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DIGITAL TWINS IN CIVIL ENGINEERING

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SUMMARY: *A plenitude of digital twin reviews have been published in recent years, most of which, however, focus on project-specific digital twin implementations or specific application areas within civil engineering. The architecture, including the composition of internal elements, and schemas of digital twins have not been studied yet in a universally applicable and systematic manner. In this study, a multivocal review of digital twins in civil engineering is conducted, combining a systematic literature review and a gray literature review to capture both peer-reviewed literature and industry practices. To achieve a shared understanding of digital twins in civil engineering, a systematic survey of definitions, schemas, system architectures, and internal elements of digital twins is conducted. Drawing from the results of the review, (i) a definition, (ii) a pattern for a schema, and (iii) a reference architecture for digital twins are proposed, serving as a blueprint for facilitating digital twin implementations in civil engineering.*

KEYWORDS: *digital twins, definitions, schema, system architecture, reference architecture, multivocal literature review.*

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1. INTRODUCTION

Sustainability and digitalization are two powerful concepts that, brought together, are capable of making a significant contribution to solving current and future global issues, such as poverty, hunger, drinking water shortage, armed conflicts as well as education and gender inequality (United Nations 2023). The ability to use digital technologies for improving sustainability is referred to as "sustainable digitalization" (German NGO Forum on Environment and Development 2019). Likewise, sustainability exerts an important impact to digitalization itself, as it is important that digitalization takes place in a sustainable way, supporting environmental and societal goals. Sustainable digitalization involves using digital tools and processes to implement sustainability improvements, such as reducing environmental impact or increasing resource efficiency. In the architecture, engineering and construction (AEC) industry, the growth of digital technologies and the need for sustainable solutions have paved the way for Industry 4.0, which denotes the implementation of cyber-physical systems for creating smart factories by using the Internet of Things (IoT), big data, cloud computing, artificial intelligence, and communication technologies in real time (Rupp et al. 2021). The introduction of new digital technologies and sustainable solutions throughout the life cycle of engineering structures provides additional means, ways, and opportunities to promote and to support sustainable digitalization and to advance information and communication technology (ICT) in the AEC industry (Kovacic et al. 2020). Moreover, new technologies and paradigms, such as the Internet of Things, cyber-physical systems and blockchain technology, have been acting as catalysts for sustainable digitalization in the AEC industry (Raj 2021).

Digital transformation is not new in the AEC industry (Wang et al. 2022a). Digital transformation describes the utilization of digital technology to facilitate change, to restructure businesses, and to create new business models and values, interconnecting products and production systems to global product networks (Verhoef et al. 2021). Digital technologies, such as building information modeling (BIM), artificial intelligence (AI), and IoT devices, have facilitated the development of ICT systems and corresponding technical transformations into digital-assisted structures (digitalization as defined by Gebre-Mariam and Bygstad (2019)) as well as the conversion of analog information into digital information (digitization as defined by Schumacher et al. (2016)). The idea of pairing the physical and the virtual (not necessarily "digital") world to predict the behavior of the world by means of twins has been a key element in the development of analog twins in ancient times, such as the Antikytherna mechanism (Moussas 2014), to digital twins in modern times, showcasing the drive towards digital transformation. The concept of digital twins dates back to pivotal work conducted within the Apollo 11 mission in 1969, involving building a spacecraft replica to mirror its counterpart in space and enable the astronauts to train and to understand how to control the actual spacecraft (NASA 1969).

Despite the vital efforts conducted in digital twin research and development, there is neither a clear definition of digital twins nor a common understanding of architectures, internal elements, and schemas of digital twins. A clear definition of digital twins, a pattern for a schema as well as a reference architecture, including the internal elements, would advance (i) efficient communication between engineers, as the meaning and description of digital twins and digital twin elements would clearly be defined, (ii) precise analysis of digital twins, as the architecture of digital twins would provide a foundation for analyzing digital twins and would allow detecting and mitigating design issues, and (iii) reusability of digital twins, as a common understanding would facilitate interoperability. Furthermore, the pattern for the schema as well as the reference architecture would serve as a blueprint for digital twin implementations in civil engineering, providing a common understanding and enhancing the reliability and performance of digital twins, with significant implications for researchers, practitioners, and policymakers. To provide an overview of the definitions, schemas, and system architectures of digital twins, this paper presents a multivocal literature review of digital twins in civil engineering. Based on the overview, the paper provides a definition of digital twins, a pattern for a schema for digital twins, a reference architecture describing systems for digital twins, including the internal elements, as well as open research questions to be addressed concerning use cases and trends.

The remainder of this paper is structured as follows: First, an overview of digital twins in engineering is provided (Section 2), followed by a presentation of the review methodology and the research questions (Section 3). Next, the results of the review are presented in the form of findings answering the research questions (Section 4). Then, the key findings are discussed, recommendations are formulated concerning the definition, use cases, trends, schema, and reference architecture for digital twins (Section 5). Finally, the paper concludes with a summary of the study and a discussion of future research to further advance digital twins in civil engineering (Section 6).

2. DIGITAL TWINS IN ENGINEERING

Nowadays, digital twin (DT) research is a vital field across the engineering disciplines (Manzoor et al 2021). In this section, an overview of DT applications in engineering disciplines is provided, followed by a discussion of standardization and abstraction of digital twins.

2.1 Applications of digital twins in engineering disciplines

In civil engineering, DT models have been gaining increasing attention (Bado et al. 2022), have been covering all life-cycle stages of buildings (Jiang et al. 2021a), and have been proving effective in enhancing operation, efficiency, productivity, quality, and cost management (Jungmann et al. 2023). Digital twins have been proposed as a basis for adaptive structures (Seifried et al. 2022) and for implementing predictive maintenance strategies in civil engineering (Smarsly et al. 2022). In transportation, using digital twins throughout the life-cycle of transportation infrastructure has improved infrastructure design, construction, operation, and maintenance (Gao et al. 2021). In the discipline of smart cities, use cases of urban DT platforms and applications have been documented, focusing on district-scale urban DT applications of buildings, transportation, energy, water, utility, and infrastructure (Alva et al. 2022), while green metrics have been combined with digital twins for sustainability planning and governance of smart buildings to help understand cities as complex sociotechnical systems (Corrado et al. 2022). In facility management, the application of digital twins throughout the "product" life-cycle offers advantages for both building operators and service providers (Siccardi and Villa 2023). In structural engineering, DT concepts have been proposed in multiple directions, e.g. to provide physical, conceptual, and methodological foundations for designing and operating engineering structures (Rolfes and Hübler 2022). In structural health monitoring, digital twins have been increasingly deployed to continuously update the digital models that mimic the corresponding engineering structures with sensor data, aiming to analyze and to predict structural conditions (Bado et al. 2022). In construction robotics, considering both robot models and building models, digital twins have been deployed to improve safety and productivity on construction sites (Lee et al. 2022).

In mechanical engineering, DT concepts have been introduced for developing machine components (Schweigert-Recksiek et al. 2020) and for modeling the complex behavior of mechanical joints (Wagg et al. 2020). Moreover, representing a focal point of DT research within mechanical engineering, DT approaches have been proposed in the automotive industry, modeling the whole life-cycle of vehicles (Piromalis and Kantaros 2022), individual vehicle production processes and vehicle operation functions (such as spot-welds) (Tabar et al. 2019), assembly of mechanical components (Bao et al. 2022), and the operation of systems in electric vehicles (Ibrahim et al. 2022). In manufacturing, digital twins have typically been implemented based on the concept of machine-to-machine communication within factories and across supply chains, aiming to advance the automation of production processes, to improve productivity, and to reduce costs (El Mokhtari et al. 2022). In additive manufacturing, digital twins are omnipresent, supporting the manufacturing processes and the information flow between the digital models and the physical components being manufactured (Zhang et al. 2020b). For example, additive manufacturing of concrete structures ("concrete printing") significantly benefits from DT concepts, as geometry, material, and process parameters may advantageously be integrated into digital twins, improving the quality as well as the cost-effectiveness and resource-efficiency of concrete structures (Asprone et al. 2022).

In aerospace engineering, as compared to most other engineering disciplines, digital twins are highly interactive and implemented with cognitive capabilities to expand technological and business horizons of aerospace applications (Li et al. 2022a). The American Institute of Aeronautics and Astronautics (AIAA), the Aerospace Industries Association (AIA), and the International Association for the Engineering Modelling, Analysis and Simulation Community (NAFEMS) have proposed a reference model, realizations, and recommendations for digital twins (AIAA Digital Engineering Integration Committee 2023). In logistics, digital twins have enabled planning and optimizing logistics processes, such as stock inventory, shipping, and procurement, to improve production efficiency as well as to reduce risks and costs (Figueiras et al. 2021). Examples of logistics applications of digital twins include supply chains (Moshood et al. 2021), resource and operation management (Kaiblinger and Woschank 2022), fleet management (Yao et al. 2018), and risk assessment for workers (Berti and Finco 2022). In healthcare, the concept of digital twins is considered a "game-changer" (Hassani et al. 2022); human digital twins may improve medical treatments and the prediction of treatment courses (De Benedictis 2022). Furthermore, controlling microbots via digital twins is a concept that can be implemented in medical operations (Alazab et al. 2023). In maritime engineering, digital twins have proven formidable in enabling maritime digitalization

(Mouzakitis et al. 2022). Maritime digital twins provide insights into the interaction between all components of maritime systems and consolidate all stakeholders throughout the lifecycle of vessels, to increase the efficiency of maritime industry, to improve ship safety, and to reduce environmental impacts (Giering and Dyck 2021).

2.2 Standardization and abstraction of digital twins in engineering

With the advent of digital twins, many engineering disciplines have witnessed rapid changes in the landscape of standards and guidelines. On the one hand, efforts to provide common ground among disciplines and to standardize digital twins are under development at an international level by the technical subcommittee ISO/IEC JTC 1/SC 41, which focuses on areas related to the Internet of Things and digital twins, and at a European level by the technical subcommittee CEN/TC 442/WG9. Standards have been published to bring consensus regarding DT concepts and terminology in ISO/IEC 30173 (ISO 2023a) as well as regarding DT use cases in ISO/IEC TR 30172 (ISO 2023b) and CEN/TR 18077 (CEN 2024), while standards under development intend to establish a reference architecture (ISO/IEC AWI 30188), a maturity model (ISO/IEC CD 30186), as well as guidelines for entity modeling and integration (ISO/IEC AWI 30153 and ISO/IEC AWI 30152) (ISO 2024b). On the other hand, numerous standards already exist that are related to DT development in various disciplines, varying according to application fields and without reaching consensus in the requirements for digital twins. For example, in civil engineering and facility management, ISO 16739 defines the Industry Foundation Classes (IFC), an open, non-proprietary format for data exchange in BIM that may serve as a basis to implement BIM-based digital twins (ISO 2018a). A unified framework for collaboration and information management over the lifecycle of built assets, such as buildings and infrastructure, is defined in ISO 19650, and it specifies requirements for information models using BIM (ISO 2018b). Owing to the wider implementation of BIM for planning and executing construction projects, digital twinning efforts have been proposed to incentivize policies towards achieving sustainability in the AEC industry within the public sector at a European level (Mitera-Kiełbasa and Zima 2024; Aragón et al. 2025). For example, in Germany, several federal ministries have issued "BIM master plans" for implementing BIM-based digital twins in the public sector for federal highways and federal buildings (BMDV 2021; BMI 2021; BASt 2024). For facility management, ISO 41001 is the international standard that provides a framework for developing, implementing and maintaining effective facility management across different disciplines worldwide (ISO 2018c).

The ISO 23247 standard has been developed to provide the framework for implementing digital twins in manufacturing (ISO 2021a). The architecture for digital twins in manufacturing is defined according to reference models and framework views. Furthermore, conceptual architectures for cognitive digital twins based on the DT framework for manufacturing defined in ISO 23247 have been issued, mapping cognition and the corresponding services to support production systems in handling disruptions (Eirinakis et al. 2022). IPC 2551 is another international standard for DT frameworks for products, manufacturing processes, and life-cycle management, enabling application interoperability for forming smart-value chains (IPC 2021). In additive manufacturing, digital twins based on ISO 23247 may be implemented by coupling concepts from the ISO/ASTM 52950 standard (ISO 2021b) and the DIN SPEC 17071 standard (DIN 2019) regarding data exchange specifications and manufacturing center requirements, respectively. In logistics, several standards exist on quality requirements for logistical processes, such as shipping and resource management, which may be used for DT implementation. For example, standards have been developed for implementing quality management systems (ISO 2015), RFID-based supply chains (ISO 2023c), life-cycle models (ISO 1999), and logistic traffic flows (ISO 2020). Last, but not least, standardized modeling languages, ontologies, and schemas, such as SensorML (OGC 2020), the Semantic Sensor Network ontology (W3C 2017), or the Observations, Measurements and Samples standard (OGC 2023b), may implicitly support digital twin implementations by providing context on distinct aspects of digital twins, e.g. on sensors and measurements.

Although standards and guidelines for digital twins emerge in engineering disciplines, neither a clear definition of digital twins nor a common schema or a common system architecture for digital twins has been reported. Diverse definitions of the term "digital twins" across various engineering disciplines have led to a lack of understanding and confusion caused by terminology with different meanings in different engineering disciplines. Investigating existing definitions of digital twins is a worthwhile objective towards establishing a clear common definition within civil engineering.

