The Systematic Literature Review on Digital Twin Architectures for TwinArch Design

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ABSTRACT

The Systematic Literature Review (SLR) presented in this document is part of the research conducted for the "TwinArch: A Digital Twin Reference Architecture" paper. This SLR aims to explore the current state of Digital Twin architectures through the lens of the Software Engineering Institute's Views & Beyond methodology. The review investigates the way in which researchers design and documents DT architectures, highlighting the architectural perspectives relevant to the design and implementation of Digital Twins. Please remember to cite the TwinArch work when referencing its findings.

KEYWORDS

Systematic Literature Review, Digital Twin, Software Architecture, Views&Beyond

1 MOTIVATION

Present the topic of the literature review, including background of research field, goal, methodology, and contribution of the paper (e.g., map of the state of the art, reusable classification approach, evaluation of results, discussion of results, and target audience)

2 BACKGROUND

3 STUDY DESIGN

3.1 Research Goal

This study aims to characterize the state-of-the-art of Digital Twin architectures with respect to the ISO 42010 standard and the SEI View & Beyond method. The research investigates how current architectural models are designed and documented, adopting the Goal-Question-Metric (GQM) approach [38] to define its core research objective.

Purpose	Characterize
Issue	Digital Twin architectures for
Object	understanding their design and documentation
Viewpoint	from researchers and developers perspective.

3.2 Research Questions

To achieve these goals, we formulated four Research Questions (RQs).

RQ1: *How are the primary studies categorized according to the SEI architectural views?*
Rationale: This research question aims to identify which SEI architectural views are most commonly used to guide the documentation of Digital Twin architectures. Understanding the alignment between the architectural views presented in the primary studies and the ones advocated by SEI (e.g., Module, Component & Connector, and Allocation views) is critical to assessing the adherence of DT architectures to standardized documentation practices.

RQ2: *How are the primary studies classified based on the SEI architectural styles?*
Rationale: The goal of this research question is to determine which architectural styles are most frequently employed and to identify the core elements and relationships commonly found in DT architectures. Architectural styles play a key role in defining system organization, communication, and constraints, and different views may require distinct styles tailored to specific purposes. By examining how these styles are applied, we can uncover patterns in element selection, common relationships, and constraints, offering insights into the design decisions made in the development of DT architectures.

RQ3: *What type of notation (informal, semi-formal, or formal) is mostly used to document DT architectures?*
Rationale: this question focuses on assessing the types of notations and modeling languages employed for documenting DT architectures. Notations can be classified into three categories: informal (e.g., textual descriptions or sketches), semi-formal (e.g., UML diagrams), and formal (e.g., Architecture Description Languages). Understanding the preferred documentation approaches within the field is essential for evaluating how well these notations convey key architectural aspects. By identifying trends in notation usage, we aim to assess how they influence the clarity, precision, and consistency of DT architecture documentation.

3.3 Initial search

The research questions were broken down into facets, and a list of synonyms, abbreviations, and alternative spellings was created for each term following the guidelines of Kitchenham and Charters [24]. Additional terms were derived from subject headings used in journals and scientific databases. The search string was constructed by combining terms using conjunctions (AND) and disjunctions (OR) for each main concept. To validate its effectiveness, the search string was tested using a set of five control studies [5, 6, 13, 40, 43, 44] previously identified by one of the authors. The accuracy of the search string was evaluated by verifying if these control studies were successfully retrieved when applied to the Scopus search engine. The finalized search string is the following:

("Digital Twin" **OR** "Virtual Twin" **OR** "Digital Replica" **OR** "Virtual Replica") **AND** (Architect* **OR** Framework **OR** Platform **OR** Document* **OR** View **OR** Style)

The selection process is illustrated in Figure 1. It began by executing the search string in the Scopus database on June 2024 that resulted in 5508 studies. The selection process we followed is shown in Figure 1, representing the steps executed and their results. In the *automated search* step, a researcher executed the search string in the electronic database Scopus[1] on June 2024. The search string was filtered by title and abstract and configured for retrieving studies published after 2019 in the areas of computer science and engineering, yielding 5508 studies.

