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Investigating Digital Twin: A Systematic Mapping Study

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Abstract. The term digital twin refers to a comprehensive digital representation of a physical system that serves as its real-time digital counterpart. Digital twin goes beyond traditional computer-aided applications and represents a two-way communication bridge between the physical and the digital worlds. In 2020, Gartner identified digital twin as one of the ten technology trends capable of a profound impact on modern society. While digital twin originates from the manufacturing domain, its recent underpinning technology maturation makes it suitable to all those domains where there is a need for studying virtual interactions with the physical environment. Despite its peak of research and adoption, there are still some grey areas related to certain aspects of digital twin such as enabling technologies and reported benefits. In this paper, we report on the planning, execution and results of a systematic mapping study, which aimed at providing a structured and detailed snapshot of the current application of digital twin, enabling technologies, reported benefits and application domains. Starting from an initial set of 675 publications, we identified 26 primary studies, which we have analysed through a rigorous data extraction, analysis and synthesis process. Based on the collected data, we drew relations between digital twin and the production domain.

Keywords. Digital twin, software engineering, systematic mapping study.

1. Introduction

In 2011, a German project focusing on high-tech strategies for the German government used the term Industry 4.0 (I4.0) for promoting manufacturing computerisation [1]. I4.0, also known as the fourth industrial revolution, promoted the idea that machines and devices, production lines and even whole factories should be connected to a computer network for controlling, analysing and tracking them throughout their whole life cycle. In parallel, the paradigms of cyber-physical system (CPSs) [2] and internet of things (IoT) [3] started to get a foothold. The IoT describes a set of interconnected physical objects that exchange data through a computer network. CPS builds on the IoT and connects these physical devices to a virtual cyberspace, which enables their controlling or monitoring. Advances in, e.g., CPS, IoT and artificial intelligence (AI), contributed to the birth of Digital Twin (DT) [4]. DT refers to a comprehensive digital representation of a physical system that serves as its real-time digital counterpart. Digital twin goes beyond traditional computer-aided applications and represents a two-way communication bridge between the physical and the digital worlds. The concept model of DT consists of three parts being the physical object in the real world, the virtual object in the digital world, and the connections between these two objects that provide data flow. In 2019, Gartner identified DT as one of the ten technology trends capable of a profound impact on modern society [5]. While digital twin originates from the manufacturing domain, its recent underpinning technology maturation makes it suitable to all those domains

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where there is a need for studying virtual interactions with the physical environment. Many researches have been conducted to investigate how DT can be applied in different domains and throughout the different life cycle phases [6]. Despite its peak of research and adoption, there are still some grey areas related to certain aspects of digital twin such as enabling technologies and reported benefits.

In this work, we provide a systematic mapping study that identifies, classifies, and evaluates trends, application domains, and enabling technologies in the current literature concerning Digital Twin. We started from an initial set of 675 publications. Through a rigorous selection process we obtained a final set of 29 primary studies. Using a classification framework, we extracted relevant data. We analysed and synthesised the extracted data using both quantitative (vertical) and qualitative (orthogonal) analyses. Eventually, we discuss the implications of our findings for the production domain.

The remainder of this work is organised as follows. In Section 2, we describe background concepts. In Section 3, we discuss the research methodology that we followed for this study along with possible threats to validity and related mitigation techniques. In Section 4, we present the results from the vertical and horizontal analyses. In Section 5, we discuss the main findings of our study. Section 6 presents some related works documented in literature. Eventually, Section 7 concludes the work with final remarks and possible directions for future research.

2. Background

In this section, we describe basic concepts related to DT, its history and applications.

2.1. History and definition of digital twin

The idea of using a digital representation of a physical system dates back to the 1970s when the National Aeronautics and Space Administration (NASA) created two identical space vehicles for mirroring conditions in the space as part of its Apollo program [7]. One space vehicle was left on the earth while the other was sent to orbit. The vehicle on earth mirrored the conditions of the vehicle in space. Besides, it provided means for astronauts training in critical situations. The first academic definition of digital twin appeared many years later in 2014. Grieves defined DT as a virtual representation of (one or more) existing physical object(s), which is created with the purpose to simulate the behaviour of real-world environments [8]. DT is composed by three entities, which are the physical objects in the real world, their digital representations in the virtual space and the data that is used to connect these two spaces. The digital object is used for evaluate, analyse, and optimise the operations of the physical object [9]. Mutual data exchange is pivotal to perform such tasks. Data from the physical world are captured through sensors and sent to the the virtual world for performing simulation and validation. Resulting data are returned to the physical world to, e.g., improve productivity and increase the work efficiency of the physical object.

