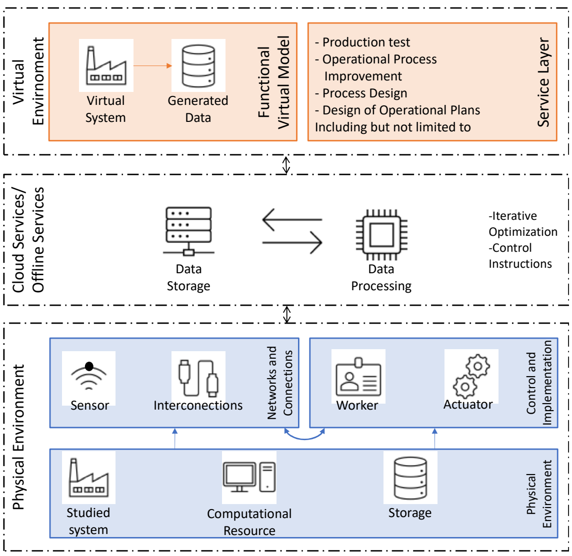

Figure 3: Proposed framework.

The proposed framework is based on the architecture described earlier, which addresses three layers: the physical environment layer, the cloud services layer based on information technologies, and the virtual environment layer. These layers and their elements are described below.

In this area, It is noteworthy that the ISO organization (International Standard Organization, 2021) formulates the document ISO 23247-2:2021, which establishes a reference framework for the use of digital twins in the field of manufacturing. This framework provides reference models from a domain and entity perspective, as well as a functional view of digital twins in manufacturing.

3.3.1 The Physical Environment

The physical environment of the system under study is divided into three interconnected layers to facilitate the flow of information: the physical environment layer, the networks and connections layer, and the control and execution sublayer. The physical environment layer, the first one, houses the system under study and relevant physical resources, as well as the computational systems necessary for data analysis and storage. The networks and connections sublayer includes sensors for data capture, such as temperature, pressure, and light sensors, converting these measurements into electrical or digital signals. Additionally, it encompasses data transfer connections, both wired and wireless. The control and execution sublayer are responsible for acting upon the information processed by the Digital Twin, using mechanical actuators and operators. The mechanical actuators automatically perform actions based on the received information, while operators act according to an operation plan generated by the Digital Twin.

3.3.2 Cloud Services/Offline Services

This layer hosts intelligent data storage and processing services, serving as the direct communication interface between the physical environment and the virtual environment. It houses data obtained from the physical model, as well as data from the virtual model resulting from information analysis and processing. This layer acts as the direct link, and a well-structured one ensures fast bidirectional transfer of information.

3.3.3 The Virtual Environment

The virtual layer is fundamental in the development and implementation of Digital Twins, as it hosts the virtual replica of the real physical system, known as the functional virtual model. Here, the services that the Digital Twin can provide are designed and executed, ranging from production tests to process design and improvement, as well as operational planning. This layer is formed through the continuous collection and analysis of real-world data, which are used to build a virtual model that emulates the behavior and characteristics of the corresponding physical system. Additionally, it allows the simulation of various scenarios and conditions to evaluate the performance and efficiency of the system in different situations, as well as to test new design strategies and techniques before implementing them in the real world.

This virtual layer is dynamic and constantly updated with the latest real-world data, allowing the Digital Twin to accurately reflect changes in the physical system in real time. The services offered by the Digital Twin are diverse and range from data analysis and simulation to assess process performance and efficiency, to predictive maintenance to anticipate failures and avoid downtime. They also include performance optimization to improve resource utilization and energy efficiency, as well as personnel training to enhance their skills and knowledge. Additionally, the integration of systems into a single platform allows for better coordination and control of production processes, improving efficiency and reducing errors. In summary, the virtual layer is essential for the effective operation of Digital Twins, facilitating constant interaction between the physical and virtual environments and enabling an iterative optimization process based on control instructions from the virtual system to the real system.

4 CONCLUSIONS

In this paper, we have explored the concept of Digital Twins within the context of Industry 4.0, providing insights into their definition, functional components, application scope, proposed framework, and architecture. Drawing upon existing literature and theoretical frameworks, we have proposed a comprehensive understanding of Digital Twins as dynamic and adaptable entities that bridge the physical and virtual realms, offering real-time representation, analysis, and optimization of complex systems.

Our proposed definition of Digital Twins emphasizes not only the accurate replication of physical reality but also their capacity to adapt and evolve in response to changing circumstances and data inputs. We have outlined key characteristics that define Digital Twins, including real-time synchronization, continuous feedback mechanisms, multidisciplinary integration, and self-adaptation throughout the lifecycle.

Furthermore, our proposed framework and architecture provide structured guidance for the effective implementation and operation of Digital Twins across various domains. The framework delineates the interconnected layers of the physical environment, cloud services, and virtual environment, highlighting the essential components and interactions necessary for seamless data flow and decision-making.

Through the proposed architecture, we have emphasized the importance of robust data management mechanisms and versatile infrastructure to support the functionalities of Digital Twins. By incorporating elements such as sensors, actuators, cloud services, and virtual models, our architecture enables real-time monitoring, analysis, and simulation, fostering informed decision-making and continuous optimization of systems.

In conclusion, Digital Twins represent a transformative technology with far-reaching implications for diverse industries and sectors. By leveraging real-time data integration, multidisciplinary modelling, and adaptive algorithms, Digital Twins have the potential to revolutionize production processes, enhance operational efficiency, and drive innovation in product development and service delivery. As the field of Digital Twins continues to evolve, further research and practical applications will be essential to unlock their full potential and realize the vision of Industry 4.0.

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