Reference Architectures for Digital Twins: Results of a Literature Review

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ABSTRACT

Context: Digital Twin (DT) technology has emerged as a key enabler in the development of contemporary systems, offering dynamic, real-time representations of physical assets and processes. By facilitating advanced monitoring, simulation, and predictive analysis, Digital Twins contribute to enhanced operational efficiency, informed decision-making, and continuous innovation. Their applicability spans a wide range of domains, including manufacturing, healthcare, transportation, and smart infrastructure. **Problem:** Despite the growing interest of industry in using DT for improving their processes, there is a lack of understanding of the software architectures for DT solutions. **Goal:** This work aims to provide an overview of reference architectures for DT, characterizing its primary stakeholders, the engineering approaches used in its creation, the industry involvement in its development, and the concerns that guide its design. **Method:** A rapid literature review was executed, using Scopus and Google Scholar as primary databases. **Results:** From an initial set of 216 studies, seventeen reference architectures for DTs were found and characterized. Most architectures have been defined since 2020 for multiple domains and purposes, encompassing the involvement of various industry sectors and stakeholders. Finally, essential concerns and limitations of those architectures are discussed, paving the way for further contributions.

KEYWORDS

design patterns, software engineering education, jigsaw, active learning

1 Introduction

We are currently undergoing a transition toward the Fourth Industrial Revolution, also known as Industry 4.0. The First Industrial Revolution was marked by the introduction of mechanical machines, which significantly enhanced productivity in factories. The Second Revolution brought increased efficiency through new models of organizing work processes. The Third Industrial Revolution was characterized by the automation of manufacturing processes, further optimizing production. Finally, the Fourth Industrial Revolution is integrating emerging technologies such as cloud storage and computing, artificial intelligence, and others, with the aim of optimizing the management of industrial systems.

Digital Twins (DTs) is emerging as a disruptive technology. With the advancement of Industry 4.0 and the exponential increase in the complexity of industrial systems, Digital Twins are becoming increasingly essential. DT is fundamental as they enable the integration between the physical and digital worlds, functioning as intermediary applications between users and industrial monitoring and control. This technology aims to generate a virtual representation of industrial assets through data collected by sensors. As a result, it becomes possible to assess optimizations and make predictions for a physical system [8].

However, the construction of Digital Twins is not a trivial task, due to the required integration needed to handle heterogeneous systems that exist across different technological domains. In this context, software architectures—particularly reference architectures—play a critical role in the development of robust systems that employ physical-digital integration, with the ability to combine diverse data sets in real time while enabling simulations, predictive analyses, and process automation. Reference architectures are important because they are considered the backbone of well-designed information systems [28]. Moreover, they are intended to provide guidelines for the development, standardization, and evolution of architectures within a specific application domain [12], which makes them highly relevant for this type of application.

Given the preceding context, it becomes evident that in Industry 4.0, the adoption of intelligent systems is transforming how industries operate and how industrial planning is conducted. Technologies such as the Internet of Things (IoT), Machine Learning (ML), Big Data, and cloud computing are being integrated into industrial systems, enabling a level of control that was previously unimaginable. In this scenario, Digital Twins play a crucial role by enabling the simulation of physical asset behavior, creating a continuous cycle of optimization and improvement. They are also key components to be integrated with emerging technologies.

The main factor that makes the use of Digital Twins particularly attractive in industry is their ability to provide a rich understanding of system behavior, generating potential insights into improvements or possible failures. In various sectors such as manufacturing, transportation, energy, and healthcare, this technology offers significant opportunities to enhance process efficiency. However, to achieve effective integration between the physical and digital worlds, reference architectures stand out as critically important, serving as structural guides for system development.

Therefore, a literature review on reference architectures for Digital Twins is of utmost importance for understanding current trends in the development of such architectures in recent years and how this process has unfolded.

Although there are some existing literature reviews on reference architectures in general—such as those conducted by [20] and [37]—none of them provide a detailed examination of architectures that specifically incorporate Digital Twins. In this regard, the

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present study aims to address this specific knowledge gap, offering a comprehensive understanding of the topic in order to identify potential research gaps and to support the more effective direction of future investigations in this area.

The remainder of this paper is organized as follows. Section 2 provides the background on reference architectures and digital twins as well as the related work. Section 3 presents the method we followed to plan, conduct, and analyse the literature review. In Section 4, we present results of the rapid review. Section 5 discusses our findings and presents the threats to validity. Finally, we outline our conclusion in Section 6.

2 Background and Related Work

2.1 Digital Twins

Digital Twins (DTs) are virtual representations of physical systems—either machines or processes—that leverage data and algorithms to simulate, optimize, and make predictions, thereby enabling real-time system monitoring. In recent years, this technology has been transforming industries by seamlessly connecting the physical and digital worlds [39]

Due to their wide applicability, Digital Twins are already being implemented across various sectors, each exploring distinct purposes and functionalities. This theoretical background highlights four different domains, for instance, manufacturing [41], healthcare [26, 40, 45], transportation [24], and energy [50]. Case studies in each of these areas demonstrate the significant impact of Digital Twins on process optimization, resource management, and preventive maintenance.

The term *Digital Twin* was first introduced in the early 2000s by Michael Grieves in the context of product lifecycle management. Over time, it evolved into a broader concept involving real-time simulation models. Ideally, a DT would replicate a physical system in complete real-time detail [23, 25]. However, such an approach poses limitations regarding the twins' capacity to learn: if the DT is an exact copy of the system, it ceases to offer an abstracted perspective necessary for learning. To address this, DTs are typically designed to operate in parallel to, but independently from, the physical system [23, 25]. Consequently, they function as simplified models that focus on essential elements, abstracting away less critical details [8].