2.2. Digital model vs digital shadow vs digital twin

When speaking about digital twins, it is crucial to avoid certain misconceptions related to digital models, shadows and twins [10]. Leskovský et al. defined a digital model as a digital version of a physical object built or planned to be built [10]. There is no data exchange between the virtual and physical objects. An essential characteristic is that once the models are built, the changes that occur on the physical model have no impact on the digital model or vice versa. Examples of digital models are blueprints of buildings, roads, and various machines. A digital shadow is a digital representation of a physical object in which the data flows only in one direction [10]. The physical object sends data to the digital one, but not vice versa. Human interventions may be needed for simplifying, processing, etc. the ammount of data sensed from the physical object. When the data travels in both directions, i.e., from the physical to the virtual object and vice versa, we have a digital twin [10]. The objects are fully integrated, which means that changes on one side automatically leads to changes on the other side.

3. Research methodology

We designed and conducted this research following the guidelines by. Petersen et al. on conducting systematic reviews in software engineering [11]. Our research method composed of three main stages being *planning*, *conducting* and *reporting*. In the planning phase, we identified the needs for this systematic mapping study, defined the research goal and related questions, and defined the protocol to be followed. The main outcome of this phase is a review protocol. In the conducting phase, we performed all the steps defined in the protocol, which are *search and selection*, *classification framework*, *data extraction*, and *data analysis*. During the search and selection step, we performed the search on one digital database, applied selection criteria to the obtained primary studies, and performed extensive backward and forward snowballing activities [12]. We used the key-wording method [11] for defining the parameters of the classification framework. The outcome of this phase is the classification framework, which we used for extracting data from the primary studies. During the data extraction step, we extracted the data from the selected primary studies using the classification framework defined in the previous step. In the data synthesis step, we have analysed the extracted data. We performed both quantitative and qualitative analyses using vertical and orthogonal analysis techniques [13]. In the reporting phase, we investigated possible threats to validity. Besides, we surveyed the literature for finding research related to our works. Eventually, we wrote this paper where we report on the design and execution of the mapping study. To support the verification and replication of our study, we provided a complete and public replication package consisting of raw data of search and selection, the complete list of primary studies, and raw data from data extraction at `https://anonymous.4open.science/r/Investigating-Digital-Twin-36C9`

3.1. Research goal and questions

We used the Goal-Question-Metric perspectives [14] for defining the research goal of this study that is to *identify, classify, and evaluate trends, application domains, and enabling technologies in the current literature concerning Digital Twin.* From this research goal, we derived the following Research Questions (RQs):
RQ1: Which are the publication trends with respect to time, venues and research type in DT research?
RQ2: Which are the enabling technologies of DT?
RQ3: Which are the most common application domains of DT?
RQ4: Which are the benefits related to the use of DT? By answering to the first research question, we describe publishing trends concerning the year, venue and research type on DT. By answering to RQ2, we provide a catalogue of the core technologies used for DT such as big data, IoT and augmented reality. By answering the third research question, we analyse the domains where DT has been used. By answering the last research question, we provide a set of benefits related to the use of DT.

3.2. Search and selection process

For this research, we searched the IEEE Xplore digital library[2]. We selected IEEE Xplore digital library for its reputation as being an effective instrument for supporting systematic

[2] `https://ieeexplore.ieee.org/Xplore/home.jsp`

reviews in software engineering [15]. To include as as many studies as possible, we used a simple search string being: *Digital Twin*. During the initial search, we collected 675 primary studies (Figure 1). On this set, we applied the following selection criteria.

- Inclusion Criteria
  1. Papers that discuss an application of DT.
  2. Papers related to technological aspects of DT.
- Exclusion Criteria
  1. Papers whose have been extended in additional papers.
  2. Papers not written in English.
  3. Papers not available as full text.
  4. Papers in the form of tutorial papers, short papers (less than 4 pages), poster papers, editorials, manuals, etc. as they do not provide enough information.

