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A multivocal literature review of digital twins, architectures, and elements in civil engineering

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Abstract. Structural health monitoring strategies in civil engineering increasingly leverage digital twins, supporting predictive maintenance and data-driven decision-making. Despite the widespread adoption of digital twin applications in structural health monitoring (SHM), there is a lack of agreement on a common definition of digital twins. Although a significant number of digital twin definitions have been proposed and a plethora of reviews have been published, little emphasis has been given to digital twin architectures and internal elements. This paper presents a multivocal review of digital twins in civil engineering, aiming to provide a panorama of the digital twin landscape in civil engineering with explicit insights into the architectures and internal elements used in digital twin applications. From a methodological standpoint, the review follows a twofold approach that encompasses (i) peer-reviewed, indexed literature ("white literature") as well as (ii) non-indexed sources ("gray literature") that include industrial digital twin applications. Furthermore, drawing from the review results, a digital twin definition is formulated and a generic digital twin reference architecture is proposed. It is expected that the definition and the generic reference architecture proposed in this study may serve as a blueprint for digital-twin-based SHM applications, with significant implications for researchers, practitioners, and policymakers in structural health monitoring.

Keywords: Digital twins, digital twin elements, digital twin architectures, reference architecture, multivocal literature review.

1. Introduction

Structural health monitoring (SHM) of civil infrastructure has witnessed significant progress, advanced by recent innovations in sensor technology and digitalization [1]. Major catalysts of the advancements of SHM are artificial intelligence (AI)-based smart sensors integrated into SHM systems [2] or the introduction of mobile SHM systems that build upon mobile robotic platforms [3]. Coupling intelligent sensor systems, AI-driven predictive analytics, and digital platforms has substantially enhanced the ability of SHM systems to provide real-time insights into structural integrity, facilitating proactive maintenance and ensuring safety and durability of civil infrastructure [4]. Hereby, digitalization serves as a fundamental driver for the evolution of SHM systems, rendering SHM systems more efficient, effective, and cost-efficient compared to early SHM approaches [5]. Specifically, digital twins play a

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pivotal role of increasing importance in propelling SHM forward, by enabling engineers and analysts to create precise and dynamic digital representations of civil infrastructure that is updated by sensor data in real time [6]. Digital twins, i.e. digital representations of civil infrastructure that represent the “physical twins”, are the core components of modern SHM systems. By seamlessly integrating real-time data from sensors with the digital twins, engineers and analysts can not only monitor structural behavior but also simulate and analyze various scenarios, predict potential issues, and plan maintenance activities proactively [7].

Digital twins have been studied in depth, as evidenced in recent comprehensive literature reviews, which cover several aspects of digital twins, such as general characteristics, definitions, applications, potential advances, and future challenges [8-15]. From the aforementioned aspects, definitions hold a central role, since clearly defining digital twins would facilitate (i) communication exchanges between engineers, on the basis of mutually understood and accepted descriptions of digital twins, (ii) precise analyses of digital twins, building upon a common architecture that helps prevent design issues, and (iii) reusing digital twins, aided by a common understanding of architectures and internal elements of digital twins, which would advance interoperability. Nevertheless, a clear definition of digital twins or, at least, a common understanding of architectures and internal elements, have yet to be reported in literature. In addition to the definition, a reference architecture of digital twins, describing in a generic abstract manner the configuration of internal elements would benefit stakeholders in implementing digital twins for civil engineering applications.

This paper presents a multivocal review of digital twins in civil engineering, aiming to provide a panorama of the digital twin landscape in civil engineering with explicit insights into the architectures and internal elements used in digital twin applications. From a methodological standpoint, the review follows a dualistic approach that encompasses (i) peer-reviewed, indexed literature (“white literature”) as well as (ii) non-indexed sources (“gray literature”) that include industrial digital twin applications. Furthermore, drawing from the review results, a digital twin definition is formulated and a generic digital twin reference architecture is proposed, expected to serve as a blueprint for future digital-twin-based SHM applications.

In the remainder of the paper, the multivocal literature review is presented in Section 2, followed by a discussion of the findings and the recommendations of a digital twin definition and a reference architecture, covered in Section 3. Next, the main findings are summarized, conclusions are presented, and future research that may be conducted to further advance digital twins for structural health monitoring is proposed.