Initially, a Digital Twin was conceptualized through three components: the physical entity, the virtual entity, and the data connection between them. Nowadays, DTs span multiple disciplines and application domains, making a singular definition insufficient. There is not a consenual definiton about Digital Twins. Following Kuhn [29], Digital Twins provide a unified interface capable of accessing and processing data, models, algorithms, and services. In Jiang et al. [27], the authors proposed an axiomatic definition of Digital Twins based on their nature and utilization. According to their framework, five fundamental characteristics define a DT: Components, Modeling, Interaction, Synchronization, and Digital Lifecycle.

- **Components** refer to the primary elements of a DT, including physical entities such as real-world assets or systems.
- **Modeling** encompasses the process of creating an accurate and functional digital representation, maintaining a meaningful relationship with its physical counterpart.
- **Interaction** is defined as the continuous, bidirectional communication between the digital and physical entities.
- **Synchronization** ensures that the DT remains updated and aligned with the current state of the physical system, thereby enabling effective application.
- **Digital Lifecycle** emphasizes that a DT should accompany its physical twin throughout its entire existence—from conception to decommissioning or recycling.

Furthermore, Jiang et al. [27] identified three core capabilities that DTs enable within industrial contexts:

- **Mirroring** involves generating a detailed digital representation of a physical asset. Techniques such as point cloud synthesis, tomography, and ultrasonic testing enhance the accuracy of these representations.
- **Shadowing** concerns the real-time synchronization between physical and virtual systems. Every event occurring in the physical world must be instantly reflected in the DT, thus enabling continuous monitoring and rapid fault detection. Technologies such as model matching, data association, and reinforcement learning contribute to maintaining this alignment.
- **Threading** refers to the ability to interconnect various operational stages and DT instances, forming digital threads that unify systems and processes. This connectivity breaks down informational silos, fosters efficient communication between subsystems, and enables real-time adjustments based on shared data. Cloud-based infrastructure facilitates large-scale data processing and analysis by distributing computational workloads.

In this perspective, it is important to propose DTs architectures that address the essential characteristics of DTs including Müller-Zhang et al. [36]: (i) continuous synchronization with their real-world counterparts, (ii) interoperability enabled by standardized data structures, and (iii) vertical integration that connects historical and real-time data streams.

2.2 Reference architectures

Software architectures are widely acknowledged as the foundational structure underlying any successful software-intensive system, playing a critical role in shaping software quality attributes such as maintainability, scalability, and performance [28]. Within this context, reference architectures are considered abstract and domain-oriented, encapsulating recurring architectural elements, patterns, and best practices derived from a family of systems within the specific technical or application domain [7]. The primary purpose of such architectures is to guide the development, standardization, and evolution of concrete software architectures in the domain [13].

Over the past decades, numerous reference architectures have been proposed and adopted across various sectors, reflecting their growing strategic importance [20]. These architectures are often the result of collaborative efforts among industrial stakeholders (e.g., manufacturers, suppliers) and academic researchers, ensuring both practical applicability and theoretical soundness.

In parallel to their practical implementation, substantial theoretical work has been undertaken to formalize the notion of reference architectures. This includes efforts to define and characterize these architectures, develop systematic methods and processes for their design, and establish criteria for their architectural analysis, synthesis, and evaluation [20].

Furthermore, research has sought to identify the potential benefits and limitations of reference architectures to inform and support decision-making processes regarding their adoption in organizations [6, 33]. From both industrial and academic perspectives, the literature highlights several key advantages of reference architectures. These include: (i) enhanced interoperability among systems and subsystems, (ii) reduction in development costs and time through systematic reuse, (iii) mitigation of risks in software engineering projects, (iv) improved communication among stakeholders via a shared architectural vocabulary, and (v) adoption of best practices, promoting architectural consistency and quality across projects.

2.3 Related work

Several literature reviews have been conducted to identify and analyze reference architectures across various application domains. These studies highlight the growing importance of reference architectures as foundational frameworks in the design of complex systems. Existing reviews have examined reference architectures in the contexts of smart grids [5], big data systems [44, 48], and Industry 4.0 [37], this last presenting a comprehensive overview of Industry 4.0 reference architectures and discusses future trends.Other studies have focused on ambient assisted living [21], self-adaptive systems [1, 19], service-oriented systems [16], the Internet of Things (IoT) [35], and cyber-defense [42]. Additionally, a broader and more encompassing analysis is provided by Garcés et al. [20], who conducted a systematic mapping study covering three decades of software reference architectures, offering insights into the historical evolution, research trends, and gaps in the field.

Although there is some literature addressing reference architectures in a vast diversity of domains, none of them offer a detailed analysis of those that specifically incorporate Digital Twins. In this context, the present study aims to contribute to this body of research by summarizing and synthesizing the existing knowledge on reference architectures involving Digital Twins.

3 Literature Review Planning

The main objective of this study is to provide a comprehensive understanding of reference architectures for Digital Twin systems, to identify potential knowledge gaps to guide future research in this field, and to analyze the trends surrounding the development of reference architectures in recent years.

The remainder of this section presents the literature review design aimed at this study, following guidelines in [11] for rapid literature reviews in software engineering.

3.1 Research Questions and Extracted Data

The research questions, the rationale behind them, and the planned extracted data to answer each question are described as follows.

