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Digital twin architectures in civil engineering: A systematic literature review

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Abstract: Numerous reviews of digital twins have been reported in recent years. However, the majority of digital twin (DT) reviews within the field of civil engineering primarily examine DT implementations tailored to specific projects or investigate particular application domains in civil engineering. DT architectures, including layers and components, have received minimal consideration until now. This study conducts a systematic literature review (SLR) of digital twins to establish a scientific basis on digital twins in civil engineering, aiming to reach a reference DT architecture that includes layers and components. The SLR is conducted for peer-reviewed, indexed literature of existing DT architectures to propose the reference DT architecture. The reference DT architecture serves as a blueprint for implementing DT applications in civil engineering, providing a common understanding and strengthening the reliability of digital twins in civil engineering.

*Keywords***:** Digital twins, digital twin architecture, digital twin layers, digital twin components, systematic literature review.

1 Introduction

The architecture, engineering, and construction (AEC) industry has recently explored concepts that merge physical and virtual world, to advance information and communication technology throughout the life-cycles of structures [1]. Merging physical and virtual world to understand and predict the behavior of the physical world, known as "digital twins", dates back to the Apollo 11 mission in 1969 [2]. Today, research on digital twins holds significant importance within various engineering fields [3]. Within the civil engineering field, digital twins have been reported in several disciplines, such as transportation [4], structural engineering [5], structural health monitoring [6], and smart cities [7]. Digital twins have also been reported in other fields, such as mechanical engineering [8], maritime engineering [9], and manufacturing [10]. Despite the recent considerable efforts in digital twin (DT) research in engineering, a shared understanding of the architecture of digital twins, remains elusive [11]. Establishing such understanding may serve as a blueprint that enhances communication and improves interoperability in DT applications, strengthening the reliability of digital twins [12].

Recent efforts have explored digital twins in civil engineering, proposing various DT architectures, layers and components. Sharma et al. [13] discuss the conceptualization of digital twins regarding components. The components of digital twins are divided into two categories, (i) elementary components, including physical entities, virtual entities and the connection between the entities, and (ii) imperative components, such as devices, data, artificial intelligence (AI), and security. Furthermore, digital twin architectures that vary depending on the applications have been proposed. Newrzella et al. [14] propose a three-dimensional reference architecture for digital twins considering functionality, dependability, and life-cycle stages and showcase an exemplary case study for the life-cycle of buildings. Alva et al. [7] present a conceptual architecture for developing urban DT applications of buildings, using three layers, a physical layer, a cyber layer, and a cognitive layer. The differences observed in the existing DT architectures, including layers and components, highlight the absence of a generally accepted understanding of DT architectures and the limited focus on assessing the reliability of digital twins.

Therefore, this paper seeks to address the reliability of digital twins in civil engineering by reviewing current research in peer-reviewed, indexed publications to define a reference DT architecture. A systematic literature review is conducted to offer an overview of DT research by analyzing DT architectures, encompassing layers and components. As a result, a reference DT architecture is proposed to enhance the reliability of digital twins in civil engineering. The remainder of the paper is structured as follows. First, the review methodology and research questions are outlined. Second, the results and findings, addressing the research questions, are presented, followed by a discussion and recommendations. Finally, the paper concludes by summarizing the findings and discussing potential future research directions.

2 Review methodology and research questions

To provide a common understanding of digital twins, a systematic literature review (SLR), i.e. a structured approach of gathering, analyzing and summarizing existing research in peer-reviewed, indexed publications, of the layers and components of digital twins is performed in this section. Architectures of digital twins reported in literature are gathered to define a reference DT architecture that serves as a blueprint for applications related to civil engineering. The SLR is conducted following the methodology shown in Fig. 1. The methodology includes three phases, planning, execution and reporting, that are illuminated in the following paragraphs.