2. A multivocal literature review of digital twins, architectures, and elements in civil engineering

The review, presented in this section, centers around digital twins for civil engineering applications, including SHM. The type of review, considered in this paper, is “multivocal”, which involves reviewing white literature as well as gray literature, the latter covering, e.g., industrial developments on digital twins. The reason for considering a multivocal literature review (MLR) is that research-and-development projects, initiated in the industry, have resulted in important advancements of digital twins in recent years, whose contributions may only be assessed by incorporating a gray literature review (GLR) into the review process. White literature, referred to as “systematic literature review” (SLR), encompasses contributions from scientific literature. The MLR is conducted in three phases, (i) a planning phase, where the review objectives and the procedures for meeting the objectives are defined, (ii) an execution phase, where contributions from the literature are searched and collected, and relevant data is extracted, and (iii) a reporting phase, which entails data analysis, extracted from the execution phase. The three phases essentially constitute the review methodology and are described in the following subsections.

2.1 Planning phase

The planning phase is conducted in four steps: (i) a set of research questions are defined, (ii) a search strategy is devised for collecting contributions in literature from research and practice, (iii) inclusion and exclusion criteria are set for filtering and selecting literature contributions relevant to the MLR objectives, and (iv) data extraction and analysis methods are defined. The research questions (RQs), posed as part of the first step in accordance with the objectives, are:

- *RQ 1: What are the application areas of digital twins in engineering, with focus on SHM?*
- *RQ 2: What digital twin definitions and architectures (including elements) have been reported?*

The search strategy, devised within the second step, is twofold, including separate procedures for the SLR and the GLR. Specifically, the procedure for the SLR involves retrieving peer-reviewed, indexed literature contributions from the Scopus database, which is characterized by user-friendly search tools, high-quality results and wide coverage. Regarding the GLR, the general-purpose repository "Zenodo" [16] (operated by the European Organization for Nuclear Research) is utilized to include literature contributions from the industry that are not included in Scopus. Upon completing the search strategy, a "relevancy ranking" is defined to promote the results that are most relevant to the objectives of the MLR. The third step involves defining inclusion criteria (IC) and exclusion criteria (EC) for the results of the second step. In addition to the IC and the EC, quality assessment criteria (QAC) are also defined, ensuring that the contents of the literature contributions, retrieved in the results, include objectives, limitations and methodologies in the respective digital twin studies; details on defining the criteria are given in [17]. Data extraction and analysis methods are defined in the fourth step, thus concluding the planning phase.

2.2 Execution phase

The execution phase is conducted in four steps: (i) the "search" step entails retrieving literature contributions compatible with the research questions and the search strategy, (ii) the "filtering" step applies filtering to the literature contributions, returned by the search step, in compliance with the inclusion and exclusion criteria, (iii) the "selection" step evaluates literature contributions resulting from the filtering step, aiming to yield only relevant literature contributions (referred to as "selected studies" in the remainder of the paper), and (iv) the "data extraction" step extracts data from the selected studies. Regarding step (ii), notable criteria with direct relevance to the search results are, e.g., publication in English language and association with the subject areas engineering, computer science, or mathematics.

The search strings for the SLR are summarized in Table 1. For clarity, some criteria, such as restrictions related subject areas or language, have been removed from the search stings shown in Table 1. The search step is performed by sequentially applying the search strings, whose refinement results in reducing the initially retrieved 17,801 literature contributions to 1,127. The filtering step isolates the 200 most-cited literature contributions as a result of the inclusion and exclusion criteria, out of which 70 satisfy the quality assessment criteria, applied in the selection step. Using snowballing, 7 more literature contributions are accounted for, resulting in 77 selected studies. In the data extraction step, the selected studies are systematically tabulated, data thereof is extracted and forwarded to the reporting phase.

As for the GLR, two search strings are considered, “digital twins” and “digital twins”. From the originally 830 literature contributions retrieved in the search step, preliminary filtering, applied using Zenodo filtering tools (e.g. “open access”, “report”, “technical note”) in lieu of refining search strings, results in 137 contributions. The filtering step reveals that 49 literature contributions meet the inclusion and exclusion criteria, and the selection step results in 8 studies meeting the quality assessment criteria, to which 7 additional studies are added via snowballing. The 15 selected studies are passed to the data extraction step, and the data extracted from the selected studies is used as input to the reporting phase.