RQ1 What is the current landscape of academic research on reference architectures for Digital Twin systems?
Rationale: The first question aims to map the current landscape of academic research, identifying when and where the key advancements in this field of knowledge are occurring. By answering this question, the goal is not only to provide an overview of scientific contributions over time but also to identify the regions or institutions leading the development of this technology.
Data to be extracted:
(1) Number of architectures proposed by year per study.
(2) Number of architectures proposed by country per study.

RQ2 How do reference architectures for Digital Twins relate to Industry 4.0?
Rationale: This second question brings forth an investigation about DTs reference architectures when considering the Industry 4.0 scenario.
Data to be extracted:
(1) Number of architectures related to Industry 4.0.
(2) Processes in which reference architectures for *Digital Twins* are integrated within Industry 4.0.

RQ3 What have been the main stakeholders of reference architectures for Digital Twins?
Rationale: This third question intends to identify the different stakeholders types involved in the construction or use of reference architectures for this domain.
Data to be extracted:
(1) Stakeholders (people, organizations, and investors) considered in each reference architecture.

RQ4 How have reference architectures for Digital Twins been engineered?
Rationale: The focus here is to understand more about the rationale behind the approaches to construct reference architectures for DTs.
Data to be extracted:
(1) Names of the architectures.
(2) Approaches used in the architecture construction.

RQ5 What is the role of industry in the engineering of such architectures?
Rationale: The fourth question seeks to understand whether the proposed reference architectures have case studies and are being applied in industrial practice. If there are successful implementation cases, this would indicate a higher level of maturity and feasibility of these models.
Data to be extracted:
(1) Number of architectures in which the industry participated in the development.
(2) Number of architectures currently used by the industry.

RQ6 What are the main concerns when engineering reference architectures for Digital Twins?
Rationale: The fifth question investigates the challenges reference architectures face. The main idea here is to map the most common difficulties in order to clarify the barriers that need to be overcome by the architectures.
Data to be extracted:
(1) List of challenges reported by the study.

RQ7 What are the main opportunities in the engineering of reference architectures for Digital Twins?
Rationale: Finally, the sixth question aims to understand the potential opportunities related to reference architectures

for Digital Twins and, thereby, identify areas with the greatest potential for growth and innovation, as well as the next steps to advance this technology. This last question seeks to highlight new application possibilities and potential directions for future research in the coming years.

Data to be extracted:

(1) List of opportunities reported by the study.

3.2 Search Strategy

The Scopus[1] and Google Scholar[2] databases were selected as the primary study sources for this review. The search string proposed was:

("Digital Twin" OR "Digital Twins" OR "Virtual Twin")
AND
("Reference Architecture" OR "Architectural Framework")

3.3 Selection Strategy

The selection strategy for primary studies was conducted following the predefined inclusion (IC) and exclusion (EC) criteria:

IC1 - The study addresses the proposal or use of reference architectures for Digital Twins.
EC1 - The study does not address the concept of reference architectures for *Digital Twins*.
EC2 - The study was not published within the last 10 years.
EC3 - The full text of the study is not available, or access restrictions prevent detailed analysis.
EC4 - The study duplicates other publications (only the most complete and recent version will be considered).
EC5 - The study is not peer-reviewed.

In the initial screening phase, duplicate and closely related studies were identified and removed. Subsequently, each remaining study underwent a preliminary assessment based on its title, abstract, and keywords, during which the inclusion and exclusion criteria were applied. The studies that passed this phase were then subjected to a full-text review in a second screening round, wherein the inclusion and exclusion criteria were applied again. Finally, the quality criterion, *"The study has followed adequately a scientific method and has a clear chain of evidence,"* was used to ensure methodological soundness and relevance.

3.4 Data Analysis

The extracted data was analyzed using qualitative and narrative synthesis methods, as recommended by [43].

4 Results

This study was conducted from October, 2024 to March, 2025 by two researchers with experience in reference architectures and software architectures. They also have experience in researching, conducting, and updating several secondary studies.

Figure 1 depicts the steps of the selection process. Adapting the search string for Scopus, considering the title, abstract, and keywords search. Regarding Google Scholar, we adapted the string filtering by title. From both searches, we obtained a total of **216** studies, and after removing duplicates, **198** studies remained. After the first selection, where we applied the selection criteria on title, abstract, and keywords, **62** studies were selected. After reading the full text of these studies and using the selection criteria again, **19** primary studies were selected. The quality of those studies was assessed, removing two studies that did not accomplish the minimum methodological rigor expected. Finally, **17** primary studies were selected for data extraction.

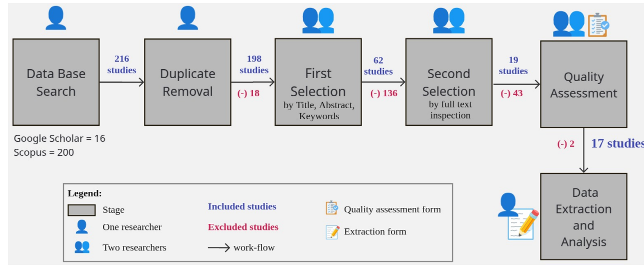

Figure 1: Literature review process

During the execution of the literature review, the Parsifal software[3] was employed to systematize and facilitate the management of the entire process. Parsifal is a tool designed to support literature reviews by assisting in the organization, selection, and tracking of articles throughout the various stages of the review. Its use streamlined the control and screening of studies, ensuring greater accuracy in applying inclusion and exclusion criteria, thereby contributing to the quality and reliability of the review.