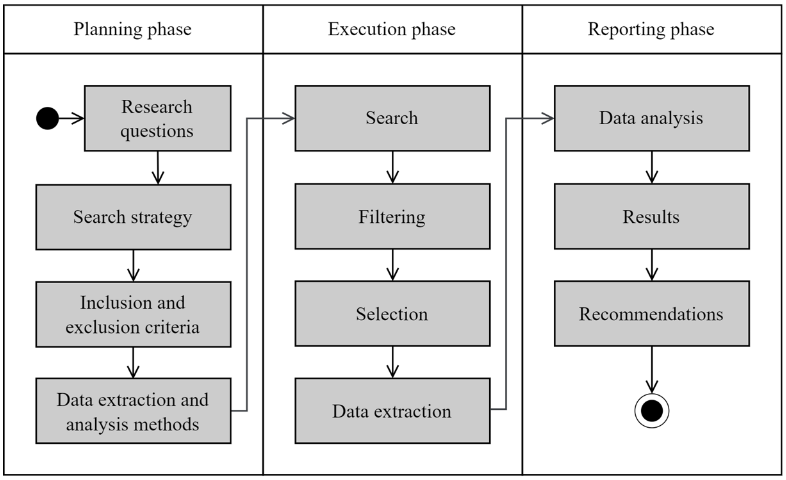

Figure 1: Overview of the SLR methodology

Planning phase: The planning phase comprises four steps, with the first step involving the formulation of the research questions to define the objectives. Two research questions are defined:

- Research questtion 1: What are the current trends of digital twins in civil engineering?
- Research question 2: What layers and components regarding DT architectures are reported?

In the second step, the search strategy is defined for selecting information sources and defining search strings. The search strategy covers indexed publications on digital twins across a wide spectrum of engineering disciplines spanning from 2013 to 2023. To retrieve indexed literature, the Scopus database is used with search strings that start broadly with "digital twin", narrowing down to the specific topics, such as "architecture" and "feature", finally limiting to specialized terms, such as "IoT" or "Industry 4.0".

In the third step, inclusion and exclusion criteria are defined (along with quality assessment criteria) to filter and select primary studies. Five inclusion criteria and two exclusion criteria, are defined. The inclusion criteria cover (i) meeting the search terms, (ii) being published in English language, (iii) being published in indexed conference proceedings or in journal papers, (iv) being related to the engineering, computer science or mathematics fields, and (v) contributes to answering any of the research questions. The exclusion criteria comprise (i) the unattainability of the full paper and (ii) the unavailability of the system architecture of the DT mentioned in the paper.

The last step of the planning phase is defining methods for data extraction and analysis. A data sheet is developed, specifying data to be extracted from the primary studies, including title, year, discipline, application, DT layers, and DT components.

Execution phase: The execution phase is conducted by implementing the methods and criteria defined in the planning phase. The four steps included in the execution phase are (i) search for studies based on the research questions, (ii) filtering according to inclusion and exclusion criteria, (ii) selection of primary studies based on the quality assessment criteria, and (iv) data extraction from the primary studies. Consequently, out of initially 12,941 studies found in the original search, 758 studies are retrieved, filtered to 120 studies with the most citations, from which 43 primary studies are selected and used to extract data and fill the data sheet.

Reporting phase: The reporting phase, where data is analyzed to achieve the objectives, encompasses three steps, (i) analyzing the data, (ii) reporting the results, and (iii) providing recommendations related to the research questions. The reporting phase is presented in the following section.

3 Results and discussion

This section presents the outcomes of the reporting phase in a form that answers the research questions defined in the planning phase. Specifically, the data is analyzed to achieve the objectives, and the results and recommendations related to the research questions are stated.

3.1 Current trends of digital twins in civil engineering (research question 1)

Current trends in the application of digital twins in civil engineering have been reported in research focusing on the life-cycle stages of construction projects [15] and on build environments [16]. From the 43 primary studies selected, 9 studies are classified in the field of civil engineering. The digital twins presented in the studies are developed for specific civil engineering applications, most of which related to smart buildings (33 %), smart cities (22 %), and facility management (22 %). Furthermore, the following trends are identified.