Table 1. Search strings and results for the SLR within the multivocal literature review. For clarity, the restrictions, such as subject areas and language, are removed from the search strings displayed below

No.	Search string	Results
1	(digital AND (twin OR shadow OR sibling))	17,801
2	(digital AND (twin OR shadow OR sibling)) AND (architecture OR framework OR platform)	6,327
3	(digital AND (twin OR shadow OR sibling)) AND (architecture OR framework OR platform) AND (feature OR service OR view)	1,408
4	(digital AND (twin OR shadow OR sibling)) AND (architecture OR framework OR platform) AND (feature OR service OR view) AND LIMIT-TO (EXACTKEYWORD (“digital twin” OR “internet of things” OR “iot” OR “industry 4.0” OR “cyber physical system” OR “architectural design” OR “architecture”))	1,127

2.2 Reporting phase

The reporting phase is conducted in two steps: (i) the “data analysis” step involves analyzing the data using statistical tools, and (ii) the “reporting” step encompasses drawing conclusions and making recommendations, based on the conclusions. In what follows, the data analysis outcomes as well as the reporting outcomes are presented together, both for the SLR and for the GLR. In particular, an overview of the selected studies is provided, followed by a summary of the main findings.

2.2.1 Overview of the selected studies

The selected studies have revealed a growing trend in digital twin studies in recent years, as evidenced by the 92 selected studies in this review (summation of the SLR and the GLR results). The 92 selected studies essentially constitute a representative sample of white and gray literature on digital twins for civil engineering. The statistical distribution of the selected studies over a period of 10 years is illustrated in Figure 1, both for the SLR and for the GLR. The data analysis indicates an increase in literature contributions on digital twins since 2017/2018. Furthermore, a statistical distribution of the selected studies according to the document type is shown in Figure 2. Evidently, most selected studies are original contributions included in journal papers and conference papers (comprising 72% of all selected studies), indicative of intensive research towards novel digital twin applications. A small percentage represents reviews, reports and deliverables, and white papers (28%).

2.2.2 Main findings

The main findings of the MLR are presented in response to the research questions.

- *RQ 1 (“What are the application areas of digital twins in engineering, including SHM?”)*
  As shown in Figure 3, the majority of the selected studies are located within the application areas of manufacturing (34), followed by civil engineering (26), general

topics related to digital twins (25), automotive (4), energy (4), mechanical engineering (3), logistics (2), and maritime engineering (2). It should be noted that studies of multidisciplinary nature may involve two or more disciplines. Digital twin applications in SHM are mostly situated in the area of civil engineering (5), followed by mechanical (2), aerospace (1), and maritime (1) engineering.

- *RQ 2 ("What digital twin definitions and architectures (including elements) have been reported?")*
  From the selected studies that meet the criteria defined in the planning phase, 67 ***definitions*** (63 from the SLR and 4 from the GLR) are available and are systematically analyzed. As shown in Figure 4, "digital representation" is the most-reported characteristic used in digital twin definitions, followed by "synchronization" and "data sources". Furthermore, in the selected studies, information on 78 ***architectures*** (70 from the SLR and 8 from the GLR) is provided. Essentially, the architectures are analyzed by investigating the layers and the internal elements of the architectures. The results are summarized in Figure 5 and Figure 6. In addition to the research question, the modeling approaches for digital twins are analyzed. As a result, none of the 78 architectures is modeled using a formal approach, with 74 informal, 4 semiformal, and 0 formal modeling approaches being reported.

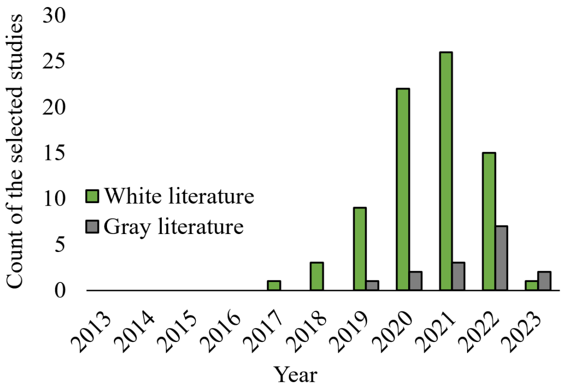

Fig. 1. Distribution by year.

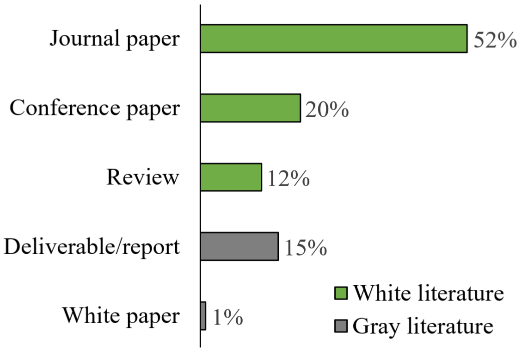

Fig. 2. Distribution by document type.