Table 1 presents the final list of reference architectures for digital twins included in this study. The data extraction results are presented below. Charts were generated using the Python libraries *matplotlib* and *geopandas* to facilitate the analysis and synthesis of the information. The code used to generate the charts is available on the Google Colab platform. This section presents the answers to the research questions that guide this literature review.

4.1 RQ1 - Landscape of academic research on RA4DT

Primary studies were analyzed to assess the current state of academic research on reference architectures for Digital Twin systems. This analysis was structured around the number of proposed architectures by year and country, offering a broad perspective on the evolution and geographical distribution of research in this domain.

Regarding the annual distribution, from Table 1, a notable peak is noticed in 2020, during which eight new architectures were proposed. In the years following 2020, a decline in the number of new proposals was observed, followed by a slight stabilization. In 2022, four architectures were introduced, while 2023 and 2024 maintained a lower average, with approximately two new proposals each year.

The years 2017 and 2021 registered the lowest numbers, with only one architecture proposed in each, indicating that research activity in this field was still in its early stages during those periods. Subsequent growth reflects the increasing prominence of the topic in both academic and industrial contexts.

[1]https://www.scopus.com/
[2]https://scholar.google.com/
[3]https://parsif.al/

Table 1: Final set of reference architectures for digital twins

ID	Ref.	Title	Venue	Year	RA Name	Industry	Case
S01	[3]	C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems	IEEE Access	2017	RA for Cloud-based Cyber-Physical Systems (C2PS)	None	No
S02	[30]	Integration of digital twin and deep learning in cyber-physical systems: Towards smart manufacturing	IET Collaborative Intelligent Manufacturing	2020	Generic Digital Twin Architecture (GDTA)	None	Yes
S03	[38]	Digital twin-based cyber physical production system architectural framework for personalized production	International Journal of Advanced Manufacturing Technology	2020	No name	None	Yes
S04	[17]	The development of standardized models of digital twin	IFAC-PapersOnLine	2020	Digital Twin Reference Model (DTRM)	Beijing Spacecrafts Limited Company	Yes
S05	[9]	Digital twin reference model development to prevent operators' risk in process plants	Sustainability (Switzerland)	2020	No name	None	Yes
S06	[51]	A generic tri-model-based approach for product-level digital twin development in a smart manufacturing environment	Robotics and Computer-Integrated Manufacturing	2020	Reference Model for Digital Twin (RMDT)	None	No
S07	[32]	A digital twin-enhanced system for engineering product family design and optimization	Journal of Manufacturing Systems	2020	General Reference Architecture for Digital Twins Systems (GRADTS)	PERA Corporation Ltd	Yes
S08	[47]	Generic digital twin architecture for industrial energy systems	Applied Sciences (Switzerland)	2020	Digital twin-based cyber physical production system (CPPS)	MSF	Yes
S09	[2]	Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model	Advanced Engineering Informatics	2021	DTDL-CPS	None	Yes
S10	[49]	Digital twin-based smart assembly process design and application framework for complex products and its case study	Journal of Manufacturing Systems	2021	Digital Twin as a Service (DTaaS)	Hynds, ThingWorx, Vuforia	Yes
S11	[15]	Digital twins in healthcare: an architectural proposal and its application in a social distancing case study	IEEE Journal of Biomedical and Health Informatics	2022	IoTwins platform	CETIM and others.	Yes
S12	[10]	A subject-oriented reference model for Digital Twins	Computers and Industrial Engineering	2022	No name	KUKA Systems Aerospace	Yes
S13	[18]	The Development of a Digital Twin Framework for an Industrial Robotic Drilling Process	Sensors	2022	Subject-Oriented Reference Model for Digital Twins (SORMDT)	None	Yes
S14	[14]	IoTwins: Toward Implementation of Distributed Digital Twins in Industry 4.0 Settings	Computers	2022	No name	None	Yes
S15	[46]	A Model-Driven Digital Twin for Manufacturing Process Adaptation	MODELS-C 2023	2023	CanTwin	Hitachi Rail	Yes
S16	[31]	Digital twin for Industrial Internet	Fundamental Research	2024	No name	Volkswagen Autoeuropa	Yes
S17	[34]	Design of an ISO 23247 Compliant Digital Twin for an Automotive Assembly Line	2024 IEEE 7th International Conference on Industrial Cyber-Physical Systems, ICPS 2024	2024	3 Layers - 4 attributes	None	No

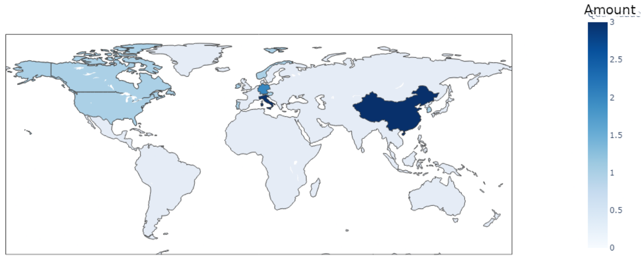

Figure 2: Geographical distribution of proposed Reference Architectures for Digital Twins (RA4DT) through 2024

As illustrated in Figure 2, the distribution of proposed architectures by country reveals that Italy and China lead in contributions, each presenting three reference architectures. Germany follows with two proposals, also demonstrating a significant research interest in the field of Digital Twins.

Other countries—including Portugal, Norway, Austria, Singapore, Ireland, New Zealand (including Hong Kong), Canada, South Korea, and the United States- contributed a single proposal. This geographic diversity underscores the global relevance of the topic, although with more pronounced activity in certain regions, particularly Europe and Asia.

