Review of digital twins in industry and civil engineering

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Abstract. Digital twins are virtual counterparts of real objects in their whole lifecycle. This concept has gained increasing popularity, also in civil engineering. Civil engineering digital twins comprise several modern techniques, e.g., Building Information Modeling (BIM), Artificial Intelligence, and Structural health monitoring (SHM). Digital twinning, however, is not only the isolated use of these methods but their integration following the idea of comprehensive semantic data-rich models. Digital twinning activities comprise both research and industrial works. This article reviews the current attempts to provide the theoretical backgrounds and propose practical use cases.

Keywords: Digital Twin, Civil Engineering, Building Information Modeling, Artificial Intelligence, Structural Health Monitoring.

1 Introduction

1.1 Current activities on digital twins

Digital twins are virtual counterparts of real objects in their whole lifecycle. This idea of semantic data-rich models is being perceived as crucial for the ongoing digitization following the principles of Industry 4.0. The concept of digital twins is still being formed, so the research is dualistic: both theoretical frameworks and definitions are being established, and practical use cases are being explored. Civil engineering digital twins comprise several modern techniques, e.g., Building Information Modeling (BIM), Artificial Intelligence, and Structural health monitoring (SHM). Digital twinning, however, is not only the isolated use of these methods but their integration following the idea of comprehensive semantic data-rich models. Digital twinning activities comprise both research and industrial works.

1.2 Scope of the article

This article describes activities regarding digital twinning in the industry and civil engineering; both attempts to provide theoretical frameworks and propose practical use cases. Since digital twinning comprises many technologies, not only research referring explicitly to “digital twins” is indeed digital twinning research; many publications about simulations, modeling, IoT devices, sensors, or intelligent algorithms can undoubtedly be classified in the digital twinning category. The categorization is even more complicated with mature BIM applications that share a plethora of features with digital twins –some articles about BIM are actually about digital twins [1], even though they do not refer to it. Nonetheless, the articles referenced in the upcoming subsections refer explicitly to “digital twins”. This approach enables disclosure of how implementors perceive digital twins.

2 Digital twins in the industry

Tao et al. [2] divide digital twinning development into three stages: formation, incubation, and growth. The *development magnitude* of the phases is well reflected in the research interest. Fig. 1 presents the scientific journals’ articles and conferences’ papers with the term “digital twin” (or “digital twins” or “digital twinning”) in the title in the Scopus database. The stages of formation and incubation (until 2015) are represented by the relatively low number of publications compared to the later growth stage of dynamic interest increase.

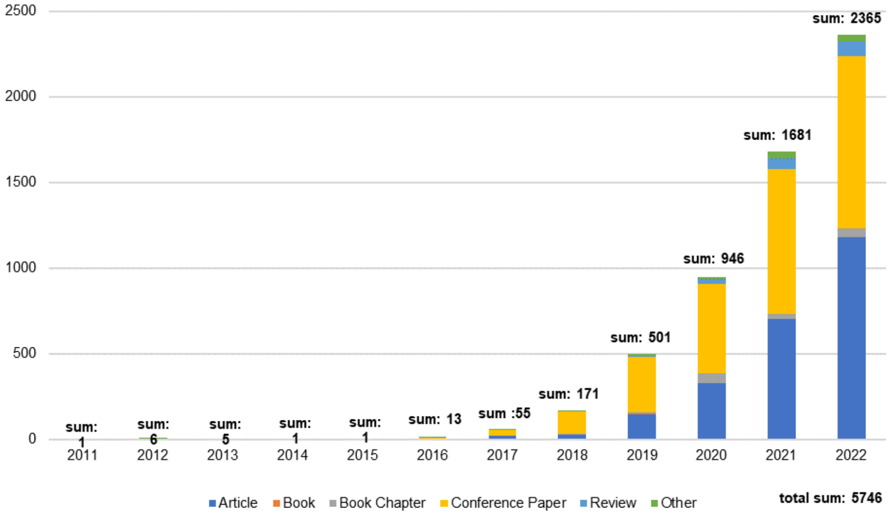


Fig. 1. Digital twinning research interest (Scopus database; access: 15.01.2023)

The growth stage brought not only research interest but also its diversification. Fig. 2 shows the areas of digital twinning research. Engineering and computer science – the origin domains – dominate, but digital twins are applied in a variety of sectors. Applications in the business and decision sciences, as well as economics, show the digital twinning business potential. Applications in social sciences, biochemistry, medicine, pharmacology, or neuroscience show that digital twinning regard not only technical objects but even humans. Niche attempts in psychology, dentistry, or veterinary show the widening of digital twinning usage.

