Survey on Digital Twins: from concepts to applications

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ABSTRACT

This study provides a systematic literature review on surveys across the topic of digital twins. The aim is to understand what have been the use cases, modelling and simulation tools/techniques, and how security is being addressed. To answer these research questions, a rigorous methodology consisting of seven steps was followed. The analysis shows that there is a misconception regarding the digital twin concept that may be leading to its misuse. Moreover, it was found that security is not a top priority, but is often mentioned as a challenge. Besides the lack of standardization, the amount of academic papers published and industrial solutions offered is increasing, showing that the consensus is not a limiting factor and the concept is gaining popularity over the years and being applied in an increasing number of sectors, mainly on manufacturing, energy, aerospace and automotive.

CCS CONCEPTS

• **Information systems**; • **Computer systems organization** → **Embedded and cyber-physical systems**; • **Security and privacy** → *Systems security*;

KEYWORDS

digital twin, architecture, framework, security

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1 INTRODUCTION

In the last five years, digital twins have been a popular topic, experiencing a meaningful increase in academic journal publications [34] and solution offerings from the industrial sector. Moreover, Gartner has listed digital twins as a technology trend for 3 consecutive years, from 2017 to 2019 [9] [10] [11], and in 2020 it still appears at Gartner, but within the trend of Hyperautomation [12].

Nonetheless, when it comes to the maturity level of digital twins, even Grieves, manufacturing specialist who conceived the term during a PLM (Product Lifecycle Management) presentation in 2002, answered an interview in 2021 [8] saying that his perception is that this trend is in its conceptual stage. Regardless of the maturity level, many studies have addressed different perspectives of digital twins, including topics such as conceptualization, use cases, and reviews. These resources allow to analyse how the technology is evolving and how it is being implemented, which is part of this paper's motivation and objectives. Our main contribution relies on identifying gaps to digital twin implementation and providing an updated compilation of previous reviews, grouping digital twin concepts from definition to its implementation regardless of the market sector or use case.

The work is structured in the following way: session 2 details the research methodology of the systematic literature review, session 3 gives a general overview on the literature analysis and the following sessions approach technical aspects of digial twins, starting with the definition (session 4), application domains and use cases (session 5), architectures and frameworks (session 6), and security (session 8).

2 RESEARCH METHODOLOGY

This literature review is based on the methodologies described by [4] and [25] consisting of seven steps: (1) Identify the purpose, (2) Draft Searching Protocol, (3) Apply practical screening, (4) Apply quality screening, (5) Extract Data, (6) Synthesize studies, (7) Write the review.

2.1 Purpose of the literature review

This study provides an overview of previous literature review studies on digital twins attempting to extract information about technical aspects regarding the framework, use cases, tools, and security. The following research questions guided this work: **RQ1:** What are the application domains and use cases of digital twins? **RQ2:** What are the techniques and tools most used for modelling and simulation? **RQ3:** What are the common frameworks for digital twin's development, its respective layers, and its operational requirements? **RQ4:** Do the studies address the security of digital twins?

2.2 Searching protocol

The papers search was conducted on two relevant bibliographic databases: ScienceDirect and IEEEXplore. We used the title query ("digital twin" AND ("review" OR "survey" OR "state of the art")) filtering for articles with the format of scientific/technical articles. The amount of collected studies was 94 from IEEEXplore and 42

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from ScienceDirect, resulting in a total of 139 before the practical screening. The search cut off date was in October 2022, providing an up to date state of art study on the topic.

2.3 Practical screening

This step consists of gathering papers that may be potentially usable. Considering that the nature of this study requires previous reviews, we initially analysed each paper to identify if it was a use case or general study in the format of review, survey or state-of-the art. No filters were applied for the field of application if the content approached the concept of digital twins as the main focus. This step resulted in 41 works for data extraction, data analysis, and synthesis.