By applying the above criteria, we obtained a new set of 544 studies. We further refined the new set of studies by screening their titles and abstracts. This led to a new set of 130 studies. We proceeded with the full-text screening of these studies and obtained the final set of 29 primary studies listed in Table 1.

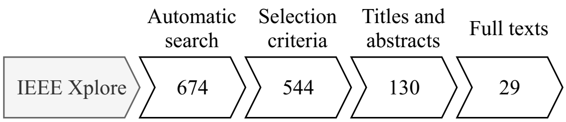

Figure 1. Search and selection process

3.3. *Data extraction*

To extract relevant data from the primary studies, we built the classification framework in Table 2. The framework consists of four facets, one per each research question. For the first research question, we had two subcategories for grouping standard publication information and information related to the type of research. The remaining facets have one category.

3.4. *Data analysis and synthesis*

In this step, we analysed and synthesised the extracted data for providing answers to the defined research questions. We provided both vertical and orthogonal analyses [13]. The vertical analysis served to analyse data for each category of the classification framework. We first analysed each study to extract relevant data according to the parameters of the classification framework. Later, we analysed the whole set of studies together. We used the orthogonal analysis to compare different categories of the classification framework. We show the results of this analyses in Section 4.

3.5. *Threats to validity*

In this section, we discuss potential threats to validity and adopted mitigation strategies.

We mitigated threats to conclusion validity by strictly applying and documenting well-known processes for conducting systematic studies, which included guidelines for data collection, analysis and synthesis. We provided a replication package for independent replication and validation of our research.

Id	Title	Authors	Ref
P1	A Methodology for Digital Twin Modeling and Deployment for Industry 4.0	Schroeder et al.	[6]
P2	Real-time Modeling and Simulation Method of Digital Twin Production Line	Gao et al.	[16]
P3	Integrate Digital Twin to Exist Production System for Industry 4.0	Assawaarayakul et al.	[17]
P4	Machine Learning Enabled FBAR Digital Twin for Rapid Optimization	Simon et al.	[18]
P5	The Design Concept of Digital Twin	Makarov et al.	[19]
P6	Digital Twin of City: Concept Overview	Ivanov et al.	[20]
P7	Establishing the utility charges spatial database using digital twin technology	Mihoković et al.	[21]
P8	Internet of Things Ontology for Digital Twin in Cyber Physical Systems	Steinmetz et al.	[22]
P9	Proposal of Digital Twin Platform Based on 3D Rendering and IIoT Principles Using Virtual / Augmented Reality	Leskovsky et al.	[10]
P10	Digital Twin: Values, Challenges and Enablers From a Modeling Perspective	Rasheed et al.	[23]
P11	Modeling Digital Twin Data and Architecture: A Building Guide with FIWARE as Enabling Technology	Conde et al.	[24]
P12	Digital Transformation Revolution with Digital Twin Technology	Erol et al.	[25]
P13	A Requirements Driven Digital Twin Framework: Specification and Opportunities	Moyne et al.	[26]
P14	Concept and Implementation of a Cyber-Pbysical Digital Twin for a SMT Line	Lin et al.	[27]
P15	C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems	Alam et al.	[28]
P16	Digital Twin-based Cyber Physical System for Sustainable Project Scheduling	Chakrabortty et al.	[29]
P17	Data Link for the Creation of Digital Twins	Ala-Laurinaho et al.	[30]
P18	Digital Twin: Enabling Technologies, Challenges and Open Research	Fuller et al.	[31]
P19	A Unified Digital Twin Framework for Real-time Monitoring and Evaluation of Smart Manufacturing Systems	Qamsane et al.	[32]
P20	Visualising the digital twin using web services and augmented reality	Schroeder et al.	[33]
P21	Developing a smart cyber-physical system based on digital twins of plants	Skobelev et al.	[34]
P22	Exploring Virtual Reality as an Integrated Development Environment for Cyber-Physical Systems	Mikkonen et al.	[35]
P23	Digital Twins for Manufacturing Using UML and Behavioral Specifications	Azangoo et al.	[36]
P24	Context Aware Control Systems: An Engineering Applications Perspective	Diaz et al.	[37]
P25	Embedding web apps in mixed reality	Peuhkurinen et al.	[38]
P26	Multiscale modeling and simulation for industrial cyber-physical systems	Demkovich et al.	[39]
P27	Digital Building Twins - Contributions of the ANR McBIM Project	Roxin et al.	[40]
P28	Design of a multi-sided platform supporting CPS deployment in the automation market	Landolfi et al.	[41]
P29	Enhancing Cognition for Digital Twins	Eirinakis et al.	[39]