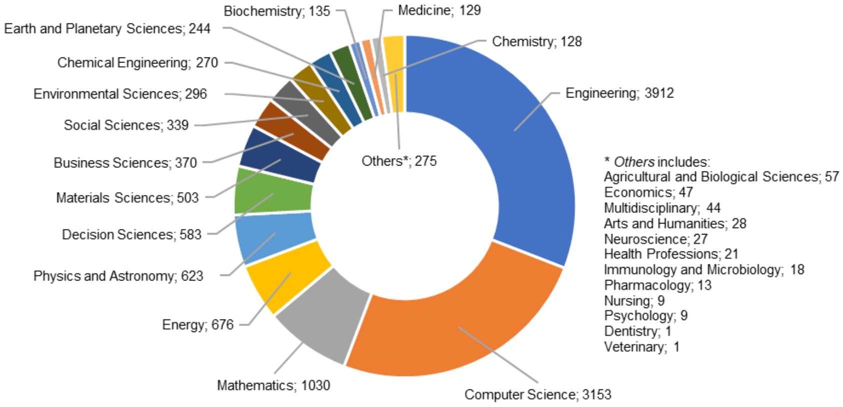
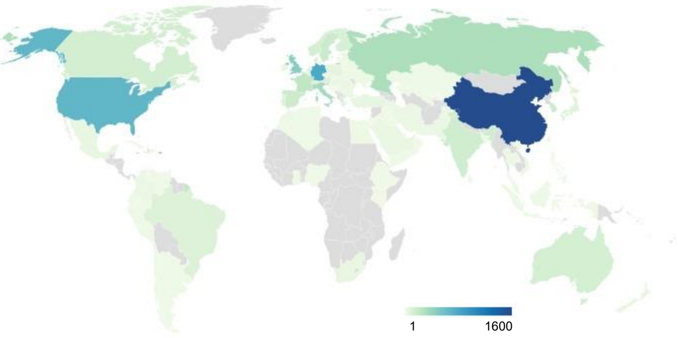


Fig. 2. Digital twinning publications areas (Scopus database; access: 15.01.2023)

Fig. 3 shows a map of publications. China is leading in publication count (which is a general trend, not specific to digital twinning). Germany, a country linked with the Industry 4.0 idea, is second, and the United States is third. Subsequent places are split between countries of various continents. Overall, digital twinning can be perceived as a global concept.

Country	*Publications*
China	1594
Germany	786
United States	671
United Kingdom	463
Italy	342
Russian Federation	303
France	216
Sweden	166
Spain	163
South Korea	158
India	147
Canada	136
Australia	127
Norway	122
Finland	111
Netherlands	104
Denmark	102
Singapore	102



** countries with more than 100 publications included*

Fig. 3. Digital twinning publications map (Scopus database; access: 15.01.2023)

Digital twinning research is also diversified in its nature. Dedicated frameworks and use cases are one of the areas. Digital twins have been applied in various engineering domains, e.g., cyber-physical systems [21,32], smart manufacturing [3–5], and product design [6], as well as for various subjects, e.g., hollow glass production line [7], space satellites [8], wind turbines [9], and printing machines [10]. The Experimentable Digital Twins [11] are an example of an inheriting concept. Extensive research is also held into orchestrating digital twinning operations, e.g., scaling digital twinning systems [12], developing them in clouds [13], and ensuring their cybersecurity [14].

Digital twins are perceived as key components of global industrial strategies like Industry 4.0 [15–17] or Made in China 2025 [5]. This is enabled by the linkage of digital twins with technological techniques: big data [16], Internet of Things [13] and Internet of Services [18] (and envisioned Internet of Everything [16]), and blockchain [19, 20]. Digital twins emerge from and are interconnected with model-based concepts like intelligent products [21], smart products [22], product avatars [23, 24], virtual factories [25, 26], and cyber twins [6]. The capabilities of digital twins make them a proper base for introducing engineering methodologies: data-driven design [16], event-driven engineering [27], simulation-based engineering [28], personalized medicine [29, 30], communication by simulation [31], and Software as a Service (SaaS; with its dedicated Digital twin as a Service [32] approach).