2.4 Quality screening

The aim of the quality screening is to select only high-quality studies to assure the efficiency, relevance and accuracy of the review. In this study, the criteria for quality screening was the methodology, which had to be rigorous and provide information on how the data collection, analysis, interpretation, and reporting was performed. This criterion did not require that the papers should follow the same methodology as our own study, but a clear definition of the method was required. To investigate the characteristics of each study, eight quality criteria (QC) regarding the methodology were assessed: (QC1) Is the methodology rigorous or not rigorous?; (QC2) Are the research questions and/or objectives clear?; (QC3) Are the search databases given?; (QC4) Is the search query given?; (QC5) are the practical screening criteria given?; (QC6) are the methodological quality criteria given?; (QC7) Is the abstraction form given?; (QC8) Is there a descriptive synthesis of the selected papers?.

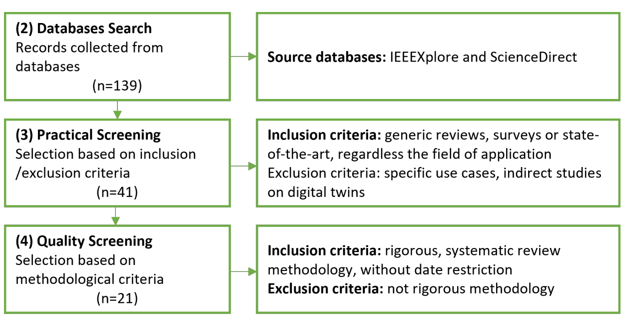

Figure 1: Summary of papers selection process

2.5 Data extraction

This step consisted of the elaboration of an extraction form to minimize subjectivity and guide the analysis of the results, not only to answer the research questions but also to provide an overview of the papers selected. Besides basic paper bibliographic information, one of the studies characteristics that was evaluated was regarding the literature review methodology quality discussed in section 2.4, mentioned here as QC1 to QC8. Furthermore, auxiliary questions were formulated to help answer the research questions and guiding the analysis and synthesis of the studies.

2.6 Synthesis of studies

The data were analyzed using two approaches. A quantitative approach was chosen for the evaluation of the methodology that has been applied by each article, and a qualitative analysis to answer the research questions of this study. The aim of the quantitative approach regarding the methodology statistics metrics is to provide an overview of how literature reviews are being conducted in this field. From the 139 papers collected, only the papers that were identified as reviews passed through the statistical analysis, and only the ones that applied rigorous methods were considered for the qualitative analysis, what means that from the eight quality criteria defined, only QC1 was considered for papers exclusion.

The qualitative analysis attempted to answer the research questions, but was performed in an open way, so that additional information could also be analysed, if applicable. This approach helped to identify the definition misconception and its impact on the following steps and to answer the research questions. Furthermore, not only the architecture and frameworks were evaluated but also further details were given by some authors, referring to them as characteristics, dimensions, or properties, among others, detailed in section 6.

2.7 Write the review

Standard writing principles were adopted for this review, following the methodology stated in section 2. The aim of presenting the methodology in details is to make the work explicit, systematic and reproducible.

2.8 Sample characteristics

QC0	QC1	QC2	QC3	QC4	QC5	QC6	QC7
Rigorous/Not rigorous	Yes	Yes	Yes	Yes	Yes	Yes	Yes
After practical screening	40 (98%)	21 (51%)	20 (49%)	19 (46%)	6 (15%)	6 (15%)	37 (90%)
After quality screening	21 (100%)	20 (95%)	20 (95%)	19 (90%)	6 (29%)	5 (24%)	21 (100%)

Figure 2: Methodological quality statistics in both screening steps

As can be seen in Table 2, around half of the potential studies did not present a rigorous, systematic methodology to perform the literature review and were excluded. When it comes to the methodology quality criteria, papers that follow a rigorous review methodology usually have clear purpose and inform the source databases, search query, and screening criteria, but applying the step of quality screening and providing the extraction form is not a common practise in this field. From the total of papers analysed for this study, only 29% included quality criteria, and 24% provided the extraction form. For databases, Scopus is the preferred source, followed by Google Scholar and IEEEXplore.