Table 1. Primary studies

Facet	Cluster	Category	Description	Value
RQ1	Publication details	Year	Identifies the year of publication	Numeric value
		Venue Type	Identifies the type of publication venue	String
	Publication analysis	Research type	Identifies the type of the research according to the taxonomy in [42]	Evaluation research, proposal of solution, validation research, philosophical paper, opinion paper, experience paper, survey paper
RQ2		Enabling technologies	List of enabling technologies as identified in the studies	String
RQ3		Application domains	List of application domains as identified in the studies	String
RQ4		Benefits	List of benefits as identified in the studies	String

Table 2. Classification framework

To mitigate threats to internal validity we defined a study protocol that followed the guidelines presented by Petersen et al. [11]. The classification framework was built using the key-wording method in an iterative fashion. We extracted quantitative data from the studies that we analysed using descriptive statistics.

We mitigated threats to construct and external validity performing our search on one of the most relevant database for computer science: IEEE Xplore. We used a simple and inclusive search string and performed snowballing activities, too. Another threat to external validity could be the exclusion of studies not written in English. We consider this threat to be minimal, as English is the de-facto standard language for scientific studies in computer science and software engineering.

4. Results

In this section we describe the results of our analyses. First, we categorised the data according to the classification framework. Later, we summarised all the occurrences of the primary studies among these categories. Eventually, we compared interesting pairs of categories.

4.1. Publication trends (RQ1)

According to our investigation, the first studies on DT appeared in 2016 (Figure 2). The collected data shows a linear growth of published studies, which confirms DT as being an highly researched topic. According to our data, only 3.4% of the primary studies were published in 2021. To this end, it is worth remarking we conducted the automatic search in the first quarter of 2021. Concerning the venue type, the majority of the studies were

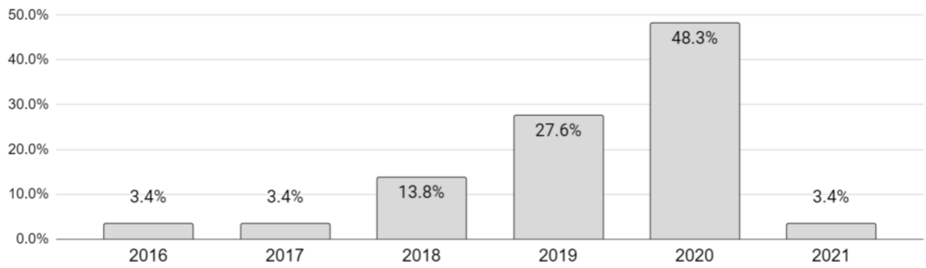

Figure 2. Distribution of publications per year

published as conference papers (72.4%). Papers published as journals account for 20.7% of the primary studies. Eventually, only 6.9% of the studies were published as workshop papers. This indicates that although DT is a rather new topic the quality of the related research is reasonable high. With respect to the type of research, the collected data show that the most common type is research proposal 72.4% (Figure 3). Other types of research

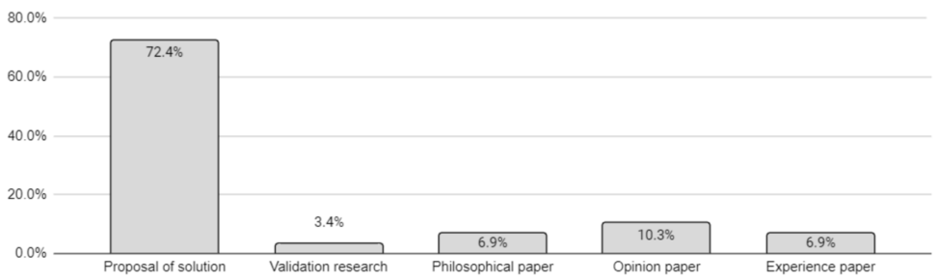

Figure 3. Distribution of publications per research type

accounts for a significantly lower number of studies. In particular, opinion papers accounts for 10.3% of the studies, experience and philosophical papers for 6.9% of the studies each and validation research for 3.4% of the studies.