Furthermore, digital twins in engineering necessitate a common schema, i.e. an abstraction describing interrelated "things" of interest within a specific domain of knowledge in the real world. Particularly in civil engineering, a

DT schema for modeling several thematic scopes, including building, infrastructure, urban and monitoring information, is necessary. Building information captures indoor data on the scale of individual buildings, while infrastructure information encompasses outdoor data associated with surrounding landscapes and infrastructure projects. Moreover, urban information pertains to outdoor geospatial data at the city scale, and monitoring information includes data from sensors and actuators. Several schemas have been established for the aforementioned thematic scopes, including IFC for building information, LandInfra for infrastructure information (OGC 2017), CityGML for urban information (OGC 2023a), and SensorML for monitoring information. In the context of digital twins, several approaches have investigated the integration of the aforementioned schemas to establish a schema for digital twins; however, the approaches have different aims resulting in a lack of consensus on a schema for digital twins. The modeling approaches utilized to model a schema are distinguished in two groups, (a) semi-formal approaches utilizing semi-formal modeling languages, such as the data modeling language entity-relationship model (ER model) (Chen 1976), the data modeling language EXPRESS (ISO 2024a), and the Unified Modeling Language (UML) (OMG 2017), and (b) formal approaches utilizing formal modeling languages, such as the Web Ontology Language (OWL) (W3C 2012).

Finally, digital twins need a common system architecture describing systems for digital twins, i.e. an abstraction describing the structure, behavior, and other views of a system. In civil engineering, a common, well-designed system architecture provides a foundation for implementing scalable, reliable, and maintainable systems for digital twins. Despite the body of research on system architectures for digital twins, most approaches have different aims, which has prevented a consensus on a system architecture for digital twins. Modeling approaches for architectures include (i) informal approaches, such as box-and-line drawings, (ii) semi-formal approaches, such as UML, and (iii) formal approaches, such as the formal architecture description languages (e.g. Darwin and C2 for service-oriented architectures) (Medvidovic and Tylor 2000).

From the previous discussion, the significance and potential benefits of digital twins in modern civil engineering is highlighted, as well as the need for a clear definition, a common schema, and a reference system architecture of digital twins. In the remainder of the paper, the multivocal review is followed by an analysis of existing definitions of digital twins, focusing on the characteristics specified within the definitions (i.e., terminologies referring to subjects), to establish the foundations for a common understanding of digital twins. Furthermore, existing schemas in terms of thematic scopes and modeling approaches of the schemas are analyzed towards developing a pattern for a common schema for digital twins. Finally, existing digital twin system architectures (including internal elements) in terms of the structure and modeling approaches of the system architectures are explored towards defining a reference architecture, i.e., a common system architecture for digital twins.

The following sections present the review of digital twins in civil engineering, which is used as a basis to provide a definition, a common schema, and a reference architecture of digital twins, and to identify research directions toward improving the reliability of digital twins.

3. LITERATURE REVIEW

The review is a multivocal literature review (MLR), encompassing a systematic literature review (SLR) and a gray literature review (GLR), and it is carried out following a methodology based on well-defined guidelines (Kitchenham et al. 2009; Kitchenham et al. 2023). The methodology, shown in Figure 1, involves three phases, (a) the *planning phase*, in which objectives of the MLR and a procedure to achieve the objectives ("objectives procedure") are defined, (b) the *execution phase*, in which the studies are collected, and data is extracted according to the objectives procedure, and (c) the *reporting phase*, in which the data extracted from the studies is analyzed according to the objectives procedure.

Each phase of the methodology comprises several steps. The planning phase comprises four steps, (i) definition of the *research questions* based on the objectives, (ii) definition of the *search strategy* to retrieve studies from research and practice, (iii) definition of *inclusion and exclusion criteria* as well as quality assessment criteria to filter and select relevant studies, and (iv) definition of *methods for data extraction and analysis*. The execution phase encompasses four steps, (v) *search*, in which studies are retrieved according to the research questions and the objectives procedure, (vi) *filtering*, in which the studies are filtered based on the inclusion and exclusion criteria, (vii) *selection*, in which the studies resulting from filtering ("filtered studies") are evaluated according to quality assessment criteria to identify relevant studies ("selected studies"), and (viii) *data extraction*, in which data is extracted from the selected studies according to the methods for data extraction. Finally, the reporting phase consists of three steps, (ix) *data analysis*, in which the data is analyzed according to the analysis methods, (x) *results*, in which findings regarding the research questions are synthesized, and (xi) *discussion and recommendations*, in which the results are discussed and recommendations are proposed. The scope of the MLR includes a broad range of disciplines, such as civil engineering and manufacturing, spanning the period from 2013 to 2025.

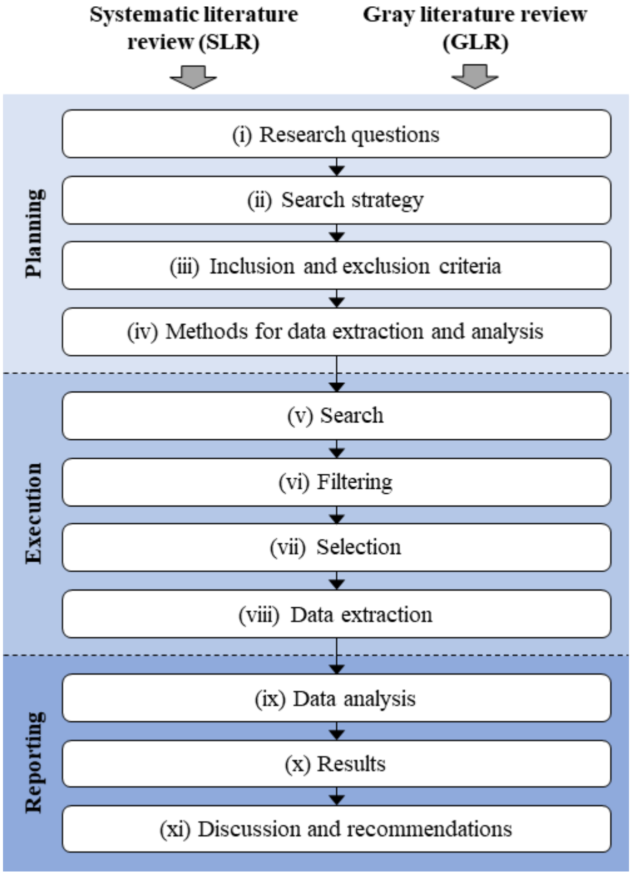

Figure 1: Overview of the research methodology.

The planning and execution phases are detailed as follows. First, the planning phase is conducted. In the first step of the planning phase, four research questions (RQs) are formulated based on the objectives of the MLR and the overview of Section 2, to gain insight into digital twin implementation:

- RQ 1: What definitions of digital twins are reported?
- RQ 2: What schemas are reported?
- RQ 3: What system architectures (including internal elements) are reported?

The set of research questions naturally leads to the formulation of one additional follow-on research question:

- RQ 4: What are the major use cases and emerging trends of digital twins in engineering?

In the second step of the planning phase, the search strategy is defined, including workflows for white and gray literature (Appendix A). For the white literature, the workflow involves selecting the source of information and defining search strings. The electronic publication database Scopus is selected to retrieve white literature because of its comprehensive coverage, quality, and advanced search options. To define the search strings, three terms (i.e. “digital twin”, “architecture”, and “feature”) are used based on the research questions. To construct the search strings, the three terms are connected using the logical operators “AND” and “OR”. Five search strings, as listed in Table 1, are constructed to retrieve the white literature. The search strings start with the broader topic of digital twins and then narrow down to the remaining topics, i.e. architecture and features. Finally, the studies are limited to include specific keywords, namely “digital twin”, “Internet of Things”, “IoT”, “Industry 4.0”, “cyber-physical system”, “architectural design”, or “architecture”. The search strings, when querying titles, abstracts and keywords, initially yield 51,289 studies, which are narrowed down to 3,236 studies for the last two search strings.

Table 1: Search strings for the SLR.

No.	Search string
1	TITLE-ABS-KEY(“*digital*” AND (“*twin*” OR “*shadow*” OR “*sibling*”))
2	TITLE-ABS-KEY(“*digital*” AND (“*twin*” OR “*shadow*” OR “*sibling*”)) AND TITLE-ABS-KEY(“*architecture*” OR “*framework*” OR “*platform*”)
3	TITLE-ABS-KEY(“*digital*” AND (“*twin*” OR “*shadow*” OR “*sibling*”)) AND TITLE-ABS-KEY(“*architecture*” OR “*framework*” OR “*platform*”) AND TITLE-ABS-KEY(“*feature*” OR “*service*” OR “*view*”)
4	(TITLE-ABS-KEY(“*digital*” AND (“*twin*” OR “*shadow*” OR “*sibling*”)) AND TITLE-ABS-KEY(“*architecture*” OR “*framework*” OR “*platform*”) AND TITLE-ABS-KEY(“*feature*” OR “*service*” OR “*view*”)) AND (LIMIT-TO(EXACTKEYWORD,"*Digital Twin*") OR LIMIT-TO(EXACTKEYWORD,"*Internet Of Things*") OR LIMIT-TO(EXACTKEYWORD,"*Industry 4.0*") OR LIMIT-TO(EXACTKEYWORD,"*Cyber Physical System*") OR LIMIT-TO(EXACTKEYWORD,"*Architectural Design*") OR LIMIT-TO(EXACTKEYWORD,"*Architecture*"))
5	(TITLE-ABS-KEY(“*digital*” AND (“*twin*” OR “*shadow*” OR “*sibling*”)) AND TITLE-ABS-KEY(“*architecture*” OR “*framework*” OR “*platform*”) AND TITLE-ABS-KEY(“*civil engineering” OR “construction industry*”)) AND (LIMIT-TO(EXACTKEYWORD,"*Digital Twin*") OR LIMIT-TO(EXACTKEYWORD,"*Internet Of Things*") OR LIMIT-TO(EXACTKEYWORD,"*Industry 4.0*") OR LIMIT-TO(EXACTKEYWORD,"*Cyber Physical System*") OR LIMIT-TO(EXACTKEYWORD,"*Architectural Design*") OR LIMIT-TO(EXACTKEYWORD,"*Architecture*"))

For the gray literature, the workflow encompasses selecting information sources and defining the search string. To retrieve the gray literature, the electronic database “Zenodo” (Zenodo 2024) is selected, due to its comprehensive collection of gray literature, including project deliverables, reports, and white papers. The search string involves the keywords “digital twin” and “digital twins”, which, combined with preliminary filters, yields 471 studies (Table 2).

Table 2: Search string for the GLR.

No.	Search string	Filters
6	metadata.title:(+digital +twin*) metadata.description:(+digital +twin*)	Open access, project deliverable, report, and pdf

In the third step, the criteria are defined, aiming to identify relevant studies by (i) including studies relevant to the search terms, (ii) excluding studies not accessible through open access, and (iii) selecting studies contributing to answering the research questions. It should be noted that particular attention is given to the terminology used in the studies, focusing on terminology that directly refers to digital twins. Even though concepts similar to digital twins are commonly grouped under the same umbrella (e.g., BIM and point clouds), digital twins have capabilities that go beyond geometry and semantic representation as provided by BIM models. The criteria are classified into three categories, inclusion criteria (IC), exclusion criteria (EC), and quality assessment criteria (QAC). Four IC (Table 3), two EC (Table 4), and four QAC criteria (Table 5) are defined.

Table 3: Inclusion criteria.

ID	Inclusion criteria (IC)
IC 1	The study has been published in English
IC 2	The study has been published in the period between 2013 and 2025
IC 3	The study is related to the areas of engineering, computer science, or mathematics
IC 4	The study uses terminology that refers directly to digital twins

Table 4: Exclusion criteria.

ID	Exclusion criteria (EC)
EC 1	The full text is not available
EC 2	The study uses terminology that does not refers directly to digital twins.

Table 5: Quality assessment criteria.

ID	Quality assessment criteria (QAC)
QAC 1	The objectives of the study are clearly stated
QAC 2	The limitations of the study are clearly stated
QAC 3	The methodology of the study is stated
QAC 4	The outcomes of the study contribute to answering one or more of the research questions

In the fourth step, methods for data extraction and analysis are defined. The data extraction method is reflected in a structured data sheet, which specifies the data to be extracted from the selected studies, including:

- Title, type, year, discipline (to gain an overview of the selected studies).
- Definition of digital twins (to address RQ 1)
- Thematic scopes of schema, i.e. specific portions of the schema focusing on a particular area within the field of digital twins (to address RQ 2)
- Modeling approach of schemas (to address RQ 2)
- Layers of system architectures (to address RQ 3)
- Modeling approach of system architecture (to address RQ 3)
- Use cases and trends (to address RQ 4)

The data analysis method is based on statistical analysis, such as frequencies of selected studies by discipline, accompanied by charts for data visualization. Upon accomplishing the planning phase, the execution phase (i.e. the steps v, vi, vii and viii) is conducted. In the execution phase, the search strings are utilized to retrieve the selected studies, the criteria are applied to filter and identify the selected studies, and the data is extracted from the selected studies and filled in the data sheet. Figure 2 illustrates the process of identifying the selected studies within the execution phase, emphasizing search (step v), filtering (step vi), and selection (step vii).