The data suggest that while interest in Digital Twins is globally distributed, specific countries, notably Italy, China, and Germany, are leading the advancement of reference architectures within this domain.

4.2 RQ2 - Relationship between RA4DT and the Industry 4.0

All 17 reference architectures address Industry 4.0, revealing that these architectures consider the application of Digital Twin to key industrial processes. The following key industry application areas were identified:

- **Real-Time Monitoring, Simulation, Control, and Optimization of Physical Systems:** This area is addressed by several studies (S01, S02, S03, S06, S07, S08, S09, S10, S11, S12, S14, S16, S17), indicating its critical role in real-time performance management of physical systems. These studies focus on enabling continuous monitoring and adaptive control mechanisms to optimize system behaviors in dynamic environments.
- **Asset Reconfiguration throughout the Product Lifecycle:** The works of S01, S03, S06, S09, S11, S13, and S14 highlight the importance of reconfiguring assets to meet evolving requirements during the product's lifecycle. This process ensures that assets remain effective and efficient through stages such as design, production, and operation.
- **Design of Intelligent Assembly Processes:** Studies S04, S08, S12, and S16 contribute to the development of intelligent assembly processes, which utilize digital twin models to optimize assembly line configurations and workflows, leading to enhanced productivity and quality control.
- **Risk Prediction:** The ability to predict potential risks is explored in studies S01, S02, S06, S09, S10, and S14. This area focuses on leveraging data from digital twins to anticipate and mitigate risks, ensuring safer and more reliable operations.
- **Predictive Maintenance:** A central theme in S01, S02, S03, S06, S09, S10, S11, and S14 is predictive maintenance. By continuously analyzing operational data, these studies propose architectures that can predict equipment failures before they occur, thereby minimizing downtime and extending asset lifespan.
- **Planning and Control of Customized Production Processes:** The studies S08, S10, and S14 address the optimization of production processes for personalized manufacturing. These architectures facilitate the customization of production lines to meet specific customer requirements, enhancing flexibility and responsiveness.
- **Optimization of Physical Spaces and Organizational Processes:** The application of digital twins to optimize physical spaces and organizational workflows is examined in S02, S05, S07, S09, S15, and S17. These studies explore how digital models of facilities and processes can enhance spatial efficiency and improve overall organizational performance.

4.3 RQ3 - Stakeholders in RA4DT

Digital twin (DT) systems encompass a broad range of stakeholders whose involvement reflects the multidisciplinary nature of these technologies. This diversity is evident in the primary studies of this review, where different actors participate in the development, deployment, and use of DT architectures. The stakeholders reported in the RA4DT can be categorized as listed in Table 2 and described below.

- **Technology providers** play a foundational role by offering the platforms, hardware, and software solutions required for implementing DT systems. These stakeholders are typically responsible for the technical infrastructure that supports the integration and operation of digital replicas (S01, S09, S11).
- **Energy managers** are engaged in the monitoring and optimization of energy consumption within industrial and smart environments. They leverage DT systems to enhance efficiency and sustainability in energy use (S02).
- **Industrial system operators** utilize DTs to oversee and control physical processes in real time. Their focus lies in improving operational safety, reliability, and responsiveness across various industrial scenarios (S02, S03, S04, S16).
- **Product designers** employ digital twins during the conceptual and development phases of complex products. DTs support iterative design, simulation, and performance evaluation (S03).
- **Manufacturers of complex products** use DTs to streamline the production of high-precision goods, ensuring alignment between design specifications and production outcomes (S04).
- **Assembly teams** interact with DTs to enhance coordination, reduce errors, and facilitate adaptive assembly procedures, especially in high-mix, low-volume manufacturing contexts (S04).

- **Manufacturing industries** adopt digital twins to optimize production workflows, monitor machine performance, and enable predictive maintenance. This group represents a significant portion of DT applications in industrial settings (S05, S07, S08, S09, S12, S14).
- **Researchers in industrial technologies** contribute to the advancement of DT methodologies and architectures, often exploring novel use cases and technical challenges associated with integration and scalability (S05, S07, S08, S11, S12, S14, S15).
- **Maintenance teams** rely on DTs for condition monitoring and predictive maintenance strategies, improving asset longevity and minimizing downtime (S06).
- **Engineering teams** benefit from DTs in tasks related to system design, integration, and lifecycle management, ensuring that engineering decisions are data-driven and aligned with system behavior (S06, S10).
- **User communities** represent the end-users of systems monitored or controlled by digital twins. These stakeholders provide feedback that can be used to improve system usability and functionality (S10).
- **Developers of digital solutions** are responsible for creating, customizing, and deploying DT applications. Their role is central in ensuring interoperability, data integration, and user interface design (S10, S15, S16, S17).
- **Small and medium-sized enterprises (SMEs)** are increasingly adopting DTs to gain competitive advantages through digital transformation. Their needs often drive the development of more accessible and scalable DT solutions (S11).
- **General industries** constitute a broad stakeholder group applying DTs in diverse domains such as logistics, supply chain, and quality assurance (S15).