4.2. Enabling technologies (RQ2)

By applying the keywording method, we collected six technologies as Figure 4 illustrates. These were either explicitly mentioned in the studies or we inferred them from the context. Some studies may have reported several technologies or no technologies at all. Hence the sum of the percentages in the plot may exceed 100%. The most reported

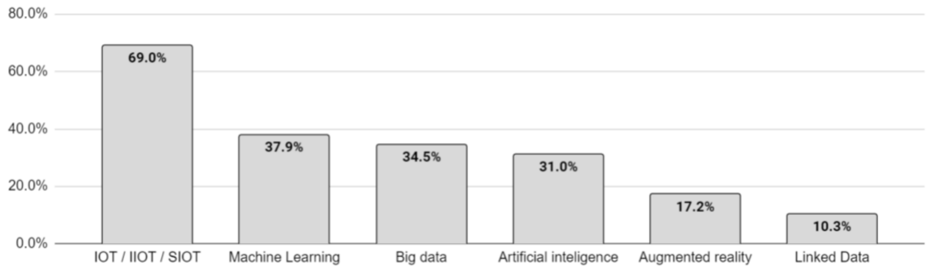

Figure 4. Enabling technologies

technology is IoT and its evolutions industrial IoT (IIoT) and social IoT (SIoT). They are mostly employed for collecting from the physical systems and send them to the virtual ones [20,22]. Data are often collected using (smart-)sensors. The next two most mentioned technologies are machine learning (ML) and big data. Both technologies build on the massive amount of data that are usually produced by DT-based systems. ML uses these data for improving machine operations through reinforcement learning hence without being directly programmed [31]. Big data techniques are mostly used to efficiently store and process the large amount of data generated by the physical objects [6]. Artificial intelligence (AI) accounts for 31.0% of the studies, while augmented reality (AR) and linked data for 17.2% and 10.3% respectively. Similar to ML, AI emphasises the creation of intelligent machines. AR techniques combines real and virtual visual components in the same scene with the aim of improve human-machine interactions. In DT-based systems, these techniques are often used for, e.g., advanced training, maintenance [33]. It is worth remarking that most of the technologies are mentioned in combination with other technologies. For instance, 80% of the studies mentioning big data also mention ML or AI.

4.3. Application domains (RQ3)

We collected six different application domains as Figure 5 shows. These were either explicitly mentioned in the studies or we inferred them from the context. Some studies may have reported several domains or no domains at all. Hence the sum of the percentages in the plot may exceed 100%. Advanced manufacturing is the most mentioned domain accounting for 62.1% of the preferences. In advanced manufacturing, DT systems are used for increasing the efficiency and the quality of the products through analysis and simulation. Besides, DT is also used for up-time, worker safety, and high-efficiency demands in operational activities and service processes. The second most mentioned domain is industrial applications (37.9%). In this umbrella domain we categorised all those DT applications related to e.g., product lines, automation systems. DTs find their applications in less traditional domains such as healthcare (17.2%), smart cities (13.8%), web services (10.3%) and automotive (6.9%) domains. In the healthcare domains, DT are used to simulate specific environments [31], to make smarter predictions and decisions on diagnoses and cures and even to plan, train for and perform surgical procedures [25]. In the context of smart cities, DT-based systems are used for, e.g., traffic congestion