3. Results and discussion

The main findings of the MLR are summarized and discussed in this section, and the recommendations, based on conclusions drawn from the MLR, are provided. Furthermore, the digital twin definition and the reference architecture are illuminated.

3.1 Summary and discussion of the results

The results of the MLR have clearly demonstrated the growing interest in digital twins across several scientific fields, including civil engineering. Digital twinning, gaining momentum across various domains, is particularly influential in SHM, both in academic research and practical applications. Particularly in recent years, the noticeable increase in selected studies seems to be fueled by digitalization, which has been driving developments in civil infrastructure operation and maintenance by introducing state-of-the-art digital technologies to SHM.

With respect to comparisons between research and practice, the MLR has revealed traits shared by digital twin definitions (case-specifically formulated), such as "digital representation" and "synchronization". Nonetheless, research approaches predominantly focus on digital representation, as opposed to industrial approaches, where emphasis is placed on synchronization, which enhances confidence in the digital twins for practical applications.

As for architectures, most digital twin architectures included in white and gray literature contributions focus on facilitating services, resulting in similar arrangements of layers and internal elements. Notably, none of the digital twin architectures analyzed in the MLR is modeled using formal modeling languages.

The key advantage of digital twinning in SHM lies in its ability to integrate real-time data with models and simulations, to monitor and analyze the performance and safety of civil infrastructure. Digital twins enable more precise condition assessments of structures as compared to traditional approaches, thus increasing maintenance efficiency and extending the life-span of structures. Considering the increasing trends in digitalization, digital twins for SHM are expected to be widespread in the future, thus underlining the importance of a common definition and reference architecture for digital twins in civil engineering, particularly in structural, health monitoring, as recommended in the following subsections.

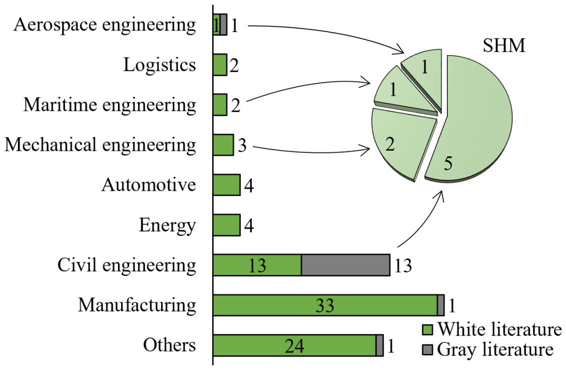

Fig. 3. Digital twin application areas.

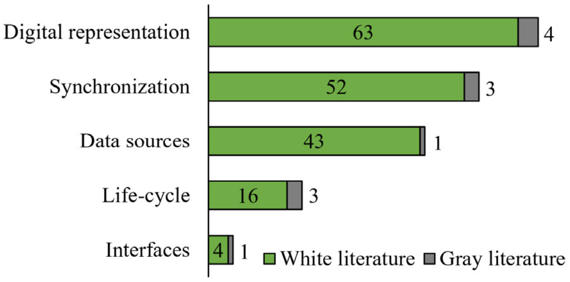

Fig. 4. Characteristics utilized to define digital twins.

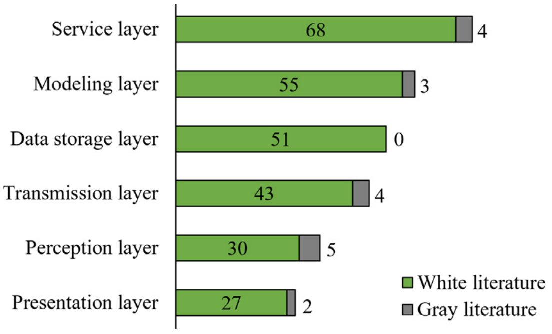

Fig. 6. Layers of digital twin architectures.