3 LITERATURE ANALYSIS

Before analysing technical concepts, this study provides an overview of the literature reviewed to point out the endeavors done so far to foster digital research. Most papers discuss theoretical aspects of digital twin's definition, characteristics, application domains, enablers, barriers, and future research.

Although this mainly theoretical approach since the term was first introduced documented by Grieves in 2002 [7], more recent studies show that digital twin technology is leaving its infancy [20] and gaining maturity through real application cases in many fields and different life cycle phases.

4 DEFINITION MISCONCEPTION AND ITS IMPLICATIONS

It is out of the scope of this paper to perform an in depth analysis of digital twins definition, however, it was noticed that a widely accepted definition is still a gap for this technology. The studies provide preliminary evidence that the most relevant definition is the one formalised by NASA IN 2012 [6], which presents digital twin as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. The digital twin is ultra-realistic and may consider one or more important and interdependent vehicle systems." From the 21 papers analysed, 13 refer to this definition [24] [2] [15] [33] [31] [5] [23] [34] [27] [20] [32] [29] [28]. According to [23], NASA was probably the first to put digital twin concept into practise and they developed a large-scale digital twin project, mapping and modeling the Langley Research Center. Such results may have contributed to make their definition the most cited, even if there is still a lack of consensus.

To demonstrate and discuss the lack of consensus and standardization, some authors compiled multiple definitions into tables to evaluate its similarities and differences [24] [2] [31] [27] [20] [32]. A meta study review [19] performed in 2021 with 24 papers shows that there is no focus on the main elements and the only common ground in all definitions is the virtual representation, which is intrinsically a vague term. The other elements assessed by the authors were the bidirectional connection, simulation, and connection across lifecycle phases. When new terms related to the virtual representation started appearing in the literature, it was perceived that they were not exactly synonyms, once the level of data integration between the digital and physical entities was different. Attempting to address this issue, Kritzinger [18] proposed a classification based on the level of data integration where the data flow exchange is the core criteria, being manual or automatic, from digital to physical object as summarized in Figure 3. Following studies used this classification to design a decision tree to determine the sub-category of the digital twin when evaluating papers [28].

Nonetheless, when deciding if a study is a Digital Model, Digital Shadow or Digital Twin, raises the question whether there is any difference between a Digital Model, for example, and computing based modeling solutions. Also, although simulation is a constant element in many definitions of digital twins, it is a well-known strategy that has been widely studied. This misconception regarding the definition is leading to a misuse of the term, hampering the distinction between its philosophy and traditional solutions.

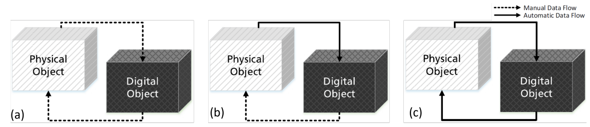

Figure 3: Data flow in (a) Digital Model, (b) Digital Shadow, and (c) Digital Twin proposed by [18]

5 APPLICATION DOMAINS AND USE CASES

As research on digital twins evolves, it is possible to identify the amount of studies for each vertical market. Once a vertical market is a group of companies that share the same needs, the outcomes of such studies may vary depending on the sector and the phase of the lifecycle that the digital twin addressed. Figure 4 extracted from [35] (2022), where 42 papers were analysed, shows that the verticals with higher publications are manufacturing and energy, followed by aerospace and automotive.

After identifying the main verticals, the following step was to identify their needs. This can be inferred by the phase of the lifecycle that the studies focus on, which was analysed by Liu [20] and can be seen in Figure 5. When [36] evaluated services applications, the sourcing cut off date was December 2018, with a total of 59 papers but few of high relevance. One of their contributions was to highlight this gap, given that, in many industries, the profit margin from services exceeds the margin of the product sale itself. Nonetheless, over the years, there has been a meaningful increase in production/manufacturing, and service phase, which is aligned with the gap indicated by [36].