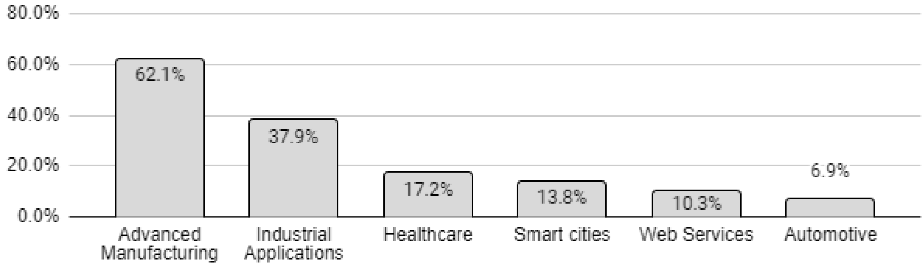

Figure 5. Application domains

avoidance and urban planning [25]. The application of DT in the web domain led to the definition of so-called Digital Twin Web (DTW) [30], which is a global network of digital twins put together in a similar internet-native and user-friendly manner as the World Wide Web.

4.4. Benefits (RQ4)

Figure 6 illustrates the catalogue of benefits extracted from the studies. The benefits were either explicitly mentioned in the studies or we inferred them from the context. Some studies may have reported several benefits or no benefits at all. Hence the sum of the percentages in the plot may exceed 100%. It is worth remarking, we focused on the technical benefits. Monitoring is by far the most reported benefit (71.4%). Although

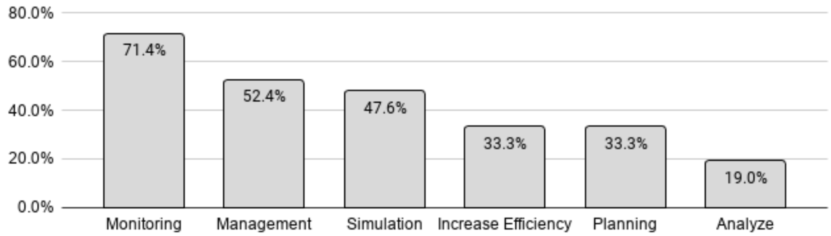

Figure 6. Benefits

DT goes beyond traditional computer-aided application, monitoring remains the most common benefit and in DT-based systems is exploited in all the development phases [20]. Management follows monitoring with 52.4% of the preferences. Management extends the benefits of monitoring with the possibility of acting on the physical or digital objects hence managing complex systems. The third mentioned benefit is simulation, which is usually linked to reduced costs, improved productivity, control and quality [6]. It is worth remarking that simulation is not perceived as equal to analysis, which is reported as the last benefit. Analysis refers to data analysis such as humidity, temperature, chemical composition of air, noise pollution and radiation level for smart cities [20]. Analysis was mentioned as beneficial for the creation of data-driven architectures [24]. Planning and increased efficiency accounted for 33.3% of the preferences, each.

4.5. Enabling technologies vs application domains

When analysing the correlation between technologies and domains we noticed that only two domains had relations with all the identified enabling technologies. We noticed that applications of DT in smart cities and automotive domains do not use augmented reality and linked data. Linked data is not used by DT applications in healthcare either. Eventually, DTs in the web domain do not use AI. On the contrary, DT-bases systems in advanced manufacturing and industrial applications seem to be the most complete ones. Among the technologies used by DTs in these domains, IoT is by far the most used one with 44.8% of relations with advanced manufacturing and 31% of relations with industrial applications.

4.6. Benefits vs application domains

When analysing the correlation between benefits and domains we noticed that five domains had relations with all the identified enabling technologies. Only web services did not have any relation with increased efficient, planning and management. However, we found this in line with the main purpose of DT in the web domain, which was the creation of a network of DTs. Among the other domain, healthcare and advanced manufacturing are those having the highest relations with the identified benefits. In particular, monitoring is the most mentioned benefits for DTs in the healthcare domain (55.2%) followed by increased efficiency (34.5%). Monitoring is the most mentioned benefits for DTs for advanced manufacturing, too with 34.5% of the preferences followed by planning and increased efficiency (20.7% each).

5. Discussion

By reading the data on publication trends, it is quite evident that DT is getting a foothold among researchers following its peak of industrial success [5]. Not only the numbers of peer-reviewed publications doubled each year from 2016, but the relevance and the quality of these publications stayed high and constant with the majority of peer-reviewed studies published as conference or journal papers.