- The studies mostly focus on modeling approaches to generate virtual representations (virtual part) of physical assets and build environments (physical part), keeping up with new technologies. The virtual representations include geometry models describing geometric characteristics, physical models describing physical parameters, numerical models describing data and physical relations, as well as semantic data.
- Digital twins in civil engineering applications present capabilities that achieve target services. For example, capabilities related to modeling, data management and integration, intelligence, and user interactions are needed for engineering services, such as monitoring, simulation, prediction, automatic control, and decision making.
- Digital twins are more frequently deployed in operation and management applications, in particular for managing resources in build environments, for real-time monitoring, and for data analysis (e.g., damage detection and performance evaluation). However, the civil engineering applications deploying digital twins are moving towards smart construction and smart urban environments.

3.2 Layers and components regarding DT architectures (research question 2)

In regards to the DT architectures, it is observed that synergies among engineering fields aid in identifying layers and components. Therefore, DT architectures are analyzed from the 43 primary studies, regardless of the engineering field classification, according to structures of DT architectures.

Analyzing structures of DT architectures involves investigating the layers and components of system architectures for digital twins. Although different names have been assigned to layers with similar functionalities, all system architectures reported in the selected studies are similar and mainly defined in four main layers, (i) a presentation layer hosting user and application interfaces (44 %), (ii) a platform layer comprising sublayers for services, virtual models and data storage (100 %), (iii) a transmission layer for data transfers between layers (58 %), and (vi) a data acquisition layer comprising data sources (65 %). For example, Josifovska et al. [17] have presented a DT architecture comprised by platforms for physical entities, virtual entities, data management and services, which maybe be mapped as follows. The physical entity platform is aligned with the data acquisition layer, the data management platform and the virtual entity platform are aligned with the platform layer, and the service layer is aligned with the both the platform and the presentation layers. The communication between the platforms are described as send-request interactions, which are aligned with the transmission layer. Similar mappings are valid for the other studies.

Components in DT architectures are specific to the individual engineering application and may be allocated in different layers or sublayers depending on how the DT architectures are deployed. For example, data schemas abstracting semantic data in the platform layer may be placed either in the sublayer for data storage as a share knowledge tank [18], in the sublayer for models as a conceptual model [19], or in the sublayer for services to facilitate smart services [20]. Fig. 2 presents an overview of DT components identified in the primary studies. As shown in Fig. 2, the most reported components include services and tools (95 %), data storage (100 %), and sensors, actuators and devices (100 %). Virtual models have been discretized into geometry models (70 %), physical models (26 %), numerical models (44 %), and semantic data (70 %).

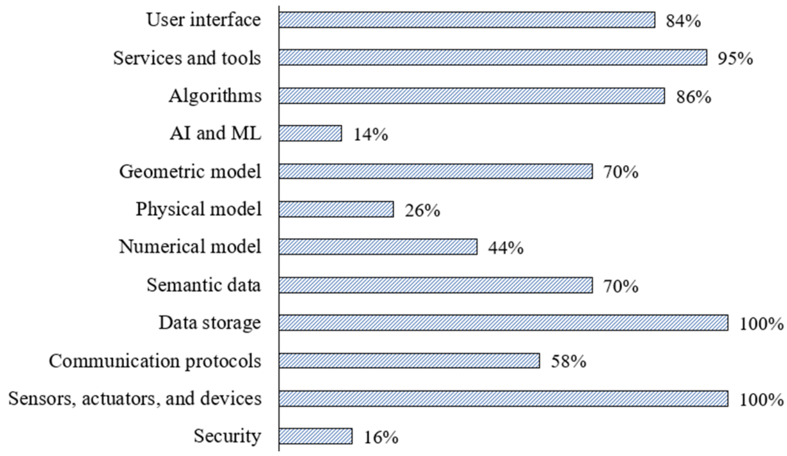

Figure 2: Components in digital twin architectures identified in the primary studies