Further evaluating the use cases, some authors list them according to market verticals [24] [2] [15] [5], others categorize per lifecycle phase [22] [20], and some papers that are already based on a specific market vertical list use cases without referring to the lifecycle phase [24] [33] [36] [1] [27]. Based on the classification done by Liu [20] and compiling additional results from other papers, common use cases for their respective lifecycle phase are:

- **Design phase:** verification; validation; what-if analysis; new business and business models; reduce capital investment;
- **Production phase:** optimization; real time state monitoring; traceability; data management; asset management; production control and planning; man-machine interaction; reduce cost; improve flexibility; improve vertical and horizontal integration;
- **Service Phase:** optimization; health monitoring and analysis; support after sales reconfiguration; what-if analysis; predictive maintenance; data management; fault detection and diagnosis; reduce operational downtime; improve change management of documents and assets; increase customer interaction and support; improve brand loyalty; adapt to specific consumer needs;

6 ARCHITECTURES AND FRAMEWORKS

It was noticed that the terms architecture and framework are used interchangeably in many papers, however, according to definitions from computer science sources, these terms have different meanings. **Architecture** is a logical view referring to the design of a solution,

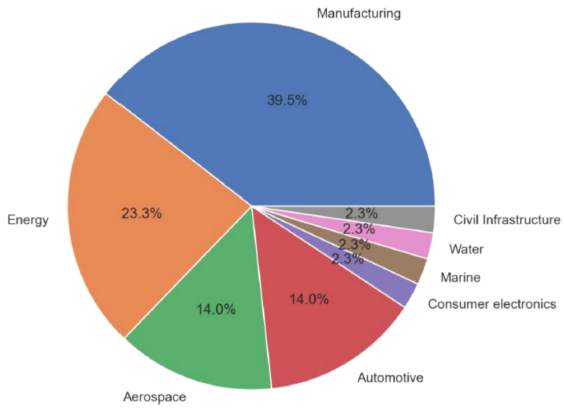

Figure 4: Percentage of papers according to market verticals [35]

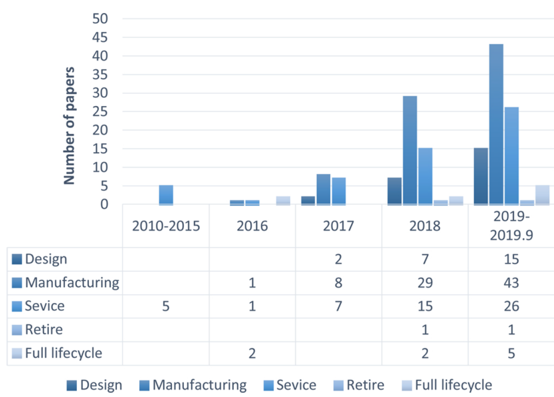

Figure 5: Papers classified according to the lifecycle phase [20]

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i.e. the structure, data flows, functions, rules and methods that guide the implementation. **Framework** is related to implementation, it provides reusable constituents for application-specific features for the implementation of an architecture [13].

Probably as a consequence of the lack of consensus for the digital twin definition, also the architecture and framework vary across the studies. The common ground is the existence of a real/physical entity, a virtual entity, and the connection between them. An example of an architecture that contains these dimensions can be seen in Figure 6 extracted from [16]. In the same paper, the authors propose a digital twin framework indicating the constituents of each functional block of the architecture (physical platform, virtual platform, data management platform, and service platform). Moreover, for each functional block, they also detail structural properties that should be taken into consideration during the digital twin implementation.