DT originated as a promising way to implement the vision of I4.0. During the last years, DT went beyond that and DT-based systems were introduced in many business domains in addition to production. Our data showed that evidences of DT applications can be found in at least six different domains ranging from healthcare to automotive. Despite its wider adoption, DT seems to still be tightly coupled to the production domain, which alone accounts for 62.1% of its applications. Indeed DT is living up to its expectations of being an enabler for I4.0. Even more, it is leading the transition from I4.0 to Industry 5.0 [43] (I5.0). I5.0 envisions people working alongside robots and smart machines. Its aim is to support - and not superseding – people. I5.0 has its main pillars in advanced technologies such as IoT, AI/ML and big data. IoT is a cornerstone for its ability of connect things and collecting data. In this sense, the results produced from our work showed that many researches are being conducted on even more advanced IoT protocols such as IIoT and SIoT. In particular, there are scientific evidences that larger sets of connected things and individuals can provide far more accurate answers to complex situations such as mass-customisation, factory on-demand. ML and AI techniques are used to analyse the set of data for monitoring and planning the work of the physical and virtual objects [31]. Other technologies such as augmented reality and linked data are far less used and perceived as optional rather than crucial to DT operations. This is not surprising as, despite the bigger potentials, DT applications are mainly employed for achieving an improved and more efficient management of the physical objects. We expect that researches and applications of these technologies in the context of DT-based systems will increase in the near future as a result of the maturation of this field. Similarly, while the perceived technical benefits of adopting DT mainly lay on the management (monitoring, planning, etc.) of the physical entities, we expect to witness the blooming of other benefits as a results of the application of DT-based systems in new scenario coming from Industry and Society 5.0.

6. Related Work

In the past years, several systematic studies have been investigated specific aspects of DT. Hereafter, we present some of these studies and briefly discuss them to motivate the need for our research.

Wanasinghe et al. conducted a systematic literature review to gain a comprehensive understanding of DT technology as well as the opportunities and the barriers associated with its application in the oil and gas industry [44]. Monitoring, project planning, and management were mentioned as key benefits in this study, while IoT, big data, and AI as enabling technologies. In contrast to Wanasinghe et al., we do not specifically focus on one domain only. However, our collected data drew similar conclusions with respect to benefits and enabling technologies.

Perno et al. [45] conducted a systematic literature review aiming at categorizing the main barriers to DT implementation. Along with these barries, Perno et al. identified key technologies, too. Our study can be seen as complementary to the one by Perno et al. as we investigated different characteristics of DT such as domains and benefits. Another research investigating DT application is the systematic literature review by Melesse et al. [46]. Their study focused on DT applications for predictive maintenance and after-sale services. Considering these applications, they have collected publication trends and benefits.

Rathore et al. conducted a systematic literature review to investigate the relationship between augmented reality, machine learning and bid data in the context of DT applications. The study by Rathore et al. seconds our findings on the enabling technologies of DT and confirms the importance of augmented reality, machine learning and bid data.

Jones et al. [47] conducted a systematic mapping study, which aimed at shading lights on definitions of DT. Besides, the study aimed at identify gaps in the knowledge related to DT. In their study, they also examined publication trends, coming to similar conclusions to ours with respect to the growing trend of DT-related literature.

7. Conclusion and Future Work

This work reports on a systematic mapping study conducted to provide a comprehensive snapshot of digital twin, enabling technologies, reported benefits and application domains. We conducted this study following the guidelines proposed by Petersen et al. [11]. Starting from an initial set of 675 publications, we identified 26 primary studies, which we have analysed through a rigorous data extraction, analysis and synthesis process. The main findings of this study are as follows:

- Research on digital twin is lively and the number of related peer-reviewed publications is constantly increasing.
- Digital twin is a cross-domain solution, which has been applied to many different business domains from production to automotive through healthcare and smart cities.
- The main enablers for digital twin are the internet of things followed by different artificial intelligence solutions.
- The most perceived benefits introduced by digital twin are monitoring, management and simulation.
- Not only digital twin lived up to it promise of enabling industry 4.0, but it is also leading the transition towards industry and society 5.0.

Future work encompasses several directions. One possible direction is to extend this systematic study. One extension may encompass the use of further scientific databases and indexing systems. Another possible extension could be to include the so-called grey literature so to include different perspectives coming from industry and practitioners in general.

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