3.3 Discussion and recommendations

As a result of the SLR, a reference DT architecture is recommended, illustrated in Fig. 3. The reference DT architecture follows a layered architecture, comprising four layers linking the real and the digital world, (i) a data acquisition layer, (ii) a transmission layer, (iii) a platform layer, and (iv) a presentation layer. The data acquisition layer, in the real world, consists of sensors, actuators, and devices operating on real-world structures that provide sensing and actuating capabilities. The transmission layer transfers data and information between the layers, using communication protocols and networks. The platform layer comprises a set of sublayers, including (a) a service layer, (b) an integration layer, (c) a modeling layer, and (d) a data storage layer. The service layer provides services that interact with the digital twins by querying, inserting, and processing data. The integration layer connects the services with the digital twins hosted in the modeling layer, ensuring a consistent update and aggregation of heterogenous data deploy in the digital twins. The digital twins encompass the virtual representations (i.e., virtual models), including building information (BIM) models, finite element (FE) models, senor models, and performance models. The data storage layer manages bidirectional data transfer between digital twins and the data repositories. Finally, the presentation layer, located in the real world, supports user and application interfaces for management and visualization.

The outcome of the SLR addresses the current trends of digital twins in civil engineering by proposing the reference DT architecture. The reference DT architecture serves as a blueprint for implementing DT applications in civil engineering, facilitating a common understanding and strengthening the reliability of digital twins in civil engineering.

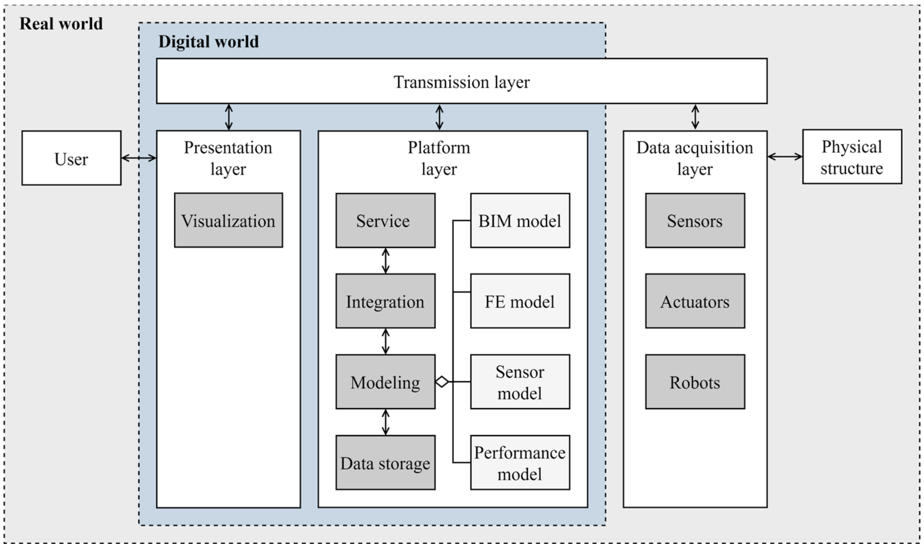

Figure 3: Reference DT architecture in civil engineering

4 Summary and conclusions

Reviews of digital twins are gaining increasing significance in recent years. Nevertheless, most of the digital twin reviews within the field of civil engineering examine DT implementations in specific projects or investigate certain application domains in civil engineering. So far, DT architectures, comprising layers and components, have received minimal consideration. A unified understanding of DT architectures would strengthen the reliability of digital twins in civil engineering. Thus, this study has conducted an SLR of digital twins, to establish a common understanding of digital twins in civil engineering, aiming to reach a reference DT architecture that includes layers and components. The SLR has been conducted for peer-reviewed, indexed publications of existing DT architectures. The SLR methodology involves a planning phase, an execution phase, and a reporting phase, resulting in 43 primary studies analyzed to evaluate layers and components of digital twins, as well as existing DT architectures. The SLR data analysis and results have led to recommendations for a reference DT architecture, facilitating a common understanding of layers and components, to serve as a blueprint for implementing DT applications in civil engineering. Future research may focus on analyzing the degree of formality in existing DT architectures and emphasizing the importance of formal DT architectures, to further improve the reliability of digital twins in civil engineering.

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