Table 2: Stakeholders of reference architectures and their related IDs

Stakeholder	**RA4DT**
Technology providers	S01, S09, S11
Energy managers	S02
Industrial system operators	S02, S03, S04, S16
Product designers	S03
Complex product manufacturers	S04
Assembly teams	S04
Manufacturing industries	S05, S07, S08, S09, S12, S14
Industrial technology researchers	S05, S07, S08, S11, S12, S14, S15
Maintenance teams	S06
Engineering teams	S06, S10
User community	S10
Digital solution developers	S10, S15, S16, S17
Small and medium-sized enterprises (SMEs)	S11
General industries	S15

4.4 RQ4 - Engineering approaches for constructing RA4DT

The analysis of reference architectures for Digital Twins reveals a diverse yet convergent set of approaches that support the development, implementation, and operation of Digital Twin systems, as listed in Table 3.

An important decision is the modeling of physical and digital components, including computational, communicational, and control elements, often supported by advanced automation techniques such as fuzzy logic and Bayesian networks (S01). Several studies emphasize as main concerns for architecting DTs the integration between physical and cyber domains, highlighting the importance of synchronization (S08, S16), real-time communication (S12), and the definition of interactions across domains (S07).

High-fidelity digital modeling and the use of contextual data play a crucial role in decision-making processes and asset control, supported by simulation systems and optimization tools such as knowledge graphs (S03). Similarly, 3D modeling and assembly process simulation are considered for architecting applications in manufacturing and industrial settings (S04).

For defining the structure of DTs architectures, some studies propose layered architectures, including physical, data, cyber, interaction, service, security, and connectivity layers (S05, S15). Others develop architectures based on established frameworks such as RAMI 4.0 (S02), or propose microservice-based modular platforms to ensure scalability and flexibility (S11).

Architectures S09 and S10 define as important DT processes the collection, transformation, and analysis of large volumes of data, involving big data analytics and machine learning to monitor and control physical systems. These functionalities can be further enhanced by AI services, data management, and the orchestration of resources across IoT, edge, and cloud infrastructures (S11).

The semantic representation of knowledge and the use of ontologies are also explored in S02 and S03 as means to improve interoperability and reasoning capabilities. Additionally, subject-oriented modeling (S13) and the use of class diagrams to define data types (S14) were employed due to the need for precise information modeling.

Moreover, several studies propose specific evaluation and validation methods, including risk assessment (S06), implementation of monitoring tools to optimize processes (S16), and staged approaches such as learning, replication, and creativity stages (S17), which align with lifecycle considerations in Digital Twin development.

4.5 RQ5 - Industry participation in the engineering of RA4DT

Two main aspects were analyzed to evaluate industry participation in the development of reference architectures for Digital Twins: the direct involvement of industry in the design of these architectures and the current use of such architectures in industrial scenarios.

Regarding the industry's direct involvement in the development process, the last two columns in Table 1 present whether the sector directly contributed to the development of the architecture and whether a case study was applied in an industrial setting.

82.4% (14/17) of the studies include case studies in which the proposed reference architecture was applied in industrial scenarios.

Table 3: Engineering of Reference Architectures for Digital Twins

ID	Approaches
S01	Modeling of key elements (computation, communication, and control); Definition of interactions between physical and digital components; Context-aware automation using fuzzy logic and Bayesian networks
S02	Analysis of Digital Twin concepts and frameworks; Architecture development based on RAMI 4.0; Proof of concept with Semantic Web
S03	Creation of high-fidelity digital models; Integration of environmental layouts with contextual data; Simulation system for asset decision-making and control; Optimization recommendations using knowledge graphs
S04	Three-dimensional digital modeling; Assembly process planning and simulation; Model-based instruction generation
S05	Physical layer; Data extraction and consolidation layer; Cyberspace layer; Interaction layer
S06	Risk assessment plan and communication/control system; Development and integration of Digital Twin tools; Model and platform validation
S07	Domains: user, Digital Twin, sensors/control, physical; Cross-domain functionalities (information exchange, security)
S08	Creation of the Digital Twin; Synchronization of the Digital Twin with real data; Use of the Digital Twin for event-driven simulations
S09	Intelligent connection and data collection; Data conversion and big data analysis; Construction and updating of digital models; Intelligence, visualization, and predictive maintenance services
S10	Definition of physical problems and development of digital model; Data analysis with Big Data and machine learning; Implementation to predict, monitor, and control physical processes
S11	User requirements gathering (testbed owners); Creation of a modular platform based on microservices; Implementation of components such as Data Management, AI services, Big Data analytics, simulation, and orchestration of resources at edge, IoT, and cloud
S12	Physical space (sensors/controllers); Cyber space (data visualization/analysis); Communication network for real-time data exchange
S13	Review and analysis of existing models; Creation and validation of subject-oriented model
S14	Use of class diagrams to describe the data types used by the Digital Twin; Software architecture description
S15	Six-layer architecture: Physical, Data, Digital Twin, Service, Security, and Connectivity
S16	Identification of Observable Manufacturing Elements (OMEs); Synchronization of OMEs with the communication domain; Creation of the Digital Twin entity for virtual representation of the physical system; Implementation of data analysis tools and simulations to monitor and optimize the process
S17	Learning stage; Replica stage; Creativity stage

However, less than the half, i.e., 47% (8/17), of the architectures (S04, S07, S10, S11, S12, S15, and S16) had direct industrial involvement in their development. In this case, most of the companies participating in the construction of RA4DT are from the automotive and aerospace industries.

4.6 RQ6 - Concerns of RA4DT

The concerns defined by the authors in their respective reference architectures were collected to address this question. Significant challenges are summarized as follows.