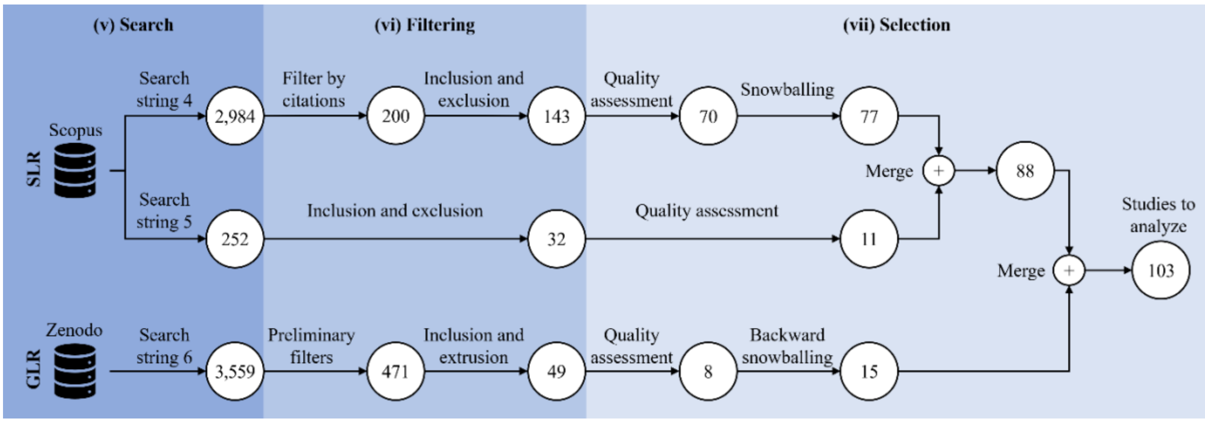

Figure 2: Process of identifying the selected studies in the execution phase.

As mentioned previously, in the execution phase of the SLR, in the search step 51,289 studies are retrieved, and narrowed down to 3,236 studies. From search string 4, the 200 most-cited studies are identified in the filtering step, from which 70 meet the quality assessment criteria of the selection step. Additionally, 7 relevant studies are identified by "snowballing", resulting in a total of 77 studies. From search string 5, 32 studies are identified in the filtering step, from which 11 meet the quality assessment criteria of the selection step. Finally, a total of 88 studies are selected from both search strings.

In the execution phase of the GLR, initially 3,559 studies are retrieved in the search step. By applying preliminary filters, also shown in Table 2, the result is reduced to 471 studies. Upon applying the inclusion and exclusion criteria, 49 studies are retained, 8 of which meet the quality assessment criteria of the selection step. Additionally, 7 relevant studies are identified by snowballing, resulting in a total of 15 studies.

As a result, a total of 103 studies are selected, including 88 studies retrieved from the SLR and 15 studies retrieved from the GLR. Then, the selected studies are forwarded to the data extraction (step viii), serving as input for the reporting phase. In the reporting phase, the extracted data is analyzed (step ix), and the results are synthesized (step x) and discussed to draw relevant recommendations (step xi). It should be noted that step (x) – the results – is outlined in Section 4, while step (ix) – discussion and recommendations – is outlined in Section 5.

4. RESULTS

This section presents the results of the MLR, in compliance with the reporting phase of the methodology. In the following subsections, an overview of the selected studies is presented (Section 4.1), and the research questions are addressed (Sections 4.2 to 4.6).

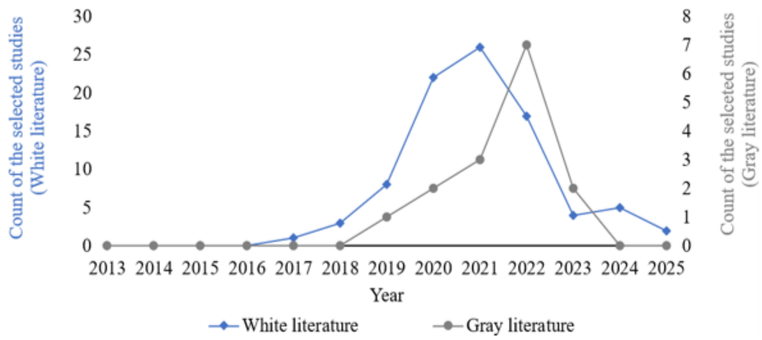

Figure 3: Distribution by year.

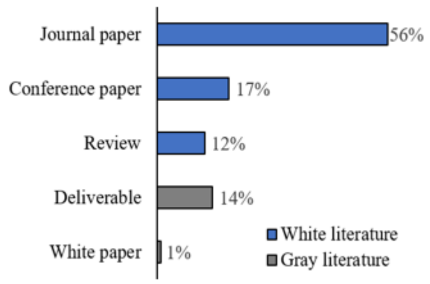

Figure 4: Distribution by document type.

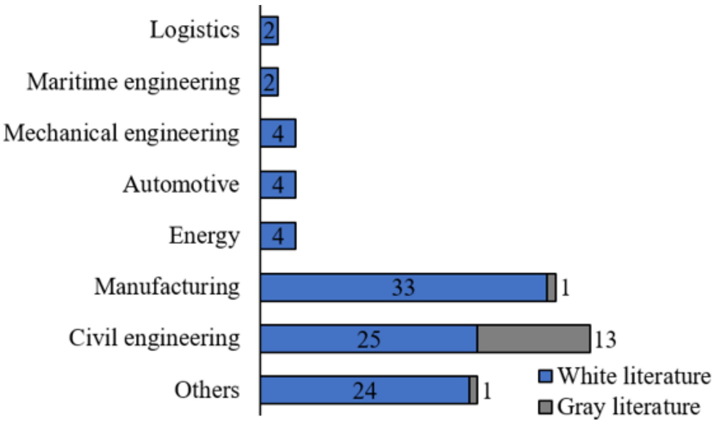

Figure 5: Distribution by discipline.

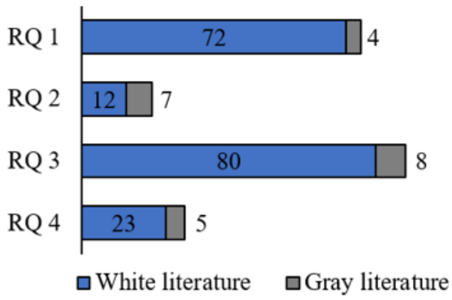

Figure 6: Distribution by contribution to research question.

4.1 Overview of the selected studies

The interest in digital twins, exhibited in recent years in both research and practice, is reflected in the 103 selected studies (encompassing 88 white-literature studies and 15 gray-literature studies) in this review, comprising a sample of the most-cited and relevant studies in white and gray literature. The selected studies are summarized in Table 6. The statistical analysis of the data extracted from the studies has revealed an increase in the number of studies on digital twins since 2017. Figure 3 shows the distribution of the studies between the years 2013 and 2025. The majority of the studies are journal papers (56%), followed by conference papers (17%), deliverables and reports (14%), reviews (12%), and white papers (1%), as illustrated in Figure 4. As depicted in Figure 5, most studies are concentrated within the discipline of civil engineering (38 studies), followed by manufacturing (34 studies), general topics concerning digital twins (25 studies), automotive (4 studies), energy (4 studies), mechanical engineering (4 studies), logistics (2 studies), and maritime engineering (2 studies). In addition, studies of multidisciplinary nature, which involve two or more disciplines, have been identified and appear in Figure 5 in more than one discipline. A mapping between the studies and the research questions is provided in Table B1 (Appendix B). Furthermore, a visual representation of the number of studies contributing to the research questions is presented in Figure 6, where 76 studies contribute to RQ 1, 19 studies pertain to RQ 2, 88 studies are relevant to RQ 3, and 28 studies are relevant to RQ 4.

Table 6: List of the selected studies, categorized by literature source.

Literature source	Studies
White literature	(Tao et al. 2018; Alam and El Saddik 2017; Aheleroff et al. 2021; Minerva et al. 2020; Li et al. 2022b; Lu et al. 2020a; Lu et al. 2020b; Park et al. 2020a; Damjanovic-Behrendt and Behrendt 2019; Zhuang et al. 2021; Rathore et al. 2021; Jiang et al. 2021b; Autiosalo et al. 2020; Saad et al. 2020b; Chen et al. 2020; Sun et al. 2021; Josifovska et al. 2019; Jiang et al. 2021c; Fan et al. 2021; Wang et al. 2021d; Zhang et al. 2020a; Zhang et al. 2022; O'Dwyer et al. 2020; Cespedes-Cubides et al. 2024; Wang et al. 2021a; Ma et al. 2020; Park et al. 2020c; Steindl et al. 2020; Saad et al. 2020a; Stojanovic et al. 2018; Schroeder et al. 2021; Park et al. 2020b; Chakraborty and Adhikari 2021; Wang et al. 2021c; Davila Delgado and Oyedele 2021; Lin and Low 2020; Wang et al. 2021b; Zheng et al. 2020; Eckhart et al. 2019; Dietz et al. 2019; Hunhevicz et al. 2022; Zheng et al. 2022; Lei et al. 2022; Villa et al. 2021; Park et al. 2021; Hoebert et al. 2019; Liu et al. 2022b; Barthelmey et al. 2019; Liu et al. 2022a; Wu et al. 2021; Lektauers et al. 2021; Kuhn et al. 2020; Kychkin and Nikolaev 2020; Ala-Laurinaho et al. 2020; Zheng et al. 2021; Corallo et al. 2021; Redeker et al. 2021; Li et al. 2023; Assad Neto et al. 2020; Steindl and Kastner 2021; Dobaj et al. 2019; Wang et al. 2022b; Fonseca et al. 2022; Borghesi et al. 2021; Latsou et al. 2021; Rasor et al. 2021; Borangiu et al. 2020; Han et al. 2023; Wu et al. 2022; Phua et al. 2022; Redelinghuys et al. 2020; Lu et al. 2020c; Boyes and Watson 2022; Newrzella et al. 2022; Pregnolato et al. 2022; Alva et al. 2022; Worden et al. 2020; Chacón et al. 2024; Khan et al. 2022; Ramonell et al. 2023; Zhao et al. 2022; Opoku et al. 2024; Hussain et al. 2024; Arsiwala et al. 2023; Lee et al. 2023; Pavón et al. 2025; Zhang et al. 2024; Gispert et al. 2025)
Gray literature	(Porkka et al. 2022; Loscos et al. 2019; Khan 2022; Hartmann et al. 2022; Chacón et al. 2023; Bonan 2020; Benach et al. 2023; Tomar 2022; Torres et al. 2022; Valluru et al. 2022; Oraskari and Bourreau 2023; Bus et al. 2021; Tsakiris et al. 2020; Chávez-Feria et al. 2020; Pascual et al. 2022)

4.2 Definitions of digital twins (RQ 1)

The research question RQ 1 concerns definitions of digital twins (“*What definitions of digital twins are reported*?”). A plethora of digital twin definitions and a broad wealth of reviews of digital twin definitions have been reported. On the one hand, out of the 103 selected studies, 27 studies neither adopt nor provide a definition of digital twins. On the other hand, 76 studies adopt or provide a definition of digital twins (72 from the SLR and 4 from the GLR). The 76 definitions are systematically analyzed to investigate characteristics explicitly or implicitly mentioned in the definitions by tagging the definitions with characteristics. Table 7 shows the characteristics and the corresponding descriptions. Tagging facilitates grouping definitions by characteristics; however, the tagging process can hardly be free from subjectivity. To ensure transparency in the tagging process, the mapping between characteristics and terms is provided in Table C1 (Appendix C).

Definitions vary depending on the discipline and the purpose of the digital twins. Definitions range from abstract to specific and focus on characteristics that satisfy the demands of the respective disciplines, with varying structures, capabilities, and levels of integration between digital and physical assets. For example, in manufacturing, digital twin definitions focus on high-quality replicas of products, machines, or production systems, aiming for mirroring real-time behavior to optimize performance, predict failures, and improve design. In comparison, digital twin definitions in civil engineering focus on virtual representations that integrate design and as-built descriptions, condition assessment, and operational data across the life cycle of built assets to support project and asset management, with periodic synchronization according to stakeholders needs. A lack of consensus on a general definition for digital twins is observed and highlighted in Davila Delgado and Oyedele (2021).

Identifying common characteristics provides a comparison point between definitions. For example, Cespedes-Cubides et al. (2024) defines a digital twin for building operations as “a digital and/or mathematical model of a physical asset which integrates sensor readings and a form of data exchange between the digital model and the physical asset”, while Wang et al. (2022b) defines a digital twin for road mobility as “a digital replica of a physical entity for real-time monitoring and synchronization of real-world activities with the virtual counterparts.” Both definitions include “digital representation” and “synchronization” as common characteristics; however, the later includes a description of the "capabilities" of the digital twin. The process of identifying characteristics is repeated for all 76 definitions.

Table 7: List of characteristics.