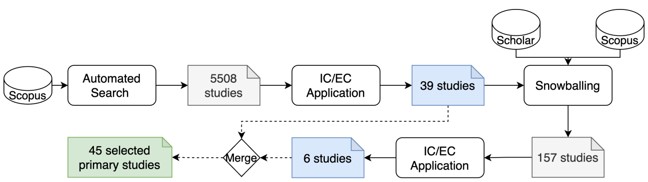

Figure 1: Systematic Literature Review Process.

3.4 Application of selection criteria

To support the selection of retrieved studies by the automated search strategy, we defined inclusion and exclusion criteria to include or discard a manuscript.

Inclusion Criteria. To be included in our analysis, a study must accomplish all the following inclusion criteria:

IC1. The study is related to the topic under investigation, i.e., defining and documenting Digital Twin architectures.
IC2. The study is written in English.
IC3. The study is peer-reviewed.
IC4. The study is a primary study.
IC5. The study has been published after 2019.
Rationale: Despite Digital Twins have over a 20-year history, publications on DT architectures have significantly increased since 2019 [20].
IC6. The study was published in journals or conference proceedings.
IC7. The study was published in high-ranking venues.

Exclusion Criteria. We excluded a publication if it satisfies at least one of the five exclusion criteria listed below:

EC1. The study is an earlier version of a more recent or complete version that has been identified.
EC2. The study treats digital twins as software characterized solely by simulated models.
EC3. The study conflates the concept of digital twins with the Metaverse.
Rationale: The Metaverse is a virtual world designed for social interactions and immersive experiences, while DTs replicate physical assets for operational use.
EC4. The study confuses the modeling aspects of Digital Twins with artificial intelligence models.
Rationale: Artificial intelligence models are tailored algorithms for specific analyses, whereas DTs offer holistic system representation integrating AI for analytics and prediction.

In the *Application of Inclusion and Exclusion Criteria* step, two researchers independently analyzed each study's title and abstract and, if necessary, read the full text, applying the IC/EC previously listed. Each manuscript was categorized as "yes", "no" or "doubt". Publications that received two "yes" votes were included, while studies with two "no" votes were excluded. The researchers discussed the remaining manuscripts to reach a consensus. At the end of this step, 5469 studies were excluded and the remaining 39 manuscripts were included in the final set of selected papers

3.5 Snowballing

To mitigate the risk of missing relevant literature, we further executed the complementary *snowballing search* step. For each of the 39 papers, we applied backward snowballing on Scopus to identify referenced studies. For forward snowballing, we used Google Scholar[2] to automate the retrieval of manuscripts citing selected ones. An author aggregated all the retrieved studies and duplicates were automatically removed, resulting in 157 papers. The inclusion/exclusion criteria step was repeated for these 157 papers, resulting in 6 additional studies. Finally, the two sets of papers were merged, resulting in the set of *45 selected primary studies* listed in Table 2.

Table 1: Data Extraction Form Design.

Research Question	*Evidence to be extracted*
RQ1: How are the primary studies categorized according to the SEI architectural views?	List of the extracted architectural views.
RQ2: How are the primary studies classified based on the SEI architectural styles?	List of the extracted architectural styles, elements and relations.
RQ3: What type of notation (informal, semi-formal, formal) is mostly used to document DT architectures?	List of the extracted notations used to document the proposal.

3.6 Data Extraction

To facilitate the data extraction process, we created the data extraction form detailed in Table 1. This form was utilized to report the evidence extracted from the selected papers to answer the research questions.

4 DATA EXTRACTION AND ANALYSIS

Two researchers used the extraction form shown in Table 1 to extract evidence from the selected primary studies for answering the research questions. Finally, they shared their findings and discussed discrepancies to reach a final consensus on the extracted data.

[1]https://www.scopus.com/

Table 2: Selected primary studies.