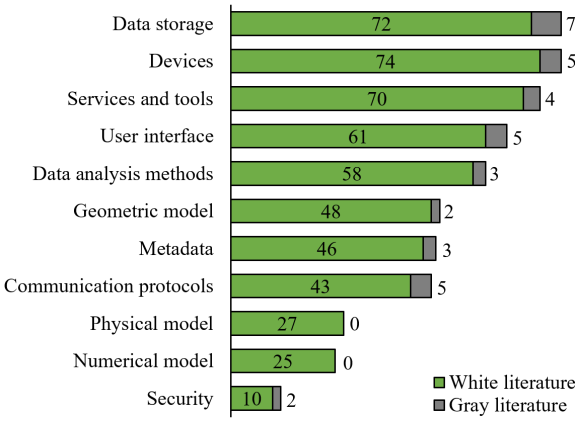

Fig. 7. Digital twin elements.

3.2 Recommendations

Following up on the needs, highlighted by the results of the MLR, a definition for digital twins is recommended, representing a common basis for understanding and analyzing digital twins across several civil engineering applications, such as smart cities, smart buildings, and structural health monitoring. The definition, provided below, is deliberately kept as generic as possible and represents the outcome distilled from the selected studies of the MLR:

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.

Building on this definition, the role of digital twins in SHM becomes particularly significant. In SHM, a digital twin serves as a dynamic, real-time mirror of a physical structure, providing one or more continuously updated models synchronized through sensor data to reflect the current state of the structure. Following the same reasoning as in the definition, the reference architecture, shown in Figure 9, represents the "synthetical" result from analyzing architectures described in the selected studies. The reference architecture is organized into layers, adopting layered, service-oriented, and cloud-oriented design paradigms, i.e. similar functionalities are organized into layers.

Specifically, the reference architecture clearly distinguishes between (i) the hardware ("data acquisition layer") used for procuring the data from the real world, (ii) the elements constituting the digital replica, for example building information models (BIM models) or finite element (FE) models situated on the "platform layer", and (iii) the visualization elements ("presentation layer") that belong to the digital world. Finally, the digital twin architecture provides services that interact with the digital twins by querying, inserting, and processing data though the "transmission layer". For example, in case of digital-twin-based SHM of a bridge, the architecture will involve sensors (data acquisition layer), feeding data into a digital model of the bridge (platform layer) for real-time structural analysis, with results presented via an interactive dashboard (presentation layer) for decision-making. For further details on the architecture, the interested reader is referred to [17].

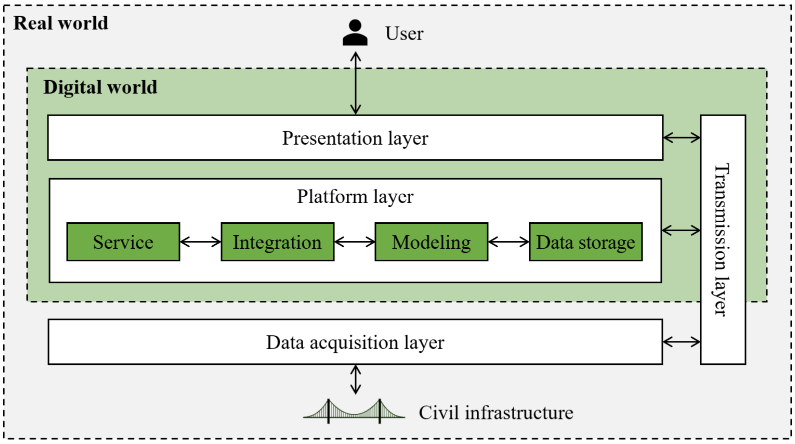

Fig. 9. Digital twin reference architecture.

4. Conclusions and future work

This paper has presented a multivocal literature review of digital twins, architectures, and elements in civil engineering. From about 18,000 studies relevant to digital twins, originally retrieved, 92 studies have been selected as relevant, including 77 white-literature (SLR) studies and 15 gray-literature (GLR) studies. The GLR studies primarily report on research and development projects and industrial applications. The review of the selected studies has provided an overview of the research and practice in digital twinning in civil engineering relevant to SHM. Furthermore, the selected studies have been analyzed in terms of contents related to digital twin architectures and a definition for digital twins, on the basis of a common understanding of the internal elements, has been provided. Last, but not least, a reference architecture that is expected to serve as a blueprint for digital twin implementations in structural health monitoring, has been proposed. In future work, the MLR may be extended to include further approaches, e.g. following the snowballing method, in an attempt to provide a more comprehensive picture of digital twinning in structural health monitoring. Moreover, extending the literature review is expected to address the lack of formal system architectures for digital twins in structural health monitoring, aiming to enhance the reliability and performance of SHM systems.

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