Characteristic	Description	Studies
Digital representation	A computer-based representation of a real-world entity.	(Tao et al. 2018; Alam and El Saddik 2017; Aheleroff et al. 2021; Minerva et al. 2020; Li et al. 2022b; Lu et al. 2020a; Lu et al. 2020b; Park et al. 2020a; Damjanovic-Behrendt and Behrendt 2019; Zhuang et al. 2021; Rathore et al. 2021; Jiang et al. 2021b; Autiosalo et al. 2020; Saad et al. 2020b; Chen et al. 2020; Sun et al. 2021; Josifovska et al. 2019; Jiang et al. 2021c; Wang et al. 2021d; Zhang et al. 2020a; Zhang et al. 2022; Cespedes-Cubides et al. 2024; Wang et al. 2021a; Ma et al. 2020; Park et al. 2020c; Steindl et al. 2020; Stojanovic et al. 2018; Schroeder et al. 2021; Park et al. 2020b; Davila Delgado and Oyedele 2021; Wang et al. 2021b; Zheng et al. 2020; Dietz et al. 2019; Hunhevicz et al. 2022; Zheng et al. 2022; Lei et al. 2022; Park et al. 2021; Hoebert et al. 2019; Liu et al. 2022b; Lektauers et al. 2021; Ala-Laurinaho et al. 2020; Zheng et al. 2021; Corallo et al. 2021; Li et al. 2023; Assad Neto et al. 2020; Steindl and Kastner 2021; Wang et al. 2022b; Borghesi et al. 2021; Latsou et al. 2021; Rasor et al. 2021; Borangiu et al. 2020; Han et al. 2023; Phua et al. 2022; Redelinghuys et al. 2020; Lu et al. 2020c; Boyes and Watson 2022; Newrzella et al. 2022; Pregnolato et al. 2022; Alva et al. 2022; Worden et al. 2020; Chacón et al. 2024; Khan et al. 2022; Ramonell et al. 2023; Zhao et al. 2022; Hussain et al. 2024; Arsiwala et al. 2023; Lee et al. 2023; Zhang et al. 2024; Gispert et al. 2025; Porkka et al. 2022; Loscos et al. 2019; Tomar 2022; Torres et al. 2022)
Synchronization	The bidirectional coordination and alignment between a digital twin and the corresponding real-world entity in terms of states and behaviors.	(Tao et al. 2018; Alam and El Saddik 2017; Aheleroff et al. 2021; Minerva et al. 2020; Li et al. 2022b; Lu et al. 2020a; Lu et al. 2020b; Park et al. 2020a; Zhuang et al. 2021; Rathore et al. 2021; Jiang et al. 2021b; Autiosalo et al. 2020; Saad et al. 2020b; Sun et al. 2021; Josifovska et al. 2019; Jiang et al. 2021c; Zhang et al. 2020a; Zhang et al. 2022; Cespedes-Cubides et al. 2024; Wang et al. 2021a; Ma et al. 2020; Park et al. 2020c; Stojanovic et al. 2018; Schroeder et al. 2021; Chakraborty and Adhikari 2021; Davila Delgado and Oyedele 2021; Wang et al. 2021b; Zheng et al. 2020; Dietz et al. 2019; Hunhevicz et al. 2022; Zheng et al. 2022; Lei et al. 2022; Villa et al. 2021; Park et al. 2021; Hoebert et al. 2019; Liu et al. 2022b; Lektauers et al. 2021; Ala-Laurinaho et al. 2020; Zheng et al. 2021; Corallo et al. 2021; Li et al. 2023; Steindl and Kastner 2021; Wang et al. 2022b; Latsou et al. 2021; Borangiu et al. 2020; Han et al. 2023; Lu et al. 2020c; Boyes and Watson 2022; Newrzella et al. 2022; Pregnolato et al. 2022; Alva et al. 2022; Chacón et al. 2024; Khan et al. 2022; Ramonell et al. 2023; Zhao et al. 2022; Arsiwala et al. 2023; Zhang et al. 2024; Gispert et al. 2025; Porkka et al. 2022; Loscos et al. 2019; Tomar 2022; Torres et al. 2022)
Capabilities	The ability of a digital twin to perform various tasks, including monitoring, analysis, simulation, optimization, and control of a real-world entity.	(Tao et al. 2018; Li et al. 2022b; Damjanovic-Behrendt and Behrendt 2019; Zhuang et al. 2021; Jiang et al. 2021b; Chen et al. 2020; Jiang et al. 2021c; Zhang et al. 2020a; Wang et al. 2021a; Park et al. 2020c; Steindl et al. 2020; Stojanovic et al. 2018; Park et al. 2020b; Wang et al. 2021c; Dietz et al. 2019; Villa et al. 2021; Park et al. 2021; Liu et al. 2022b; Lektauers et al. 2021; Zheng et al. 2021; Corallo et al. 2021; Li et al. 2023; Assad Neto et al. 2020; Steindl and Kastner 2021; Wang et al. 2022b; Han et al. 2023; Redelinghuys et al. 2020; Alva et al. 2022; Worden et al. 2020; Hussain et al. 2024; Arsiwala et al. 2023; Zhang et al. 2024; Gispert et al. 2025)
Life-cycle	A period throughout the life of a real-world entity, including design, construction, operation, and disposal.	(Tao et al. 2018; Jiang et al. 2021b; Ma et al. 2020; Park et al. 2020c; Wang et al. 2021b; Dietz et al. 2019; Zheng et al. 2022; Park et al. 2021; Liu et al. 2022b; Lektauers et al. 2021; Zheng et al. 2021; Latsou et al. 2021; Rasor et al. 2021; Borangiu et al. 2020; Khan et al. 2022; Loscos et al. 2019; Tomar 2022)

As shown in Figure 7, "digital representation" is the most-reported characteristic, followed by "synchronization", "capabilities", and "life-cycle". The majority of the definitions, despite the differences in terminology, describe "digital twins" as digital representations of real-world entities (Wang et al. 2021a; Park et al. 2020c; Torres et al. 2022). Moreover, the majority of the definitions highlight the characteristic of "synchronization" by emphasizing (i) real-time and bidirectional data exchanges as well as (ii) controls between the digital representations and the corresponding real-world entities (Li et al. 2022b; Jiang et al. 2021b; Lu et al. 2020c). The characteristics of "capabilities" are also included in several definitions, highlighting the ability to perform engineering tasks, such as monitoring, analysis, simulation, optimization, and control of real-world entities (Jiang et al. 2021c; Dietz et al. 2019; Liu et al. 2022b). Despite the advantages provided by digital twins over the full life-cycle of real-world entities, only a minority of the definitions include the characteristic of "life-cycle" (Park et al. 2021; Lektauers et al. 2021; Zheng et al. 2021).

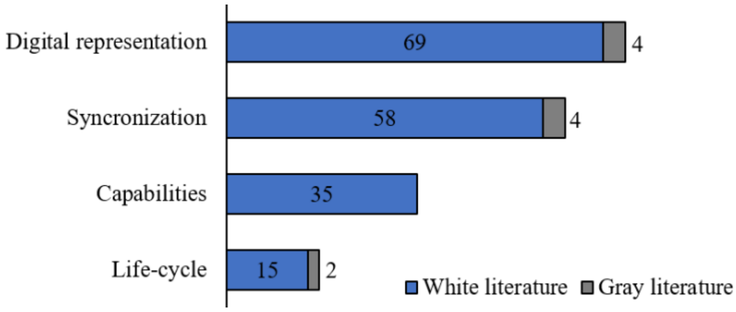

Figure 7: Digital twin characteristics included in definitions of digital twins.

In summary, the statistical analysis provides the following main findings for RQ 1:

- Digital twin definitions vary according to disciplines and to purpose of the digital twins, showcasing varying levels of granularity.
- A consensus on defining digital twins in the context of civil engineering has not been reached.
- Common characteristics are evident in the definitions across disciplines, such as "digital representation", "synchronization", "capabilities", and "life-cycle".

4.3 Schemas proposed for digital twin implementations (RQ 2)

The research question RQ 2 investigates schemas proposed for digital twin implementations ("*What schemas are reported*?"). In the selected studies, information is provided on 19 schemas (12 schemas from the SLR and 7 schemas from the GLR). Essentially, the schemas are analyzed by investigating the thematic scopes, which are specific portions of the schemas focusing on a particular area within the field of digital twins. Figure 8 shows the distribution of white and gray literature into thematic "sub-scopes", which are grouped into thematic scopes, such as building information, urban information, and monitoring information, and manufacturing information. It should be noted that a schema may include several thematic scopes, meaning that a schema may appear in Figure 8 in more than one thematic scope. Notably, the white-literature studies focus primarily on the 3D modeling of buildings, monitoring information related to sensors and actuators, and manufacturing information, while the gray-literature studies span a broad range of thematic sub-scopes. Furthermore, both white and gray literature are limited in addressing urban information. While the gray-literature studies emphasize a limited subset of thematic sub-scopes, comprising geographic location and outdoor environment (e.g. weather), other relevant thematic sub-scopes, such as 3D modeling of cities, green spaces, transportation spaces and water bodies, receive limited attention. In summary, none of the studies focus on schemas with infrastructure information.

In addition to thematic scopes, the distribution of literature where well-established schemas are reused for specific thematic sub-scopes is analyzed, as shown in Figure 9. In the gray-literature studies, for example, IFC, ifcOWL and RealEstateCore ontology are utilized for 3D modeling of buildings, while the Building Topology Ontology (BOT) and the Damage Topology Ontology (DOT) are employed for topology information and for damage information in structures, respectively. The World Geodetic System 1984 (WGS84) is utilized for geographic positioning. For representing monitoring information, the ontologies used are the Semantic Sensor Network (SSN) ontology, the Sensor, Observation, Sample, and Actuator (SOSA) ontology, the Brick ontology, and the Smart Appliances Reference (SAREF) ontology. The white-literature studies are limited to IFC, emphasizing that a focus of academic research is related to the 3D modeling of buildings. Furthermore, novel schemas for representing monitoring information and manufacturing information have been proposed in the white literature instead of reusing existing schemas.

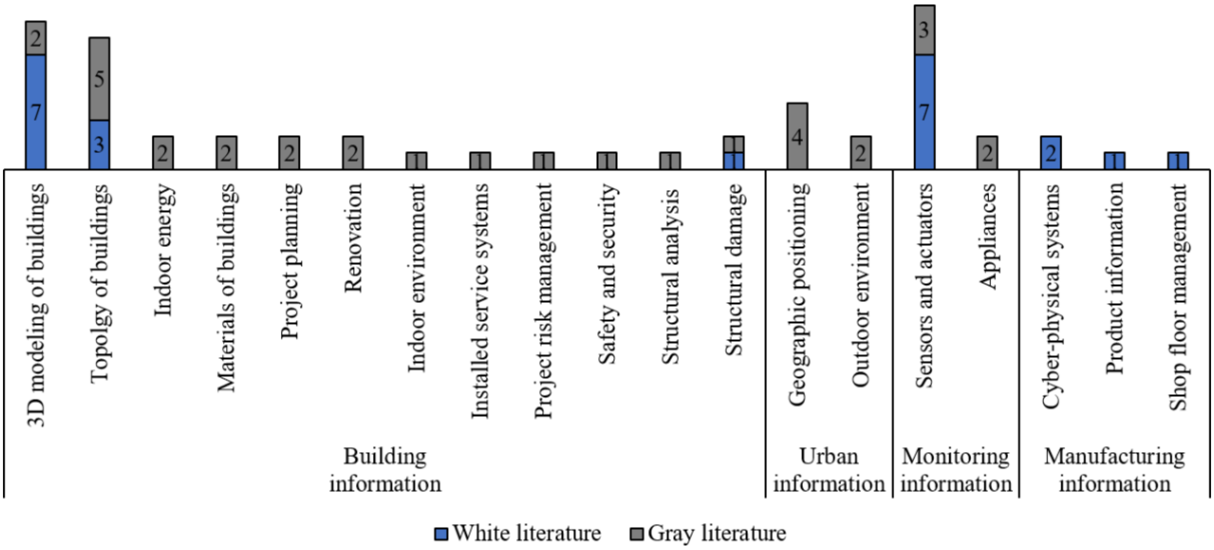

Figure 8: Distribution of schemas by thematic scopes.

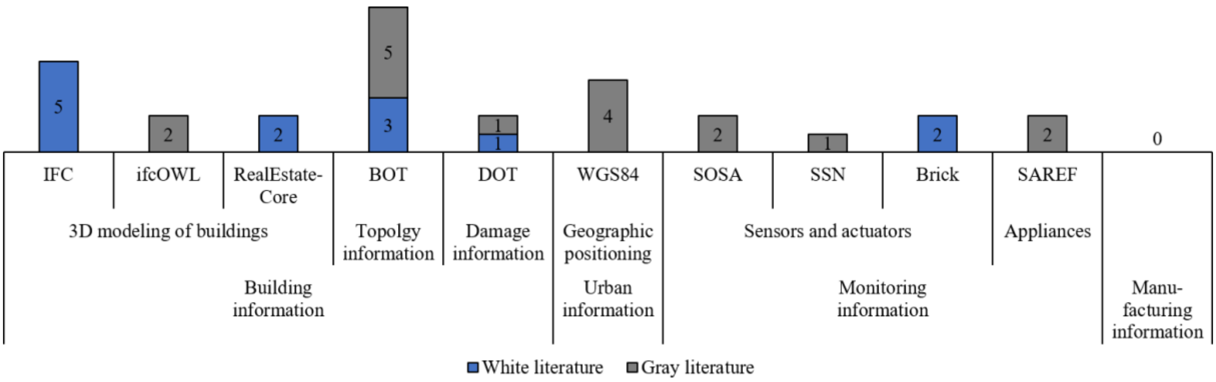

Figure 9: Number of times schemas are reused for specific thematic sub-scope.

Furthermore, the modeling approaches adopted for the schemas are analyzed, as illustrated in Figure 10. Among the 19 schemas examined herein, 7 schemas have utilized semi-formal approaches (e.g., Lu et al. (2020a) used EXPRESS), and 11 schemas have employed formal approaches (e.g., Valluru et al. (2022) and Bus et al. (2021) used OWL).

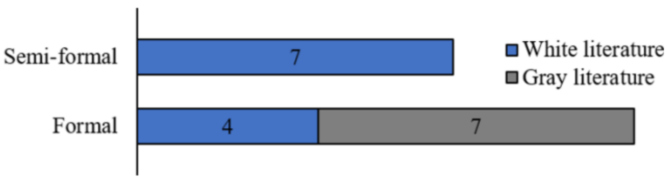

Figure 10: Modeling approaches of the schemas.