ID	Title	Ref.
M01	A Blockchain-based Digital Twin for IoT deployments in logistics and transportation	[11]
M02	Knowledge-based digital twin system: Using a knowledge-driven approach for manufacturing process modeling	[42]
M03	Designing and prototyping the architecture of a digital twin for wind turbine	[27]
M04	The convergence of Digital Twins and Distributed Ledger Technologies: A systematic literature review and an architectural proposal	[39]
M05	A digital twin framework for large comprehensive ports and a case study of Qingdao Port	[48]
M06	Towards a Distributed Digital Twin Framework for Predictive Maintenance in Industrial Internet of Things (IIoT)	[1]
M07	Digital Twin Platform for Water Treatment Plants Using Microservices Architecture	[35]
M08	Smart City Digital Twin Framework for Real-Time Multi-Data Integration and Wide Public Distribution	[2]
M09	makeTwin: A reference architecture for digital twin software platform	[43]
M10	Digital Twins for Smart Spaces—Beyond IoT Analytics	[23]
M11	Digital Twins for Anomaly Detection in the Industrial Internet of Things: Conceptual Architecture and Proof-of-Concept	[12]
M12	OpenTwins: An open-source framework for the development of next-gen compositional digital twins	[34]
M13	Digital Twins in Healthcare: An Architectural Proposal and Its Application in a Social Distancing Case Study	[13]
M14	Towards AI-assisted digital twins for smart railways: preliminary guideline and reference architecture	[14]
M15	A Theoretical Open Architecture Framework and Technology Stack for Digital Twins in Energy Sector Applications	[22]
M16	Reference architecture for digital twin-based predictive maintenance systems	[46]
M17	Edge intelligence-driven digital twin of CNC system: Architecture and deployment	[49]
M18	A Model-Driven Digital Twin for Manufacturing Process Adaptation	[40]
M19	Towards a Product Line Architecture for Digital Twins	[31]
M20	Architecting Digital Twins Using a Domain-Driven Design-Based Approach*	[26]
M21	Digital twins: An analysis framework and open issues	[5]
M22	Collaboration of Digital Twins Through Linked Open Data: Architecture With FIWARE as Enabling Technology	[8]
M23	A digital twin framework for online optimization of supply chain business processes	[30]
M24	Symbiotic Evolution of Digital Twin Systems and Dataspaces	[45]
M25	Modeling Digital Twin Data and Architecture: A Building Guide With FIWARE as Enabling Technology	[9]
M26	IoTwins: Toward Implementation of Distributed Digital Twins in Industry 4.0 Settings	[10]
M27	Cognitive Digital Twins for Resilience in Production: A Conceptual Framework	[15]
M28	Digital Twin Platforms: Requirements, Capabilities, and Future Prospects	[25]
M29	Conceptualizing Digital Twins	[17]
M30	Key-Components for Digital Twin Modeling With Granularity: Use Case Car-as-a-Service	[41]
M31	The Forging of Autonomic and Cooperating Digital Twins	[33]
M32	Digital Twin for Intelligent Context-Aware IoT Healthcare Systems	[16]
M33	Self-Adaptive Manufacturing with Digital Twins	[4]
M34	A Methodology for Digital Twin Modeling and Deployment for Industry 4.0	[37]
M35	Process Prediction with Digital Twins	[6]
M36	An intelligent agent-based architecture for resilient digital twins in manufacturing	[47]
M37	Systems Architecture Design Pattern Catalog for Developing Digital Twins	[44]
M38	A six-layer architecture for the digital twin: a manufacturing case study implementation	[32]
M39	A design framework for adaptive digital twins	[18]
M40	Modeling and implementation of a digital twin of material flows based on physics simulation	[21]
M41	A Four-Layer Architecture Pattern for Constructing and Managing Digital Twins	[28]
M42	Model-driven development of a digital twin for injection molding	[3]
M43	Model-based digital twins of medicine dispensers for healthcare IoT applications	[36]
M44	Leveraging Digital Twins for Healthcare Systems Engineering	[29]
M45	Cloud-Native Architecture for Mixed File-Based and API-Based Digital Twin Exchange	[19]

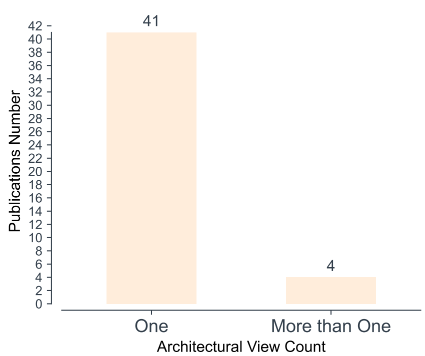

Figure 2: View count.