- **Devices and Data Integration:** The efficient integration between physical and digital components emerges as one of the major challenges (S01, S02, S10), reflecting the difficulty in combining data and systems of different natures. In particular, architectures S04 and S06 face challenges in building high-fidelity multiscale models, requiring advanced technologies for real-time processing, and encountering limitations in data interfaces and communication protocols.
- **Synchronization and Control:** DT requires capturing large amounts of real-time data from distributed devices and systems (S01, S16). Such data must be synchronized in a manner that allows high-fidelity information to be transmitted to the digital models (S02, S03, S04, S06). However, most of the time, there are hardware limitations that generate high latency between the DT systems' communication and application layers (S05).
- **Digital Model Fidelity:** There are still some difficulties in constructing a high-fidelity, multi-scale DT system for realistically representing physical entities (S02, S03, S04, S06). There is a need for systems with context-awareness capabilities to operate effectively in dynamic environments (S03, S09). However, some challenges remain regarding the integration of predictive models with real-time data and harnessing model fidelity. Therefore, there is a need for better artificial intelligence models, considering the nature of the DT systems (S12).
- **Maintainability:** DT systems must be easy to maintain or change when variations occur between the digital model and the real system (S09). Therefore, real-time maintenance and updating of digital replicas are required (S16). This capability is important to guarantee the resilience of the DT due to changes in real systems' behaviors.
- **Security and Privacy:** This is also a significant concern, as these systems manage sensitive data and must ensure deterministic transactions in distributed environments (S01, S06, S15). The diversity of communication protocols and the lack of standardization (S08, S17) complicate ensuring interoperability and reliable connectivity between different systems and devices.
- **High-Cost:** Some financial and technical challenges are reported in the studies, such as the high cost and time required for development (S12), which particularly affect architectures aimed at small and medium-sized enterprises (SMEs), given their more limited resources for implementation. Another challenge mentioned is the continuous adaptation of digital models (S16).
- **Multi-organizational collaboration:** Further challenges involve institutional and collaborative issues, as well as the creation of political incentives to foster cooperation between academia and industry (S17).

4.7 RQ7 - Contributions of the RA4DT

The contributions of reference architectures for Digital Twins (DTs) analyzed in this review can be grouped into the following categories:

- **Interoperability and Standardization:** Several studies propose solutions aimed at standardizing and integrating heterogeneous systems to foster interoperability. Study S02 stands out for adopting the RAMI 4.0 model and Semantic Web technologies (such as RDF and OWL) to achieve interoperability in industrial energy systems. S07 proposes a generic model with well-defined layers and an analysis of DT maturity phases. S08 presents a class diagram and an information model (P4R) designed for customized production, facilitating the structuring of other architectures. Study S11 adopts a modular approach based on microservices and open communication standards. S13 introduces a subject-oriented framework focused on clarity and interoperability, while S16 aligns its proposal with ISO 23247 and RAMI 4.0 standards, reinforcing system compatibility.

- **Architectures Based on Industrial Standards:** Some architectures explicitly rely on well-established industrial models, such as RAMI 4.0 and ISO 23247. Studies S02, S10, and S11 use RAMI 4.0 as their foundational model, whereas S12 is based on ISO 23247 for robotic drilling applications. Study S16 adopts both standards, promoting interoperability and alignment with Industry 4.0 practices.
- **Integration with Artificial Intelligence and Machine Learning:** The incorporation of artificial intelligence (AI) and deep learning techniques is an important trend. Study S05 employs graphs and computational models for real-time failure prediction and processing. S09 integrates deep learning techniques into the 5C-CPS framework, enhancing analytical capabilities and decision-making. S15 applies AI models in healthcare applications, combining connectivity with security.
- **Support for Customized Production and Product Redesign:** Studies such as S03, S08, and S10 focus on the flexibility of the production process. S03 presents a three-layer architecture to support product family redesign, integrating IoT and knowledge graphs. S08 emphasizes the structuring of architectures oriented toward production customization through the P4R model. S10 highlights the use of DTs as services accessible via the internet, targeting mass customization and iterative development cycles.
- **Optimization of Industrial Processes and Manufacturing:** Several studies propose architectures designed to enhance efficiency, reliability, and precision in manufacturing processes. S03 and S04 focus on product reconfiguration and intelligent assembly, respectively. S05 and S06 address real-time optimization and operational safety. Although less detailed, study S14 addresses the optimization of manufacturing processes.
- **Scalable, Modular, and Cloud-Based Architectures:** Scalability and modularity are emphasized in studies such as S01, S05, S10, and S11. S01 proposes an ontology-based architecture featuring hybrid interaction modes and strong cloud integration. S05 presents a low-latency solution for real-time computing. S10 emphasizes DTs as remotely accessible services. S11 offers a modular, distributed architecture based on microservices, suitable for SMEs.
- **Security, Privacy, and Trustworthiness:** Studies such as S06, S15, and S17 address essential attributes for sensitive industrial environments. S06 proposes safety solutions for operators in critical environments. S15 includes a dedicated security layer for healthcare applications. Finally, S17 stands out by directly addressing the attributes of privacy, security, real-time capability, and situational awareness—elements considered fundamental in Industry 4.0.

5 Discussion

The concept of Digital Twins (DTs) originated in the early 2000s. However, it is only in recent years—fueled by rapid technological advancements—that DTs have gained significant traction as enablers of industrial processes across diverse domains. Despite the relative maturity of the Digital Twin concept itself, the construction of formal artifacts such as reference architectures for supporting DT-based applications remains an emerging area of concern within both academia and industry.