Focusing on the studies related to the discipline of civil engineering, a trend similar to the trend described above is observed, where the thematic scopes of the white-literature studies are limited, compared to the gray-literature studies. While the majority of the schemas reported in white literature focus on building information and monitoring information, the schemas from studies in the gray literature are broader. For example, on the one hand, the white-literature study of Lu et al. (2020a) presents a schema addressing building and monitoring information. On the other hand, the gray-literature study of Valluru et al. (2022) reports a schema entitled Digital Construction Ontologies (DiCon), addressing multiple thematic scopes to represent digitalized construction processes, including construction workflows from construction to renovation. The DiCon ontologies reuse well-established ontologies, such as ifcOWL for building information and SSN for monitoring information, and use location data for spatial referencing based on the geographical coordinate system WGS84. In addition, the gray-literature study of Bus et al. (2021) introduces a set of ontologies for the project BIM2TWIN that focus on construction management. By reusing the ontologies BOT and SOSA, the ontology set of BIM2TWIN covers topology information, i.e. a sub-scope of building information emphasizing the topology of buildings, and monitoring information, respectively. Neither DiCon nor BIM2TWIN capture the thematic scope of the urban information.

The schemas related to the discipline of civil engineering are selected according to information requirements necessary to fulfill the purpose of the respective digital twins. For example, the schema selection for describing building information depends on the needs regarding geometry description, semantic descriptions, spatial relationships, and interoperability style. Similarly, the schema selection for describing monitoring information depends on the needs for observation-centric information or device-centric information. Table 8 summarizes the main aspects for selecting schemas for building and monitoring information.

Table 8: Main aspects for selecting schemas for building and monitoring information.

Aspect		IFC	ifcOWL	BOT	RealEstateCore	SOSA/SSN	Brick	SAREF
Geometry description		X	O	-	-	-	-	-
Semantic description		X	-	O	X	X	X	X
Spatial relationship		X	X	X	O	-	O	-
Interoperability style	File-based	X	-	-	-	-	-	-
	Linked data	-	X	X	X	X	X	X
Device description		O	O	-	O	X	X	X
Observation description		-	-	-	O	X	O	O

Strong support (X), partial support (O), not supported (-)

In summary, the statistical analysis provides the following main findings for RQ 2:

- A consensus on a schema for digital twins in civil engineering has not been reached.
- There is an increasing trend towards formal approaches, as confirmed by 11 recent studies reporting on utilizing formal modeling languages for schemas, such as OWL.
- Most studies related to the discipline of civil engineering report on schemas addressing three main thematic scopes, building information, urban information, and monitoring information.

4.4 System architectures and internal elements (RQ 3)

The research question RQ 3 seeks to explore system architectures and internal elements of digital twins ("*What system architectures, including internal elements, are reported*?"). System architectures are presented in 88 of the studies considered herein (80 studies retrieved from the SLR and 8 studies retrieved from the GLR). The 88 system architectures share similarities, particularly evident in the layers characteristic of the architectures, with each layer representing an organizational unit that serves particular functional purposes. The analysis of the 88 system architectures involves listing the layers, as shown in Figure 11, as well as the internal elements embodied in the layers, shown in Figure 12. As shown in Figure 11, six layers are most commonly identified:

- A ***service layer*** providing software services facilitating interaction with the digital representations in the modeling layer,
- A ***modeling layer*** responsible for hosting the digital representations,
- A ***data management layer*** dedicated to data storage and maintaining organized repositories for the information managed by the modeling layer,
- A ***transmission layer*** dedicated to data transfer between all layers,

- A ***perception layer***, which is integral in data acquisition and device control, serving as the intermediary between the real-world and the digital representation by collecting real-world data from sensors and interacting with the real world via devices, and

- A ***presentation layer***, which hosts user interfaces and provides visual accessibility for users to engage with and interpret digital representations in the modeling layer.

Figure 12 illustrates the internal elements identified from the architectures. The most frequently reported internal elements include "data storage", "devices", "services and tools", "user interface", and "data analysis methods". Furthermore, the modeling approaches employed to describe system architectures for digital twins are examined, as illustrated in Figure 13. Among the 88 architectures, none have been modeled using formal approaches, while 84 have utilized informal approaches (e.g., box-and-line drawings as used by Davila Delgado and Oyedele (2021) and Pascual et al. (2022)), and 4 architectures have employed semi-formal approaches (e.g., UML representations used by Park et al. (2020c)).

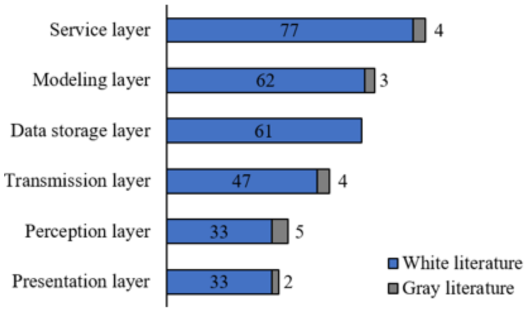

Figure 11: Layers identified in the system architectures.

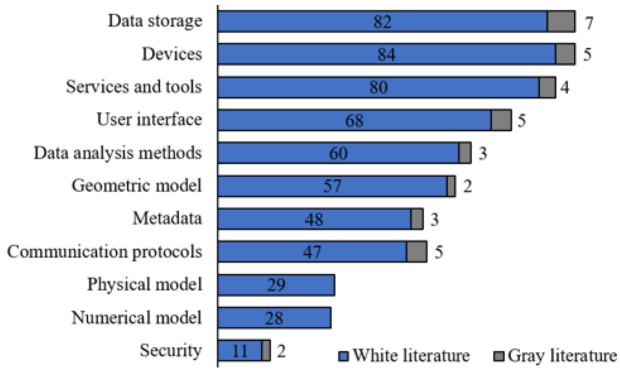

Figure 12: Internal elements identified in the system architectures.

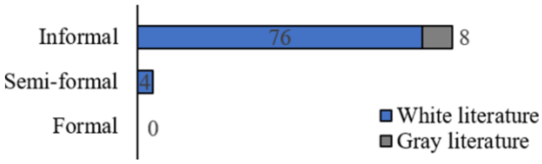

Figure 13: Modeling approaches.

As previously indicated, the 88 system architectures share similarities, although the names of the layers vary. The names of the layers can be mapped to the terminology outlined in Figure 11. For instance, Davila Delgado and Oyedele (2021) propose a system architecture for digital twins for built environments. The system architecture encompasses the so-called "physical space" and "digital space", which are analogous terms to "real world" and "digital world". The digital space comprises a data layer, a data processing layer, a model and algorithm layer, and an analysis and control layer. Pascual et al. (2022) propose a slightly different approach with a system architecture for digital twins for life-cycle management of buildings focusing on big data and encompassing four layers, data source, data management, data processing and analysis, and data output. In summary, the statistical analysis provides the following main findings for RQ 3:

- The system architectures for digital twins in civil engineering share common aspects that can be abstracted on a meta level. Depending on the use case, different capabilities are needed that can be expressed as services within the system architectures.

- Most studies report on system architectures comprising six layers, including a modeling layer, a service layer, a perception layer, a data management layer, a presentation layer, and a transmission layer. The internal elements most frequently reported include "data storage", "devices", "services and tools", "user interface", and "data analysis methods".

- Most studies report on system architectures modeled using informal approaches.

In the following sub-section, the follow-on research question is addressed, summarizing the findings regarding major use cases and emerging trends of digital twins in engineering.

4.5 Use cases and trends of digital twins in engineering (RQ 4)

The research question RQ 4 aims to explore the use cases and trends of digital twins in engineering ("*What are the major use cases and emerging trends of digital twins in engineering?*"). Different engineering disciplines present divergent understandings of digital twins, which influences the corresponding use cases. Out of the 103 selected studies, 28 studies (23 from the SLR and 5 from the GLR) are exemplary used to analyze the use cases and trends of digital twins.

Use cases related to the discipline of civil engineering are identified in 10 studies, encompassing maintenance (e.g., structural health monitoring), construction planning and management, facility management, smart cities and smart buildings. As part of maintenance, digital twins have been utilized for real-time monitoring, maintenance prediction, and structural analyses by simulating the behavior of structures under different loading conditions (Chakraborty and Adhikari 2021; Pregnolato et al. 2022). In construction planning and management, digital twins have been utilized to enhance efficiency and resource management within the construction process by facilitating scheduling and real-time monitoring of resource allocation and processes (Chacón et al. 2024; Hussain et al. 2024; Khan 2022). In facility management , digital twins have been employed to analyze energy efficiency of buildings by simulating energy consumption (Cespedes-Cubides et al. 2024; Tsakiris et al. 2020), and to monitor heating, ventilation, and air conditioning systems to ensure comfortable indoor environment conditions (Lu et al. 2020b; Villa et al. 2021; Opoku et al. 2024). Moreover, in smart cities and smart buildings, primarily urban planning (Lu et al. 2020a), urban management (Zhang et al. 2024), and building efficiency (Arsiwala et al. 2023; Porkka et al. 2022) are aided by digital twins to reduce costs, reduce emissions, automate systems, and improve decision-making.

Use cases related to the disciplines of manufacturing and mechanical engineering report, for example, on product design and development (Tao et al. 2018), production planning and optimization (Ma et al. 2020), control of cyber-physical systems (Park et al. 2020; Wang et al. 2021d; Tomar 2022), and shop floor management (Corallo et al. 2021). In studies related to the automotive industry, use cases such as autonomous vehicle development (e.g. vehicle communication (Alam and El Saddik 2017), digital road (Wang et al. 2022b) and quality control (Zheng et al. 2021)) are identified. In studies related to the energy industry, use cases are reported on grid management (O'Dwyer et al. 2020; Chakraborty and Adhikari 2021) and power plants management (Lei et al. 2022). Moreover, use cases regarding ship design and development (Fonseca et al. 2022) are related to maritime engineering while use cases regarding supply chain control (Park et al. 2020c) are related to the logistics industry.

Representing the second aspect of research question 4, emerging trends have been observed across the selected studies, from utilizing new technologies to exploring new application areas. New technologies, such as Internet of Things (IoT), artificial intelligence (AI) and mixed reality, and new computing paradigms enhance the functionalities of digital twins, while new application areas extend the implementation of digital twins to support future demands within industries. In the following, a short overview of the emerging trends is presented:

- *IoT integration*: Integrating IoT devices with digital twins facilitates real-time data collection, enhancing the accuracy and utility of simulations and models.
- *AI and machine learning*: Leveraging AI and machine learning to analyze data from digital twins improves the accuracy of predictions and facilitates the automation of decision-making processes.
- *Mixed reality*: Coupling mixed reality and digital twins enhances the interaction of users with digital twins to evaluate user experience, reduce risks in the real world, and develop skills. Furthermore, mixed reality aids the collaboration among stakeholders by providing a shared and detailed visualization to improve communication and decision making.
- *Cloud and edge computing paradigms*: The cloud computing paradigm outlines services that can be accessed across the cloud on demand, while the edge computing paradigm outlines distributed computing models for data processing and storage close to data sources at the periphery of a network. Cloud computing may be leveraged to handle large amounts of data generated and processed by digital twins, providing dynamic, scalable, and flexible cloud solutions. Edge computing leverages local data processing and reduces latency, enabling real-time decision-making and responsiveness.

- *Sustainability*: Digital twins may be used to support sustainable development and circular economy goals, including optimizing resource management and energy efficiency, reducing emissions, and supporting sustainability initiatives using circular economy strategies.
- *Life-cycle management*: Digital twins may be extended to support the entire life cycle of assets, products, systems, and projects. In particular for civil engineering, integrating BIM and digital twins provides more detailed and actionable insights throughout the life cycle of a project, from design and construction to operation and decommissioning.

In summary, the statistical analysis provides the following main findings for RQ 4:

- Most studies in the discipline of civil engineering report on use cases regarding structural health monitoring (within maintenance), smart cities and smart buildings, and facility management.
- AI and machine learning are the most frequently implemented technologies to analyze large volumes of data, in combination with cloud and edge computing paradigms to leverage cloud services and distributed data processing.

5. DISCUSSION AND RECOMMENDATIONS

This section presents the last step, step (xi), in the reporting phase of the MLR, the discussion of the results and suggestion of recommendations. To provide an insight into the results, the following discussion includes the key findings of each research question, along with explanations and identification of open research issues. Based on the discussion, recommendations for digital twins in civil engineering are proposed to advance digital twin implementations, including (i) a definition, (ii) a pattern for a schema, and (iii) a reference architecture for digital twins.

5.1 Discussion of the key findings

The findings within RQ 1 ("*What definitions of digital twins are reported*?") highlight the lack of consensus on a definition for digital twins. However, common characteristics emerge across various definitions, as confirmed by 76 studies reporting on "digital representation", "synchronization", "capabilities" and "life-cycle". The lack of consensus regarding a definition, despite the presence of common characteristics, can be attributed to the interdisciplinary nature of digital twins. Digital twins span multiple disciplines including computer science, manufacturing, and civil engineering, as well as various multidisciplinary fields, such as smart cities. Each discipline defines digital twins differently, reflecting specific demands and perspectives of the respective discipline. A balance between granularity and abstraction should be achieved to define digital twins in a generally valid manner according to discipline. Thus, achieving consensus of defining digital twins remains an ongoing challenge, where continuous exchange among engineers in various disciplines is necessary so as to align diverse demands and perspectives. By identifying the common characteristics of digital twins in civil engineering, a generally valid definition could be extrapolated.