When it comes to further detail digital twin layers, different authors use different terms, such as: characteristics, properties, or enabling technologies. Table 1 exemplifies it by extracting such elements from different papers. Evaluating the description given

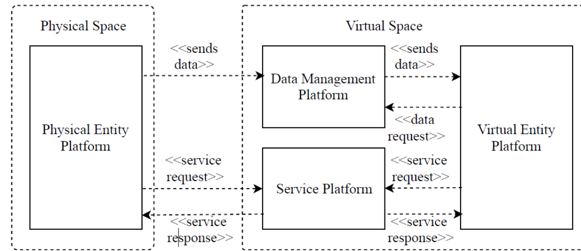

Figure 6: Example of digital twin architecture extracted from [16]

by the authors, it is possible to identify overlapping terms even if categorized in another way. This is probably due to the diverse researchers background and the low maturity of the concept, but it highlights the need for future research on the standardisation of all levels,not only the definition.

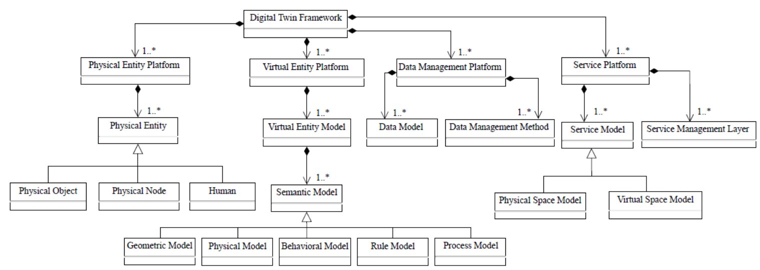

Figure 7: Example of digital twin framework extracted from [16]

Paper	DT details type	Description
[2]	Characteristics	integrated system; clone/counterpart; ties/links; description/construct/information; simulation/test/prediction; virtual mirror/replica
[15]	Characteristics	Physical Entity/Twin; Virtual Entity/Twin; Physical Environment; Virtual Environment; State; Realisation; Metrology; Twinning; Twinning Rate; Physical-to-Virtual Connection/Twinning; Virtual-to-Physical Connection/Twinning; Physical Processes; and Virtual Processes)
[15]	Parameters	form, functionality, health, location, process, time, state, performance, environment, misc. Qualitative
[31]	Components	RFID, Wireless sensor networks, RFID sensor networks, unit level, system level, system of systems level, middleware (service oriented architecture - SOA), communication protocol, communication protocol interface (AutomationML), wireless communication, programming interface API, data driven methods, geometry model, physical model, behaviour model, collaborative information model, decision making model, scalability, model interoperability, fidelity, dinamicity, modularity, application interface layer.
[5]	DT Domain / Enabling technologies	Application Domain: model architecture and visualisation, software and APIs, data collection and pre-processing Middleware Domain: storage technology, data processing Network Domain: communication technology, wireless communication Object Domain: hardware platform, sensor technolgy
[34]	Category / Dimensions	Context: reference object, tangible product life cycle phase, benefits, application domain Data: data storage, data scope, data quality, data sources, data interpretation Computing capabilities: trygger types, model look-ahead perspective, computing timing capabilities, update frequency/input, update frequency/output Model: digital twin creation approach, modelled characteristics, digital model types, model authenticity, model maintenance, modularity Integration: digital twin interaction, hierarchy, connection mode, user focus, interorganizational integration/collaboration Control: level of cognition, level of autonomy, learning capabilities Human-machine interaction: types of interaction devices, human interaction capabilities
[27]	Enablers	AI, IoT, IIoT, VR/AR, hardware, communication technologies, knowledge building, design process, development technologies
[16]	Building blocks / Properties	Physical Entity Platform: physical object (is observed), physical node (observes), human VIrtual Entity Platform: semantic model with geometric model, physical model, behavioral model, rule model, process model Data Management Platform: data models, data management methods Service Platform: service models (physical/virtual), service management layers
[32]	Dimension / Level	Update frequency: immediate real-time, event driven, every day, every week Connectivity modes: automatic, bi-directional, uni-directional Integration breadth: world (full object interaction), field/factory environment, near field/prodction system, product/machine Product lifecycle: begin of life, mid of life, end of life Human-interaction: smart devices, VR/AR, smart hybrid Digital model richness: geometry/kinematics, control behaviour, multi-physical behaviour Simulation capabilites: look-ahead perspective, Ad-Hoc, dynamic, static CPS intelligence: autonomous, partial autonomous, automated, human triggered
[20]	Key technologies	Data related technologies, high fidelity modeling technologies, model based simulation technologies
[29]	Supporting tools types	Integration and simulation, digital twin modeling, bridging and twin control, big data processing, big data storage, AI-ML and APIs