In this study, multiple reference architectures for Digital Twin applications were identified. Notably, all these architectures exhibit a close alignment with the principles and technological stack of Industry 4.0, underscoring the critical role of DTs in the ongoing digital transformation of manufacturing and related sectors. The wide range of stakeholder involvement—spanning academic researchers, industrial practitioners, technology providers, and system integrators—demonstrates the cross-sectoral relevance and applicability of Digital Twin systems. Each stakeholder group contributes uniquely to the evolution and practical deployment of DTs, fostering a dynamic and collaborative ecosystem.

The motivation behind constructing these reference architectures was consistently linked to advancing capabilities in manufacturing, asset management, maintenance, and process optimization. These domains frequently serve as testbeds for the application and validation of DT solutions, reflecting their readiness to adopt emerging technologies that enhance operational efficiency and decision-making.

Moreover, the analysis revealed notable cases where industrial stakeholders actively participated in or supported the development of reference architectures. These collaborations between academic initiatives and major industrial organizations illustrate a shift in industry perspective, signaling a growing appreciation of the strategic importance of standardized architectural approaches. This scenario marks a departure from earlier observations—such as those noted in [20]—in which industrial engagement in the formulation of reference architectures was sporadic or absent.

Nonetheless, the analysis also reveals an ongoing divergence in architectural proposals, suggesting that a unified, universally accepted reference architecture for Digital Twins has yet to emerge. This diversity reflects the heterogeneous nature of application domains, the varying levels of technological maturity, and the integration of complementary technologies such as ontologies, knowledge graphs, simulation, artificial intelligence, and Semantic Web frameworks. Each proposed architecture thus tends to be tailored to its specific context, embodying distinct design priorities and implementation strategies.

Ultimately, these findings point toward the pursuit of innovative and adaptive reference architectures, capable of addressing the complex and evolving requirements of Industry 4.0 and other emerging technological paradigms. The continued development of such architectures will be critical for ensuring the scalability, interoperability, and intelligence of future Digital Twin systems.

Threats to validity

The primary threats to validity identified in this literature review, as is typical for secondary studies [4], include study selection validity, data extraction validity, and overall research validity. This section outlines the strategies employed to mitigate these threats.

Study selection validity: The construction of the search string may compromise the relevance of the primary studies identified. To mitigate this threat, we followed the guidelines for rapid literature review proposed by [11]. The search string was designed to return as many studies as possible; for this, no filters based on title, abstract, keywords, or year were applied. Two databases, Google Scholar and Scopus, were used, as they index studies in both academic databases, such as IEEE Xplore, ACM DL, Elsevier, as well as other gray literature sources, including ArXiv, ResearchGate, and books. However, despite our efforts to obtain the most significant quantity of primary studies, it is possible that some reference architectures for DTs were missed.

To ensure an unbiased selection process, we predefined research questions and established explicit inclusion and exclusion criteria. The protocol for this secondary study was reviewed by all authors with experience in secondary studies, ensuring its methodological rigor. The questions and criteria were designed to provide transparency in the selection of primary studies. To enhance the reliability of the process, each study was independently assessed by two researchers, with disagreements resolved through peer discussion. Nonetheless, some studies proposing reference architectures may have been excluded during the initial screening due to insufficient information in key sections such as the title, abstract, keywords, introduction, or conclusions.

Data validity: Another potential threat to this work concerns the data extraction process from primary studies, as not all information was explicitly available to directly answer the research questions, requiring some degree of interpretation. To mitigate this, any disagreements between reviewers were resolved through discussion until full consensus was achieved. Additionally, the extracted data were cross-checked to reduce the risk of researcher bias.

Research validity: The rapid literature review method was selected over other secondary study methods due to the intended scope (i.e., to define an overview of primary studies rather than to assess results or compare contributions of those studies) and the available resources (i.e., time and personnel) for this study. Rapid reviews are an effective strategy for consolidating knowledge in a particular domain [11]. Regarding the generalizability of this study, we acknowledge a limitation arising from the inclusion of only studies published in libraries indexed on Scopus and Google Scholar. This approach may limit the generalizability of our findings, as it could exclude reference architectures developed in industry or those disseminated through gray literature, such as standards repositories (e.g., ISO, IEC, or IEEE). To achieve generalizability, this study's results could be further extended with evidence obtained from gray literature through a Multivocal Literature Review (MLR).

6 Conclusion

Although the concept of Digital Twins is not new, the associated technologies and applications have only recently demonstrated significant potential to transform industrial processes and drive innovation across various sectors, including healthcare, agriculture, the automotive industry, and smart grids, among others. Considering DT architectures and ways to standardize such applications is a growing concern in both industry and academic contexts.

This study presents a literature review on reference architectures for Digital Twins, aiming to understand the current state of research, identify prevailing trends, challenges, and opportunities in this emerging field. The findings revealed a significant increase in research interest in Digital Twin architectures since 2020, with prominent contributions from Italy, China, and Germany, primarily in the aerospace and automotive industries.

The review confirms a strong link between Digital Twins and Industry 4.0, particularly in applications such as real-time monitoring, process optimization, predictive maintenance, and product personalization. Key challenges identified include the integration of physical and digital systems, data security and privacy, and the lack of standardization and interoperability. Conversely, the study highlights opportunities related to the development of scalable and modular architectures, adoption of recognized industry standards, and emphasis on essential attributes such as real-time processing and interoperability. Addressing the identified challenges and capitalizing on the opportunities will depend on sustained research efforts and stronger collaboration between academia and industry.

ARTIFACT AVAILABILITY

Artifacts related to data collection and analysis used in this study are available in [22].

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