The findings related to RQ 2 (*"What schemas are reported*?*"*) reveal the absence of consensus on a schema for digital twins. However, common thematic scopes are evident across the various schemas identified in the selected studies covering building information, urban information, monitoring information, and manufacturing information. Despite the presence of common thematic scopes in studies related to civil engineering, the absence of consensus on a schema arises from the heterogeneous data associated with digital twins, including data on buildings, infrastructure, cities, robots as well as cyber-physical systems, sensors, and simulations. The heterogeneous data represents different standards, data structures, and formats, entailing interoperability obstacles. To reach consensus on a schema for digital twins in civil engineering, guidelines and standards promoting interoperability are essential. The findings of RQ 2 also highlight a growing trend towards employing formal approaches for schemas of digital twins, as reported by 11 studies, which have used formal modeling languages, such as OWL. This trend may be attributed to the ability of formal approaches towards facilitating reasoning about digital twins through logical inference on schemas. While formal approaches pose challenges for engineers, as specialized mathematical or computer science expertise is required to develop and understand the schemas, the advantages in terms of reasoning and formalization often outweigh the challenges. Hence, for developing a schema for digital twins in civil engineering, employing formal approaches and incorporating guidelines and standards from various disciplines may be considered to advance digital twin implementations.

The findings obtained in RQ 3 (*"What system architectures, including internal elements, are reported?"*) emphasize the absence of agreement on a common system architecture for digital twins. However, common layers and internal elements are observed across the various system architectures, as confirmed by 88 studies reporting on system architectures composed mainly of six layers, including service, modeling, data management, transmission, perception, and presentation layers. An explanation for the lack of consensus on a system architecture – despite the existence of common layers – lies in the interdisciplinary nature of digital twins, with each discipline featuring unique functional requirements, data formats, and communication protocols, and thus resulting in difficulties in reaching agreement on a common system architecture. Conversely, the existence of common layers and internal elements stems from common functional requirements shared by the various system architectures of digital twins, regardless of discipline or application. The common functional requirements include modeling, data storage, analysis, simulation, and data visualization. Reaching an agreement on a common system architecture for digital twins could be achieved by developing a reference architecture as a product of collaboration between research, industry, and standardization committees. With respect to modeling approaches for the architectures of digital twins, it has been observed that informal approaches are favored over semi-formal and formal approaches, as indicated by 85 studies focusing on informal approaches. The preference for informal approaches lies in the ease and the intuitive means of communication offered by informal approaches, allowing engineers to collaborate on designing system architectures without the need for training on special notations associated with semi-formal and formal approaches. However, there is a notable lack of formal approaches for modeling system architectures. Formal approaches, such as formal architecture description languages, aid in evaluating system architectures by uncovering potential design flaws, which is a capability not provided by informal and semi-formal approaches. Hence, utilizing formal approaches for modeling system architectures for digital twins may serve to advance efforts in defining DT architectures.

The findings obtained in RQ 4 ("*What are the major use cases and emerging trends of digital twins in engineering?*") highlight the diverse use cases of digital twins across multiple disciplines. Digital twin implementations are developed according to the particular needs of each discipline, resulting in a wide range of use cases that require specific functional requirements. Hence, digital twins are usually tailored to specific use cases that require diverse schemas and system architectures. Furthermore, emerging trends reflect the current demands for digital twins, aiming to enhance innovation and efficiency. Common emerging trends have been identified across the disciplines. The most common trends are the deployment of AI and machine learning to analyze large volumes of data, together with cloud and edge computing paradigms to leverage cloud services and distributed data processing. New approaches for digital twins are necessary to achieve sustainability and to support life-cycle management, considering a trade-off between level of detail, computational cost, and synchronicity. In summary, a digital twin reference architecture becomes necessary to serve as a common guideline for digital twins, particularly in civil engineering, capable of supporting diverse use cases and presenting sufficient flexibility to incorporate current and future trends.

5.2 Recommendations

Based on the findings revealed by the analysis of definitions, schemas, system architectures, and internal elements of digital twins as well as by the use cases and trends, (i) a definition, (ii) a pattern for a schema, and (iii) a reference architecture for digital twins in civil engineering are proposed, followed by recommendations concerning use cases and trends.

5.2.1 Definition of digital twins in civil engineering

Drawing from the findings of RQ 1, which highlight common characteristics of digital twins, including "digital representation", "synchronization", "capabilities" and "life-cycle", a definition of digital twins is synthesized as follows. The definition reflects the concepts of digital twins by encapsulating the common characteristics emerging from the MLR, encompassing a broad range of engineering disciplines, including civil engineering:

A "digital twin" is a digital representation of a real-world entity that dynamically mirrors and synchronizes with its real-world counterpart throughout either a part or the entirety of its life-cycle. A digital twin possesses capabilities to perform engineering tasks, which may include monitoring, analysis, simulation, optimization, and control of the real-world entity.

The definition highlights the differences between digital twins and BIM, where BIM models can be (but do not need to be) an element within a digital twin. On the one hand, digital twins reflect observable and relevant aspects regarding state and behavior of built assets throughout their life cycle, owing to near real-time data exchange, state awareness, and feedback loops, all of which facilitate monitoring, analysis, prediction and decision-making. On the other hand, BIM provides an information management framework, focusing on documentation and coordination of built assets. BIM models are descriptive, offering geometry representations and semantic information at specific points of the life cycle of built assets, but do not support dynamic synchronization with the built asset nor temporal semantics. BIM models may evolve into digital twins when static information models become continuously synchronized with the built assets and are capable of representing, analyzing, and influencing real-world behavior over time.

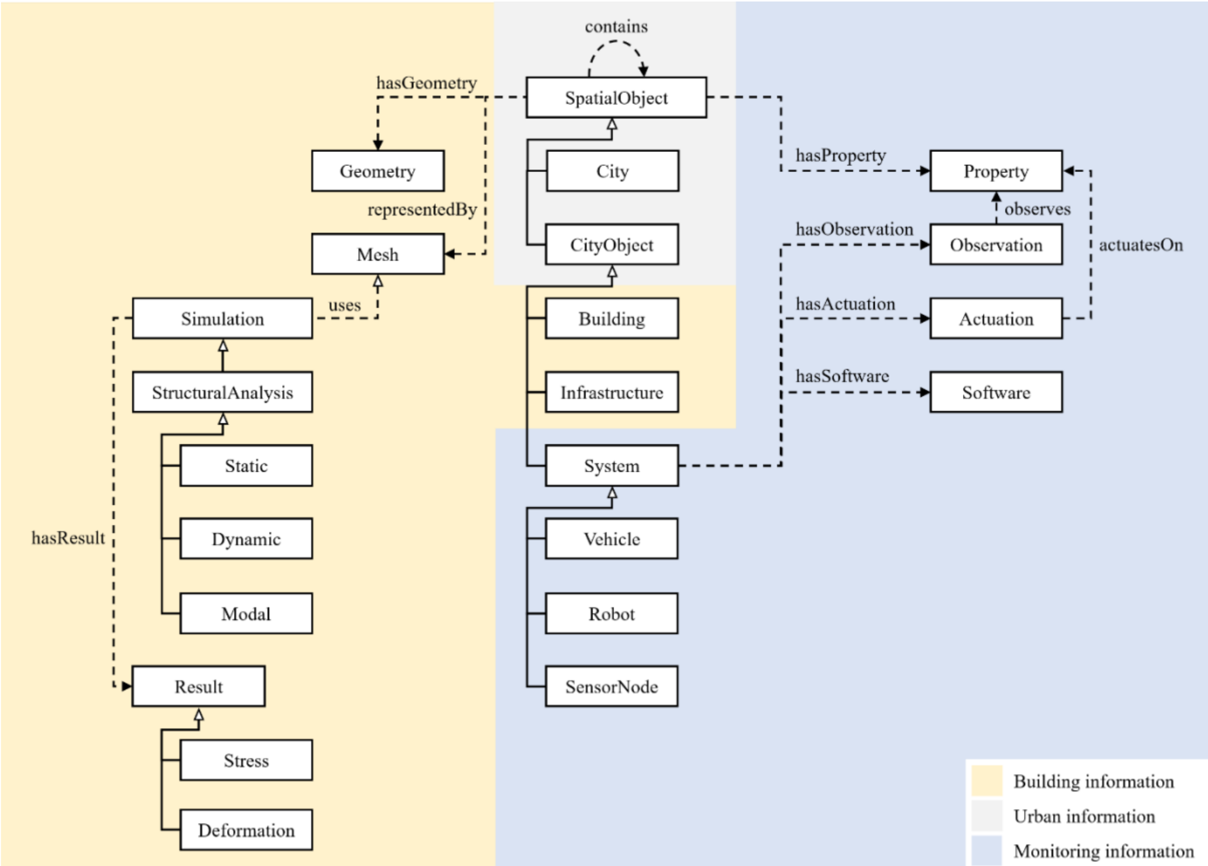

Figure 14: Pattern for a schema for digital twins in civil engineering in UML notation.

5.2.2 A schema for digital twins in civil engineering

Given the findings derived from RQ 2, a pattern for a schema for digital twins in civil engineering is proposed, as shown in Figure 14. The pattern is recommended to be adopted by researchers and practitioners as a baseline for designing schemas for digital twins. The pattern is not intended for merging specific standard metamodels (e.g. IFC, Landinfra, or CityGML), which would face challenges caused by semantic differences in the respective classes and relationships. The pattern is intended as an example on how schemas may be defined for civil engineering applications. The pattern encompasses classes essential for representing the core thematic scopes relevant to digital twins in civil engineering, incorporating building information, urban information, and monitoring information. It should be noted that manufacturing information is intended mostly for the manufacturing discipline and it has not been possible to identify a well-established schema in the selected studies, as stated in Section 4.3. Therefore, for the purposes of the pattern proposed herein, a thematic scope for manufacturing information is not included. As shown in Figure 14, the *SpatialObject* class represents entities occupying space (e.g. cities). The *City* class represents urban areas administratively organized by authorities (e.g. cities or towns). The *CityObject* class represents objects in a city (e.g. buildings, infrastructure, systems). The

Geometry class represents geometry information, while the *Mesh* class represents finite element (FE) models associated with a spatial object. To incorporate structural simulations, the *Simulation* class represents techniques for analyzing physical behaviors of spatial objects under external conditions (e.g., mechanical loads) utilizing FE models. To incorporate monitoring information, the *System* class represents entities (e.g., robots or sensor nodes) performing actions or gathering measurements from a spatial object.

An example of a schema for a digital twin of a bridge developed following the proposed pattern is described in Figure 15. First, existing ontologies covering topics related to the pattern are selected to build a schema for the digital twin of a bridge, which are then aligned to ensure compatibility. Building information of the bridge can be described using the ifcOWL ontology, while real-time monitoring information can be represented using the SOSA ontology. Furthermore, the PROV-O ontology (W3C 2013) can be used to provide traceability for simulation data. Second, new classes and relationships are defined to support topics not yet defined in the selected ontologies. For example, classes and relationships defining concepts concerning simulations for structural analysis are created. Third, the schema is verified and validated to ensure semantic correctness. As a result, the schema for a digital twin of a bridge is realized and can be instantiated as shown in Figure 15. An alignment with the IFC standard can then be easily realized and the schema can be developed to comply with information requirements defined in ISO 19650.

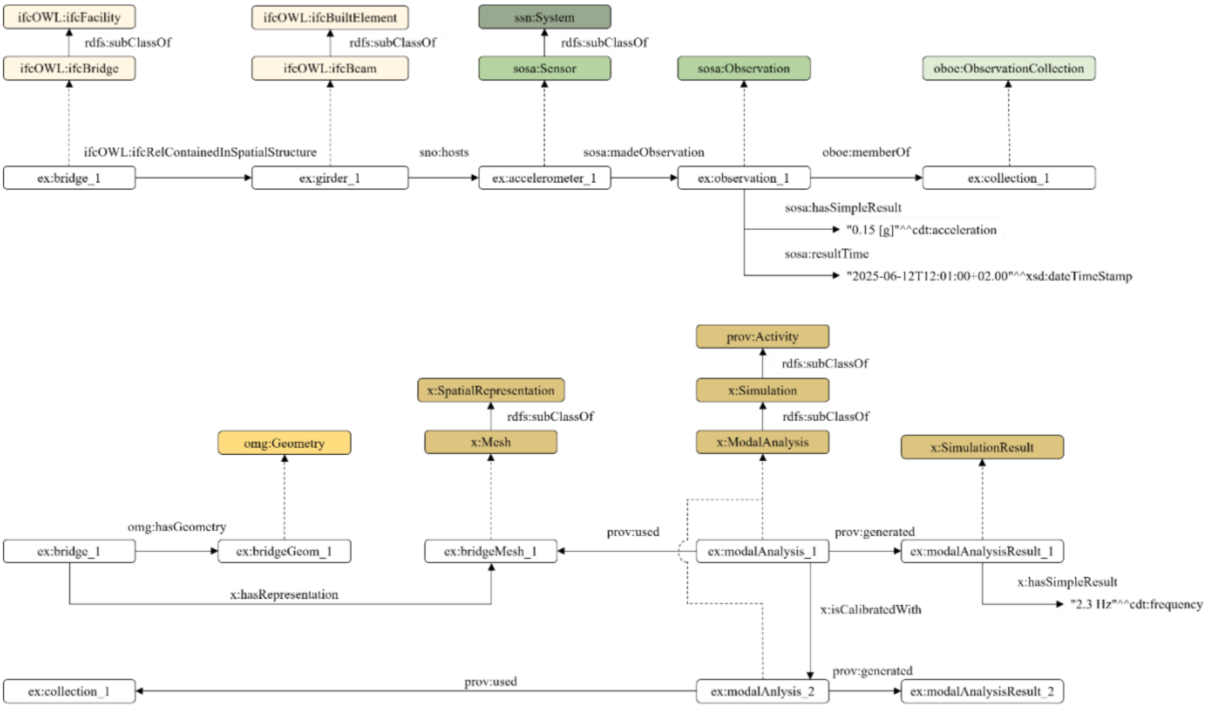

Figure 15: Example schema for a digital twin of a bridge.