Table 1: Compilation of categories used for detailing digital twins.

Category	Tool/Technique
Bridging / Integration	Azure (Microsoft) , AWS (Amazon), MindSphere (Siemens), Predix (GE), ThingWorx (PTC), IBM Maximo Asset Health Insights (IBM) , RFID, MTConnect, OPC UA, MQTT, ZigBee, XML, IndraMotion MTX (Rexroth), Beacon (Fii-Foxconn), TwinCAT (Beckhoff), SAP (SAP), Codesys (Codesys Group), edge/foggy computing
Data processing	Data fusion algorithms, BigQuery (Google), Spark/Storm/S4/Hive/Mahout/Flink/Pig/Impala (Apache), edge/foggy computing, VoltDB (VoltDB), Azure (Microsoft), AWS (Amazon),
Data storage	MongoDB (MongoDB), MySQL(Oracle/Others), Hadoop/Hbase/Kafka (Apache), Oracle, Azure (Microsoft), AWS (Amazon), BigQuery (Google)
Data analytics	AI algorithms (e.g. feature selection, feature extraction, pattern recognition, stocastic optimization, evolutionary, etc), ML algorithms (neural networks, fuzzy logic, etc), TensorFlow (Google), Azure (Microsoft), AWS (Amazon), BigQuery (Google)
Modeling	Meta-information and semantics, ontologies, AutomationML, finite element, finite element alternating method, AnyBody Modeling System (AnyBody Technology), service-oriented-architecture (SOA), representional state transfer (REST), Matlab (MathWorks), Matpower (Matpower), InterPSS (InterPSS), OOPS, PowerFactory (DIgSILENT), Modelica (Modelica), Markov chain, ANSYS Twin Builder (ANSYS), NX (Siemens), SolidWorks (Dessault Systèmes), AutoCAD (Autodesk), 3D Max (Autodesk), FreeCAD (Freecadweb), Azure (Microsoft), AWS (Amazon),
Simulation	FEM simulation, Montecarlo simulation, CFD simulation, DDSIM (Damage and Durability Simulator), S2S DFS, Simulink (MathWorks), CAE-based simulation, (CATIA) Dessault Systemes, CIROS Studio (VEROSIM), Simcenter 3D (Siemens), ANSYS Twin Builder (ANSYS), PSS R NETOMAC (Siemens), MWorks (Tongyuan), SUMO (Eclipse), Open Simulation Platform (DNV-GL), Azure (Microsoft), AWS (Amazon)

Table 2: Compilation of some tools and techniques according to categories.

7 TOOLS

Although the research question 3 was about tools for modeling and simulation of digital twins, some papers suggested more categories which were also adopted for this paper. It is worth noticing that some tools can be utilized in more than one category, for example, the cloud services from Amazon and Microsoft. This is due to the fact that some companies offer several solutions, but it is out of the scope of this study to identify all tools and their respective category. Moreover, the tool set varies depending on the market vertical and minor solutions could appear in a more comprehensive list. Table 2 shows a summary based on the work of Rathore [29] and the additional attribution of tools mentioned in other studies to the proposed categories. The solution providers are identified in brackets and generic techniques without brackets.