4.1 RQ1. How are the primary studies classified according to the SEI architectural views?

To identify the architectural views that have been adopted to document Digital Twin architectures, a thorough analysis was conducted on sentences extracted from the selected primary studies to answer this research question. Figure 2 highlights the number of publications that present one or more architectural views, revealing that 41 out of 45 studies (91%) use a single architectural view to document Digital Twin architectures, while only four studies [11–13, 46] apply multiple views. Specifically, these four studies combine two views to document the proposed architecture.

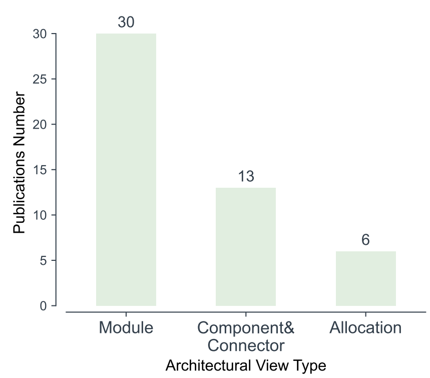

Figure 3: View type distribution.

[2]https://scholar.google.com/

Figure 3 classifies these studies according to SEI's module, component and allocation views [7]. It shows that 66% (30 out of 45) of studies rely on the module view, mainly for documenting Digital Twins at a high level of detail. Another 29% (13 out of 45) use the Component-and-Connector view to depict development aspects, such as the interaction of components at runtime for implementing specific features. Only 13% (6 out of 45) utilize the allocation view to map architectural elements to hardware devices or Commercial-off-the-shelf (COTS) software components.

Figure 4 illustrates the occurrence of categories like basics, software interface, and behavior which are the beyond aspects defined by the SEI. Figure indicates that 17% (8 out of 45) of studies include basic elements such as context diagrams to define the scope of the Digital Twin. Additionally, 31% (14 out of 45) describe software interfaces to explain interactions between components, including data flows or API calls. Finally, 86% (39 out of 45) document behavioral aspects by detailing execution steps through events and actions. These include performing specific use cases, such as wind turbine predictive maintenance [1] or a Smart City Digital Twin [2].

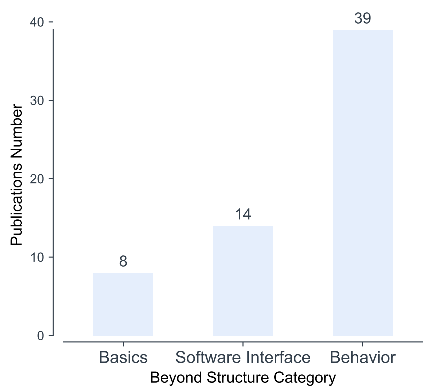

Figure 4: Beyond aspect distribution.

This analysis highlights the significant need to describe complex architectures like Digital Twins at a high level of detail, to document fundamental elements and their interrelationships. Furthermore, the results suggest that at lower abstraction levels, authors document specific functionalities by illustrating the interactions between software components. When detailing the implementation of Digital Twins for specific application domains or technologies, the Allocation View proved to be an effective model for design.

4.2 RQ2. How are the primary studies classified based on the SEI architectural styles?

To answer RQ2, we analyzed the evidence collected from the selected primary studies regarding the architectural styles used in modeling the architectural views of Digital Twin documentation. The architectural styles we consider are those defined by the SEI for each type of view. Since SEI specifies multiple styles per view, we focus on the specific styles applied within DT architectures.

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