5.2.3 Reference architecture for digital twins in civil engineering

Given the findings related to RQ 3, a reference architecture is proposed and visualized as a schematic diagram, shown in Figure 16. The reference architecture, representing a blueprint for digital twins, consists of four layers, (i) a platform layer, (ii) a transmission layer, (iii) a perception layer, and (iv) a presentation layer.

The *platform layer* is the centerpiece of the reference architecture, providing data management and business logic capabilities. The platform layer is composed of four sub-layers, (a) a service sub-layer, (b) an integration sub-layer, (c) a modeling sub-layer, and (d) a data management sub-layer. The service sub-layer provides services to other sub-layers to interact with the digital twins, and the integration sub-layer ensures consistent updates of the digital twins. Digital twins are hosted in the modeling sub-layer, comprising model instances and a schema, where its schema integrates various sub-schemas for particular thematic scopes following the pattern recommended in Figure 14, e.g. IFC for building information, CityGML for urban information, and SOSA for monitoring information. The model instances compose the specific real-world entities that are digitally represented based on the schema, such as building information models, finite element models for structural analysis, and monitoring system models. The data management sub-layer persists the digital twins through bidirectional data transfer between digital twins and data repositories, such as relational databases. The *transmission layer* provides messaging transfer between the other layers using various communication networks and technologies, such as Internet, Wi-Fi, Zigbee, or 5G. The *perception layer* provides sensing and actuating capabilities using devices, such as sensors, actuators and robots, operating on engineering structures of interest, i.e. on the real-world entities. The devices use the transmission layer for inter-device interaction and for interaction with the platform layer. Finally, the *presentation layer* supports user interfaces that deploy the digital twins for management and visualization. Management primarily refers to human activities conducted through user interactions, while visualization of the digital twins is provided in the form of 2D or 3D renderings via web or desktop applications.

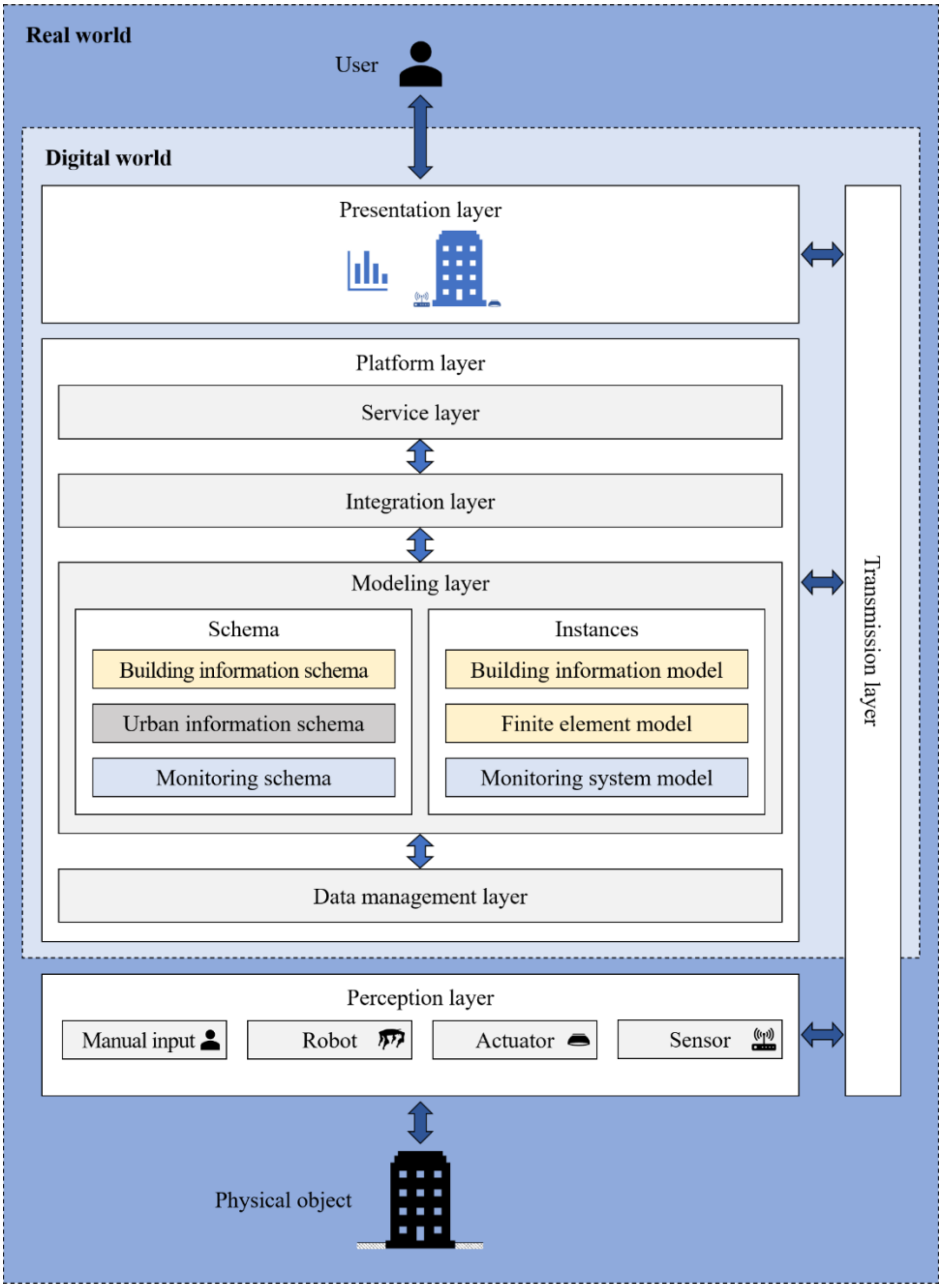

Figure 16: Reference architecture for digital twins in civil engineering.

The reference architecture facilitates the implementation of digital twins in alignment with existing standards, such as ISO 23247, ISO/IEC 30173, and ISO 19650, and it realizes concepts in compliance with ISO 23247 and ISO/IEC 30173 at the system level. The reference architecture facilitates bidirectional data flow between layers as well as services for monitoring, simulation, and control. The perception-transmission-modeling data flow allows continuous synchronization, feedback loops, and the integration of IoT devices. Furthermore, structuring of the modeling layer into schema and instances may support federated models and semantic interoperability, necessary for managing life cycle data and multi-domain data of built assets in accordance with ISO 19650 as well as complementary data from FE models and monitoring systems.

Finally, the following informal definition of the reference architecture is recommended: "*A reference architecture for digital twins in civil engineering is an abstraction encompassing layers; each layer encapsulating a specific set of functions that support engineering tasks. The layers essentially involve a platform layer, a transmission layer, a perception layer, and a presentation layer*". The definition proposed in Equation (1), utilizing formal notations, is a formal representation of the visual illustration of the reference architecture shown in Figure 16. The reference architecture $RefArch_{\mathrm{DT}}$ for digital twins in civil engineering is defined as:

$$RefArch_{\mathrm{DT}}=L_{\mathrm{Platform}}\otimes L_{\mathrm{Transmission}}\otimes L_{\mathrm{Perception}}\otimes L_{\mathrm{Presentation}} \quad (1)$$

In Equation (1), the composition operator $\otimes$ denotes the integration of layers, L_{Platform} refers to the platform layer, $L_{\mathrm{Transmission}}$ refers to the transmission layer, $L_{\mathrm{Perception}}$ refers to the perception layer, and $L_{\mathrm{Presentation}}$ refers to the presentation layer. An example implementation of the reference architecture for digital twins is shown in the following subsection.

5.2.4 Example implementation of the reference architecture for digital twins in civil engineering

The following discussion considers a digital twin illustratively devised for a laboratory-scale single-span steel beam. The steel beam has a rectangular hollow section with dimensions 50 × 30 × 3 mm and a span of 4.00 m, and it rests on two hinged supports with horizontally movable bearings that allow rotation and horizontal displacement. The setup is illustrated in Figure 17 as its physical (left) and digital (right) representation. Sensors and actuators are mounted on the beam to observe the dynamic behavior of the beam. An accelerometer is mounted next to an electrodynamic shaker at midspan, and a second accelerometer is mounted at a quarter point of the span to collect measurements. Additionally, a displacement sensor is mounted at the midspan for reference measurements. For test purposes, the beam is excited with the electrodynamic shaker and a modal hammer. Harmonic sinusoidal loading is applied using the electrodynamic shaker, and impulse loading is applied using the modal hammer at a quarter point, a third point, and midspan.

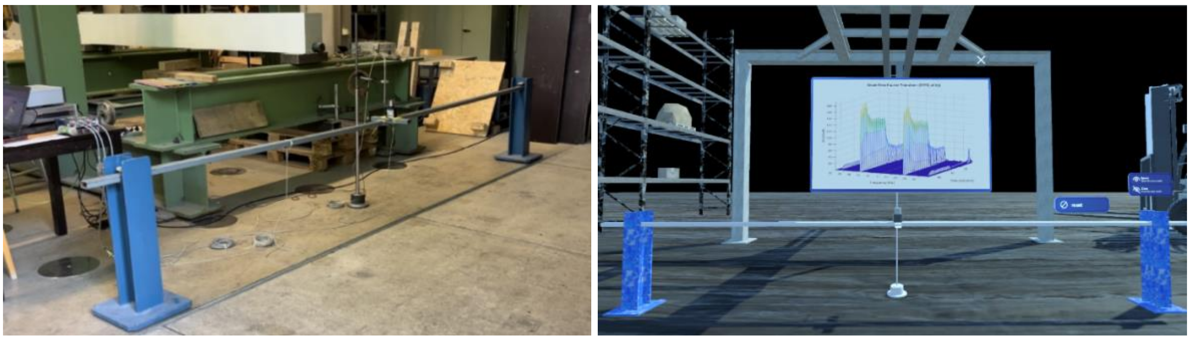

Figure 17: Prototype implementation of the digital twin with physical object (left) and digital object (right).

Following the reference architecture, the illustrative digital twin combines the physical object, sensing and actuation hardware, and a software stack organized into a presentation layer, a platform layer, a perception layer, and a transmission layer (Figure 18). The perception layer includes the sensors mounted on the beam and an LED actuator connected to a control circuit. The platform layer combines Revit (Autodesk, Inc.), a BIM software, Ansys (Ansys, Inc.), a finite element software, Node-RED (IBM Corporation), a development tool for data ingestion, analysis, and dashboards, as well as CSV files for data storage for local logging. The transmission layer routes measurement and control messages via Mosquitto (Eclipse Foundation), a message broker, and publishes dashboards via a Local IP address or via ThingSpeak (MathWorks), a cloud platform. The presentation layer delivers visualization and interaction through Unity (Unity Software, Inc.), a game engine, combined with the

HoloLens (Microsoft Corporation) mixed reality glasses, and the Remote-RED (Looking4Cache UG) mobile app. Selected communication paths of the described instantiation are shown in Figure 18.

During the operation of the digital twin, the measurements are streamed via Message Queuing Telemetry Transport (MQTT) protocols to Mosquitto and then to Node-RED, writing time-stamped records to a CSV file and evaluating threshold logic for alert generation. Node-RED outputs processed indicators to ThingSpeak for cloud storage and further logical evaluation. Node-RED provides dashboards over Hypertext Transfer Protocol Secure (HTTPS) at a Local IP address for browser access, Unity web views, and Remote-RED notifications. Users can send control commands via the Unity interface on the HoloLens or the Remote-RED mobile app. Control commands traverse via HTTPS to Node-RED and return via MQTT to the LED actuator, enabling physical interaction between visualization and laboratory hardware. Further comparison overlays can incorporate response quantities derived from Ansys and Revit.

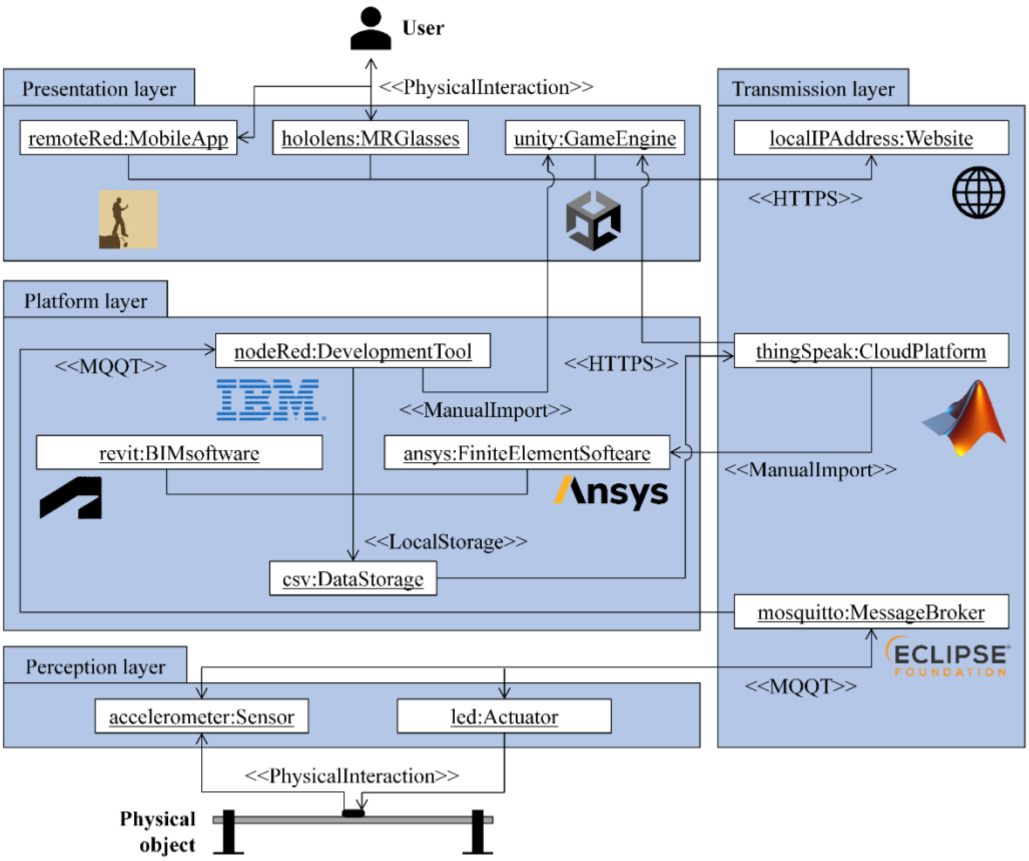

Figure 18: Instantiation of the reference architecture with selected communication paths.