Digital twinning is not restricted to engineering. Human-related digital twins are an emerging research area. Digital twins are applied in medicine for, e.g., drug discovery (the Virtual Liver concept [33]), precision nutrition [30], dentistry [34], and psychology [35]. Clothes design [36] is another human-related digital twins application. Digital twinning is also utilized for animals [37]. The premise of digital twinning capabilities triggers futuristic visions: [38] envisions a human digital twin as a technological approach to immortality (in a Steven Spielberg's Avatar fashion); [39] envisions a digital twin of Earth.

The digital twinning capabilities and its current and potential use cases place digital twinning as a sociological phenomenon. It is reflected in research on digital twinning impact [40] and its ethical implications [29]. Maturing of digital twinning research is reflected in the multitude of review articles [2, 41–47] describing definitions, frameworks, use cases, technologies, challenges, and business perspectives. Digital twinning is also announced in *apostolic* articles, like "Make more digital twins" in Nature [48].

The digital twinning research brought many concepts and general principles. [49] described three parts of the digital twinning system: physical product, virtual product, and connected data linking the physical and virtual products. The parts are linked by interactions: physical-physical, virtual-virtual, and virtual-physical [2]. [9] introduced five-dimensional architecture consisting of a physical entity, virtual model, physical-virtual connection, data, and services [9]. [50] divided digital twin types into digital twin prototypes (the prototypical framework) and digital twin instances (the virtual model describing the physical counterpart) existing in the digital twin environment. [51] introduced digital thread, the aggregation of processes leading to creating and utilizing digital twins. [41] defined digital twinning levels of integration regarding manual and automatic data flow between the physical and virtual counterparts: digital model (manual data flow), digital shadow (automated data flow from physical to virtual and manual from virtual to physical), and digital twin (bi-directional automated data flow). The capabilities of these concepts resulted in the conclusion that digital twins are the next wave in simulations [31].

3 Digital twins in civil engineering

Digital twinning, as a global concept, also reached civil engineering resulting in both scientific and industrial interest. Similar to the general trend, civil engineering digital twinning research is divided into applications and establishing principles. The research often sources from current AEC techniques, like Building Information Modeling (BIM) or structural health monitoring (SHM), enhancing it with, e.g., artificial intelligence. Especially the view on BIM is controversial – as a methodology based, in practice, on data-rich models, BIM is sometimes perceived as digital twinning. More thorough analyses, however, highlight their differences.

3.1 Frameworks and theoretical principles

Civil engineering digital twinning principles are already being structured into initial frameworks. The frameworks – though not unified in all concepts – form a great foundation for civil engineering digital twinning.

[55] introduces the Construction Digital Twin (CDT). The framework attempts to address the limitations of BIM (incompatibility with IoT and dynamic data; lacks in automation and interoperability) with the addition of semantic web-linked data, big data, artificial intelligence, and services. Construction Digital Twin is based on the physical part (sense, monitor, actuate), the data (BIM, IoT, data linking, knowledge storing), and the virtual part (simulate, predict, optimize, agency). Construction Digital Twin framework also suggests the evolutionary approach of three generations: 1) monitoring platforms (as-built BIM; features: sensing, analyzing, monitoring), 2) intelligent semantic platforms (web-based platform with limited intelligence linking digital twin with IoT devices; features: sensing, analyzing, monitoring, AI), and 3) agent-driven socio-technical platforms (fully autonomous systems; features: sensing, simulating, AI, optimizing, learning, end-user engagement).

[56] introduces the Digital twin construction (DTC). The framework is based on BIM, lean construction, automated data acquisition, and artificial intelligence. Although BIM plays a role in the framework, the article highlights the naivety of the synonymization of BIM models and digital twins: digital twins for construction are connected to physical counterparts, not only replicate them; they also operate in a network with other digital twins. The framework highlights the importance of modeling both product characteristics and processes. It also envisions the lifecycle of digital building twins and their physical counterparts, differentiating Foetal Digital Twin, Child Digital Twin, