Digital Twins in Industry 4.0: A Literature Review

Hanan Amthiou[1*], *Mounir* Arioua[1], and *Tajjedine* Benbarrad[1]

[1]National School of Applied Sciences, Laboratory of Information and Communication Technologies (LabTIC), Tangier, Morocco

Abstract. Digital Twin is one of the most promising fields in Industry 4.0 due to its advantages related to real-time monitoring, performance analysis, and predictive maintenance. It is a virtual up-to-date representation of a real-world asset, system, being, and even city that is updated in real-time with data from its physical counterpart. By bridging the physical and digital, it is considered to be the innovation backbone of the future. In this contribution, we review the concept of digital twins, the development of its uses in industrial applications, and the level of integration in scientific work.

1 Introduction

There is no doubt that industrial revolutions have had a massive impact on every aspect of our life. On a large scale, it improved the standard of living and contributed to deep economic and social change. Beginning from 1765 through the present day, we have perceived four industrial revolutions: From coal, gas, electronics, and nuclear to artificial intelligence, processes became mechanized and manufacturing became smarter and faster. There is no doubt that industrial revolutions have had a massive impact on every aspect of our life. On a large scale, it improved the standard of living and contributed to deep economic and social change. Beginning from 1765 through the present day, we have perceived four industrial revolutions: From coal, gas, electronics, and nuclear to artificial intelligence, processes became mechanized and manufacturing became smarter and faster.

The world has recognized the importance of adopting Industry 4.0, digital has become essential for companies wishing to meet the ever-increasing needs of tomorrow and remain competitive in the future world. With advanced automation, monitoring, and real-time communications, the impact of Industry 4.0 on manufacturing drives unprecedented advances in quality, reliability, and agility.

Recently, this new paradigm has been the subject of several scientific contributions; cyber-physical systems and technologies like the Industrial Internet of Things, data mining, and cloud computing offer the potential to transform industrial fields from the factory floor to logistics. Nevertheless, current industrial practices based on CPS are prone to some limitations that can hinder several desirable objectives. This is due to their heterogeneous nature, complexity, and process of implementation.

This paper provides a systematic review that discusses the concept of the Digital Twin in the context of production science, an overview of the key enabling technologies, areas of

* Corresponding author: amthiou.hanan@etu.uae.ac.ma

application, and the general level of integration in scientific work. This review serves as the basis for further work in the field of the Digital Twin in Industry 4.0. It concludes with perspectives.

2 Key Technologies of Digital Twins

2.1 Overview

In an increasingly dynamic world, digital twins are powerful masterminds to significant growth in the coming years and drive innovation and performance in various industries like manufacturing, automotive industries, energy, agriculture, and healthcare [1, 2].

Significant market growth is expected in the coming years in the digital Twin market; It will help companies improve the customer experience by better understanding customer needs, enhancing existing products and services, and driving the innovation of new business opportunities. Digital twin technology seems to be a perfect solution that helps companies in realizing Industry 4.0 standards.

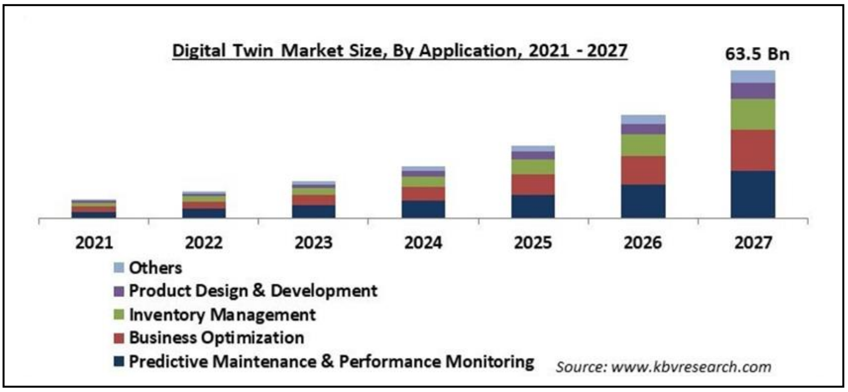

Fig. 1. Digital twins market growth [3].

The economic value of the digital twin technology will vary widely, depending on the monetization models that drive them. For complex and expensive industrial businesses, improving utilization by reducing asset downtime and lowering overall maintenance costs will be extremely valuable, making internal software competencies critical to driving value with digital twins.

2.2 Enabling Technologies for digital twins

Digital twin technology uses a variety of enabling technologies to support different modules of DT: The asset and its physical environment, the virtual representation of the asset, and the communication channel between the physical and virtual representations [4].

For the physical entity (PE), it is essential to exploit abstract knowledge and understanding of the physical world. Digital Twins involves a prerequisite knowledge of mechanics, electromagnetism, materials science, etc. Combined with the Industrial Internet of Things IIOT, smart sensing, and intelligent perception systems that take multi-source signals as inputs and deliver more reliable results with the aid of information fusion and adaptive learning [5, 6] make the models more accurate and closer to reality.

For the virtual model (VE) that exhibits similar behavior to its physical counterpart, various modeling technologies are essential it uses machine-learning algorithms to process the large quantities of data collected by sensors and identify the patterns. Artificial intelligence and machine learning provide data insights about optimization, maintenance, and efficiency.

Data is the key to the development and application of digital twin technology. The implementation of digital twins will introduce large computational loads. Thus, cloud computing and big data technologies are suitable solution is to improve the operational performance of data [7].

3 Digital Twins in Industry 4.0

3.1 Implementation of Digital Twins

The first stage of the process of implementing a digital twin includes analyzing the practical needs to make long-term strategic reform plans and modeling the static properties of the asset to determine the system requirements and constraints, functionalities, and behaviors, including the functional decomposition. Model data flow and communication are also considered, as the logical structure, architecture of the asset, and the technical requirements to implement the solution, including physical and software parts.

The second stage focuses on the system specifications and the targets of the design. The VE is meant to be designed as a mirror of the PE. Therefore, a high level of modeling precision is required to design the DT. In the same cases, synchronization delay and measurement error are not tolerable.

The third stage establishes the appropriate modeling techniques to meet the practical need. In terms of the geometry features, the use of mechanical drawing software for digitalization is recommended. In terms of the physical characteristics, they are described by using first principle knowledge, system identification, and data-driven modeling.

3.2 Industrial Applications of Digital Twins

The development of digital twins started in the Aerospace Industry. However, manufacturing is exploring the technology the most. Digital twins are the key enablers of Industry 4.0 and Smart Manufacturing.

In the process of manufacturing, products go through four main phases: design, manufacture, operation, and disposal. The intervention of smart twins is possible in all four phases of the product [8].

In the first phase, Digital twins offer the possibility to verify design virtually, enabling them to test different product versions and choose the best one. Using real-time data from the products of previous generations, designers get an insight into the features that are working best for the consumers and those which need improvements. This makes the process of improving the design easier, more efficient, and faster.

During the second step, the raw materials are turned into the final product. Digital twins can ensure management, production planning, and process control by planning, executing the orders automatically, and improving decision support through a detailed diagnosis, maintenance by evaluating and analyzing machine conditions, identifying any changes in the production system and its effects, and taking reactive maintenance [9] by predicting failure and remaining useful life (RUL), and thus identify and apply the required maintenance to avoid possible breakdowns.

The final phase of the product can be managed by digital twin technologies also by trucking the real-time product operation state via its DT and developing a maintenance strategy accordingly, which can improve the next generation product.

4 Integration in scientific work

4.1 Methodology

This article emphasizes the review of digital twin integration in Industry 4.0, by highlighting the current state-of-art in scientific work.

A systematic literature review was conducted to analyze the current use of Digital Twins in manufacturing processes. As suggested by the guideline for systematic literature review [10]. First, databases were chosen to capture the wide range of digital twin applications. Here, we searched three multidisciplinary bibliographic databases, including Scopus (ScienceDirect, Elsevier), Web of Science, and SpringerLink. The search was limited to the subject areas of engineering and computer science. To elaborate on the current developments on this topic, the timeframe was limited to the years 2019 to 2023.

The term Digital Twin in Industry 4.0 resulted in 1918 hits. When further duplicate and no full text available were excluded, 773 were found.

After identifying relevant and qualitative papers, a broad search strategy was used to obtain a comprehensive data set for the analysis in this research, limiting the search to only the two focus areas of digital twins and Industry 4.0. To fulfill the overall aim of this paper, a screening title and abstract were adopted to assess for illegibility. Irrelevant, duplicated topics and in-progress research were excluded at this step. As displayed in Fig. 2 below, the PRISMA method was used for the systematic literature review, although the method has been slightly adapted regarding a backward search as suggested in the guideline for reporting systematic reviews [11].

The papers found were analyzed by their content and categorized according to their different perspectives. Firstly, the publications were classified by year of publication to indicate the increasing research interest in this topic. Then concerning their type – if they were case studies, concept papers, or reviews. When a publication could be within more than one category of type, the dominant one was chosen. Furthermore, the focused area as well as the technologies mentioned were derived from the paper's contents.

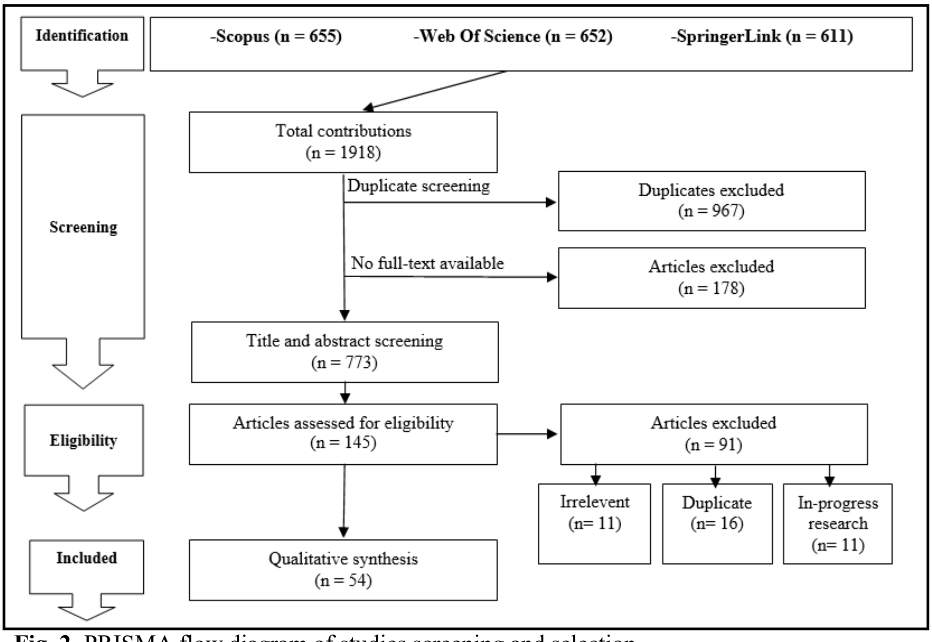

Fig. 2. PRISMA flow diagram of studies screening and selection.

4.2 Evolution of digital twins scientific contributions

There is no doubt that advances in science and technology and their integration into the real world are channelized by scientific research. The Digital twin is one of the research technologies that will affect business interpretation in the future. Although digital twin technology has been practiced since the 1960s by NASA, it gained recognition in 2002 after the presentation of Michael Grieves at the University of Michigan on technology. The number of contributions has started to increase since 2019. Last year, 2516 contributions has been done and great growth is expected this year.

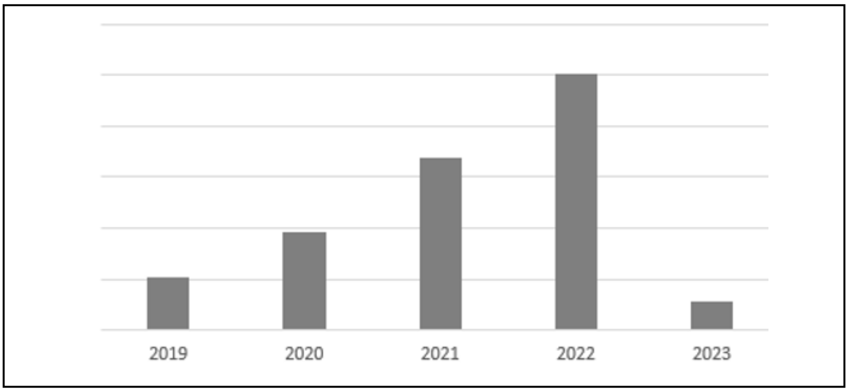

Fig. 3. Publications per year.

4.3 Publications type

As mentioned before, digital twins integration in scientific research is developing increasingly, The majority of the reviewed literature is conference papers and articles as shown in the graphic of Fig. 4.

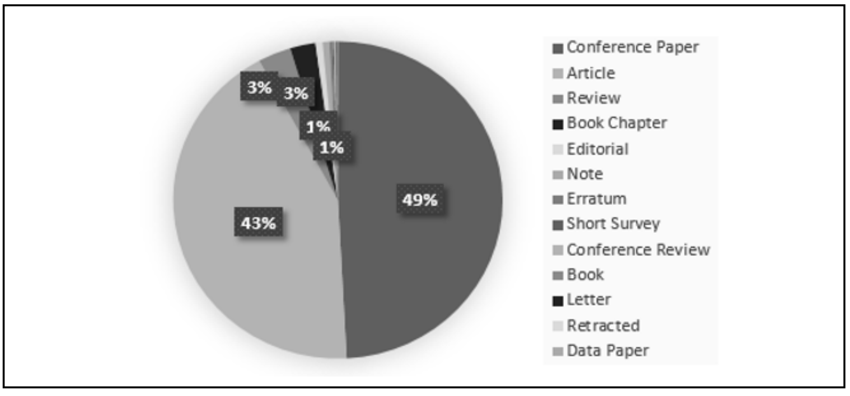

Fig. 4. Classification by publication type.

4.4 Focused area

When it comes to the focused area within the analyzed publications, the majority of them focused on production planning and control, predictive maintenance, and product lifecycle management [12].

Qinglin Qi and Fei Tao [13] reviewed Digital twins in manufacturing, the study includes the concept of DT as well as their applications in product design, production planning, manufacturing, and predictive maintenance. To provide insight into intelligent manufacturing Zhang et. al., [14] propose a data- and knowledge-driven framework for digital twin manufacturing cells which could support autonomous manufacturing by an intelligent perceiving, simulating, understanding, predicting, optimizing, and controlling strategy. Jinsong Bao, Dongsheng Guo, Jie Li, and Jie Zhang [15] propose an approach to modeling and operations for the digital twin in manufacturing. Bazaz et. al., 2019 [16] propose a comprehensive model of a Digital Twin approach for a manufacturing environment and related production processes. Redelinghuys et al. [17] introduced a digital twin architecture capable of exchanging data and information between remote simulations or simulations and the physical twin, which includes a local data layer, an IoT gateway layer, a cloud-based database, and includes simulation.

5 Concluding remarks and perspectives

Digital twins present an opportunity to merge the physical world and digital world and then, help in addressing the challenges faced by Industry 4.0. With the support of digital twin techniques, Industry 4.0 brings a wide range of tasks, covering different economical aspects.

The applications of digital twins for any product can be realized through its lifecycle, from design to disposal, and addressing the challenges faced by Industry 4.0 by remoting monitoring and predictive maintenance. There has been objective progress since the inception of digital twin technology; however, practical applications and implementations of the technology in the Industry remain uncharted territory.

This paper emphasizes the challenges in the industrial practice of today and presents an overview of the economic benefits of adopting the digital twins and their enabling technologies; it will act as the backbone of Industry 4.0.

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