5.2.5 Recommendations concerning use cases and trends for digital twins in civil engineering

In civil engineering, the use cases of digital twins mostly focus on the construction phase or the operation and management phase of the life cycle of structures, where BIM integration together with AI and cloud services has resulted in dynamic and scalable solutions. However, to further advance the implementation of digital twins, additional potential research directions should be explored.

- *Standardization and interoperability*: Considering the various digital twin schemas and system architectures, industry standards are required to ensure interoperability between digital twin systems and tools. BIM integration provides a basis for data exchange between tools, however, there is a need for data mapping when tools are based on different conceptual models to ensure data integrity and avoid the loss of semantics. A common reference architecture and schemas will advance the efforts towards standardization and interoperability.

- *Model and data quality assurance*: Digital twins integrate heterogeneous models and data, with various levels of quality. Data integration is key to abstract and transform data between different conceptual models. Hence, a framework to evaluate model and data quality assurance is needed to ensure correctness and completeness to fulfill the intended use cases according to data requirements. Concepts, such as smart contracts, may help to ensure consensus among stakeholders to determine data requirements.
- *Cybersecurity*: With the increase deployment of cyber-physical systems for the automation of built environments, the need for data protection and encrypted systems increases. Furthermore, as the use cases expand from building level to city level, digital twins may encompass data that requires cybersecurity solutions to protect sensitive data and the integrity of the digital twins. Concepts, such as blockchain technology, may help to ensure trust and traceability in data management.
- *Automated schema transformations*: As the pace of technological advancements is accelerating and new innovations and emerging technologies continuously reshape engineering practice, it can be expected that digital twins will be extended to allow representing physical twins that emerge from new paradigms, such as dynamic, robot-based entities (including 3D printers), quantum and quantum-inspired computing, and biologically-inspired or “living” buildings. Therefore, the corresponding schemas need to be extended, rendering automated, verifiable schema extensions useful, facilitating efficient and correct adaptations to new paradigms.

6. SUMMARY AND CONCLUSIONS

In civil engineering, digital twins have been proposed as a new paradigm to couple digital representations of civil engineering structures and the counterparts in the real world. Reviews and studies have been published in recent years, investigating the role of digital twins and proposing various definitions, schemas, and system architectures. Despite the importance of reviews in research and practice, reviews providing a comprehensive picture and assessment of the state of the art and the state of practice regarding the existing definitions, schemas, architectures, and internal elements of digital twins have received little attention.

This study has presented a multivocal literature review on digital twins in civil engineering. The multivocal literature review encompasses a systematic literature review and a gray literature review, summarizing and assessing the existing definitions, schemas, and system architectures (including internal elements) as well as use cases and trends reported in research and practice. Out of more than 50,000 studies initially found, 103 selected studies (88 from white literature and 15 from gray literature) have been analyzed. The multivocal literature review has been conducted following well-known guidelines, ensuring a rigorous and systematic approach underlying the review process. However, the multivocal literature review still has limitations. For instance, only one research database, i.e. Scopus, has been utilized to retrieve white literature within the systematic literature review to avoid duplicated search results. Moreover, potential threats to validity, such as publication bias (primarily subject to the tendency of publishing positive results rather than negative results), may affect the findings of the systematic literature review. To mitigate the publication bias, the systematic literature review has been complemented with the gray literature review to reflect the industry perspective.

The analysis of the selected studies has yielded several findings, including the lack of consensus on a definition, on a schema, and on a system architecture of digital twins. In addition, common characteristics across various definitions, common thematic scopes across diverse schemas, as well as common layers and internal elements across various system architectures have been observed. Furthermore, a trend towards utilizing formal approaches for modeling schemas and informal approaches for modeling system architectures has been exposed. Regarding use cases and trends, upcoming demands for standardization and interoperability, quality assurance, cybersecurity, and automated schema transformations have been identified, the latter considering the emergence of new paradigms to be represented by digital twins, such as quantum or biologically inspired computing. Drawing from the analysis and the findings, recommendations have been proposed to advance the implementation of digital twins in civil engineering, including (i) a definition of digital twins providing a common understanding based on the common characteristics revealed in the findings, (ii) a pattern for a schema, and (iii) a digital twin reference architecture, representing a blueprint for digital twin implementations in civil engineering. Future work towards further enhancing the aforementioned aspects may include fostering the dialogue among engineers from various disciplines to align diverse perspectives in defining digital twins, developing guidelines and standards for schemas of digital twins, as well as employing formal approaches, such as formal architecture description languages, to enhance digital twin reliability and interoperability.

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APPENDIX A: CATEGORIZATION OF LITERATURE

To clearly distinguish between white literature and gray literature, a categorization adopted from Kitchenham et al.(2023) is utilized as follows:

- White literature refers to formally published literature such as books, book chapters, trade and professional journals, magazines, conference proceedings and workshop proceedings.
- Gray literature refers to informally published literature such as technical reports, industry and government white papers, preprints (e.g., arXiv.org, Zenodo, Figshare).
- Social media posts refer to online communication media, such as blogs, tweets, wiki articles, websites articles, news articles, vlogs, online videos, or Q&A sites (e.g., StackOverflow).
- Personal communications refer to industry and government internal communications, such as memos, emails, meeting notes, minutes, or agendas.

APPENDIX B: SELECTED STUDIES

Table B: List of the selected studies, emphasizing the contribution to the research questions.

Study	Type	RQ 1	RQ 2	RQ 3	RQ 4
(Tao et al. 2018)	White	*		*	*
(Alam and El Saddik 2017)	White	*		*	*
(Aheleroff et al. 2021)	White	*		*	
(Minerva et al. 2020)	White	*		*	
(Li et al. 2022b)	White	*		*	
(Lu et al. 2020a)	White	*	*	*	*
(Lu et al. 2020b)	White	*	*	*	*
(Park et al. 2020)	White	*	*	*	*
(Damjanovic-Behrendt and Behrendt 2019)	White	*		*	
(Zhuang et al. 2021)	White	*	*	*	
(Rathore et al. 2021)	White	*		*	
(Jiang et al. 2021b)	White	*			
(Autiosalo et al. 2020)	White	*		*	
(Saad et al. 2020)	White	*			
(Chen et al. 2020)	White	*		*	
(Sun et al. 2021)	White	*			
(Josifovska et al. 2019)	White	*		*	
(Jiang et al. 2021c)	White	*		*	
(Fan et al. 2021)	White			*	
(Wang et al. 2021d)	White	*		*	
(Zhang et al. 2020a)	White	*		*	
(Zhang et al. 2022)	White	*			
(O'Dwyer et al. 2020)	White			*	*
(Cespedes-Cubides et al. 2024)	White	*		*	*
(Wang et al. 2021a)	White	*		*	
(Ma et al. 2020)	White	*		*	*
(Park et al. 2020c)	White	*		*	*
(Steindl et al. 2020)	White	*		*	
(Saad et al. 2020a)	White			*	
(Stojanovic et al. 2018)	White	*		*	
(Schroeder et al. 2021)	White	*		*	
(Park et al. 2020b)	White	*		*	
(Chakraborty and Adhikari 2021)	White	*		*	*
(Wang et al. 2021c)	White	*		*	
(Davila Delgado and Oyedele 2021)	White	*	*	*	
(Lin and Low 2020)	White			*	
(Wang et al. 2021b)	White	*		*	
(Zheng et al. 2020)	White	*		*	

Study	Type	RQ 1	RQ 2	RQ 3	RQ 4
(Eckhart et al. 2019)	White			*	
(Dietz et al. 2019)	White	*		*	
(Hunhevicz et al. 2022)	White	*			
(Zheng et al. 2022)	White	*		*	
(Lei et al. 2022)	White	*		*	*
(Villa et al. 2021)	White	*		*	*
(Park et al. 2021)	White	*		*	
(Hoebert et al. 2019)	White	*	*	*	
(Liu et al. 2022b)	White	*		*	
(Barthelmey et al. 2019)	White		*	*	
(Liu et al. 2022a)	White			*	
(Wu et al. 2021)	White			*	
(Lektauers et al. 2021)	White	*		*	
(Kuhn et al. 2020)	White			*	
(Kychkin and Nikolaev 2020)	White			*	
(Ala-Laurinaho et al. 2020)	White	*		*	
(Zheng et al. 2021)	White	*		*	*
(Corallo et al. 2021)	White	*		*	*
(Redeker et al. 2021)	White			*	
(Li et al. 2023)	White	*		*	
(Assad Neto et al. 2020)	White	*		*	
(Steindl and Kastner 2021)	White	*		*	
(Dobaj et al. 2019)	White			*	
(Wang et al. 2022b)	White	*		*	*
(Fonseca et al. 2022)	White			*	*
(Borghesi et al. 2021)	White	*		*	
(Latsou et al. 2021)	White	*		*	
(Rasor et al. 2021)	White	*		*	
(Borangiu et al. 2020)	White	*		*	
(Han et al. 2023)	White	*			
(Wu et al. 2022)	White			*	
(Phua et al. 2022)	White	*		*	
(Redelinghuys et al. 2020)	White	*		*	
(Lu et al. 2020c)	White	*		*	
(Boyes and Watson 2022)	White	*		*	
(Newrzella et al. 2022)	White	*		*	
(Pregnolato et al. 2022)	White	*		*	*
(Alva et al. 2022)	White	*		*	
(Worden et al. 2020)	White	*			
(Chacón et al. 2024)	White	*		*	*

Study	Type	RQ 1	RQ 2	RQ 3	RQ 4
(Khan et al. 2022)	White	*	*		
(Ramonell et al. 2023)	White	*	*	*	
(Zhao et al. 2022)	White	*		*	*
(Opoku et al. 2024)	White			*	*
(Hussain et al. 2024)	White	*		*	*
(Arsiwala et al. 2023)	White	*	*	*	*
(Lee et al. 2023)	White	*		*	
(Pavón et al. 2025)	White		*	*	
(Zhang et al. 2024)	White	*		*	*
(Gispert et al. 2025)	White	*	*	*	
(Porkka et al. 2022)	Gray	*	*	*	*
(Loscos et al. 2019)	Gray	*			
(Khan 2022)	Gray		*		*
(Hartmann et al. 2022)	Gray			*	
(Chacón et al. 2023)	Gray		*	*	
(Bonan 2020)	Gray			*	
(Benach et al. 2023)	Gray			*	
(Tomar 2022)	Gray	*		*	*
(Torres et al. 2022)	Gray	*			
(Valluru et al. 2022)	Gray		*		
(Oraskari and Bourreau 2023)	Gray		*		
(Bus et al. 2021)	Gray		*		
(Tsakiris et al. 2020)	Gray			*	*
(Chávez-Feria et al. 2020)	Gray		*		
(Pascual et al. 2022)	Gray	*		*	

APPENDIX C:MAPPING OF CHARACTERISTICS AND TERMS

Table C: Mapping of characteristics and terms, utilized for tagging the definitions.

Characteristic	Terms
Digital representation	3D model, computational model, computer model, cyber twin, data driven representation, digital counterpart, digital duplicate, digital equivalent, digital information construct, digital mapping model, digital model, digital replica, digital representation, digital replication, digital version, distributed semi-physical simulation, dynamic representation, exact cyber copy, formal numerical representation, framework consisting of a physical and virtual space, information construct, logical component, probabilistic simulation, representation of the operational dynamics of the physical counterpart, simulates, virtual, virtual asset, virtual counterpart, virtual data, virtual entity, virtual information constructs, virtual model, virtual object, virtual product, virtual representation, virtual replica, virtual version, digitalized replica.
Synchronization	Bidirectional data exchanges and controls, communication, connection, connection between cyber and physical twins, consistency between the ideal model and the actual state, dynamic, evolution, evolve continuously, evolve in real-time, information matching, interactive feedback, interaction, linked, linked to a real-world entity, linkage between the virtual replica and the physical asset, live digital coupling, live setting, mapping, mimic the corresponding twin, mimics the real-world behaviors of an asset, mirror, mirror the life of its corresponding flying twin, mirror the of its corresponding twin, real-time, real-time mapping, reflects the physical asset configuration, replication, synchronization, synchronize, transmission of data, represents the functionalities of a physical system, two-way dynamic mapping, synchronous understanding, updated through the exchange of information, combines data.
Capabilities	Analysis, communication, control, feedback, forecast, interpretation, learning, reasoning, management, mirroring, monitor, monitoring, optimization, optimize, optimizing, perceive, prediction, predictive, processing, simulate, simulating, simulators, storage, synchronization, test, validate, analytics, simulation.
Life-cycle	Instance stages of the physical asset, life, lifecycle, life cycle, Life-cycle, lifespan, represents the state of the physical entity.