8 SECURITY

One of the main goals of this study was to evaluate if and how the security is being addressed in the field of digital twins. Some authors state that it requires an additional security strategy because it introduces new vulnerabilities [33] [20], but most of the reviews just mentioned it as a challenge [2][22] [5] [19] [26], without detailing the necessary dimensions of security. It was also mentioned as a possible perceived benefit by [15] [21] [31], but the authors do not discuss if this would be somehow first conditioned to the security of the digital twin itself. From both perspectives, be the focus on the digital twin as an additional security layer or on the security of the digital twin itself, some dimensions should be taken into consideration, similarly to what would be done with traditional solutions. A proposal for an initial compilation is:

- **Network:** the individual design of each solution may impact the security products chosen to secure the network, but common options include proper network segmentation, firewalls implementation, data diodes, Intrusion Detection System (IDS), Intrusion Prevention System (IPS), Anomaly Detection, patch management, among others [17].
- **Internet connection:** special attention must be given to any external connection that have the potential to make sensitive data vulnerable. In this case, not only security products apply, but also the evaluation of the data content, so that in case of leakages, no regulation is violated. This is a matter that involves very closely security and privacy [30].
- **Software and Hardware updates:** the virtual entity of a digital twin is composed by basically the same types of assets and the real entity, possibly containing servers, IIoT devices, operational system, software, hardware, etc. Thus, the update management [14] is also a necessary security measure to maintain the assets with the last available security packs.
- **Cloud infrastructure as a service:** a good summary of the shared responsability model when it comes to cloud services was given by Checkpoint [3]. They explain that "in general, the cloud provider is responsible for the security of the underlying infrastructure that they lease to their customers, while the customer is responsible for the security of the areas of the cloud infrastructure over which they have control".
- **Sensitive data sharing:** sensitive data can be both personal or industrial. The security triad of confidentiality, availability, and integrity, such as other measures of authenticity, encryption, and whatever is suitable to the application, must be addressed.
- **AI:** being considered as one of the enabling technologies for the development of digital twins, AI raises many security and privacy concerns, including the discussion of data ownership. Regulation is being pointed as a need not only by the security perspective, but also due to many other ethical issues regarding the possible outcomes it can generate and their consequences.

9 CHALLENGES AND FUTURE TRENDS

There are yet several challenges to allow a wide real world application of digital twins. The challenges start with the lack of standard definition, architecture and framework, but extends to the difficult of obtaining high fidelity models, appropriate tools, and many other levels discussed in session 6. For all these levels, security and privacy are of major concern and, financially speaking, the high cost for implementation against the cost-benefit perceived by customers can also be a barrier.

Nevertheless, the possibility of predicting failures, continuous optimizing the system, improve decision making based on real time simulation and so on, is tempting and the increase of publications and solutions development about digital twins from academia and industry proves that there is room to deepen this research field. The main future trends identified during this study are the broader application of digital twins to provide services, the role of humans, and further work on standardizations.

10 CONCLUSION

This work shows that Grieves perception given in an interview in 2021 [8] about digital twins being still in a concept stage is shared by many authors who argue that a widely accepted definition standardization is necessary to enable real world complex applications. As discussed in the definition session, from the point of view of academic publications, the content type is transitioning from conceptual to real cases, what can be understood as a sign that the technology is evolving its maturity level, besides the definition issue. This paper contributes to show that the lack of consensus for the definition may be leading to the same problem in the next steps, given that a common challenge highlighted in many papers is the lack of standard for the architecture, frameworks and tools. Besides this study is limited in scope for papers that approach reviews on digital twins regardless of the market sector, hence not focusing on its features including security, our findings point a lack of considerations on both perspectives of security: the digital twin as a security layer, or the security of the digital twin itself. A further study could assess how the definition is impacting digital twin implementations and propose enhancements that would make the subsequent steps more uniform and leverage real world applications that also take into consideration cyber security from a wider perspective range. The gap findings of this work provided the following insights for our future research: the need for in depth market specific review, which, in our case will be focused on the energy sector, and the need to approach security and reliability, which was not addressed by the reviews, but is a main topic to enable the implementation of digital twins in critical sectors.

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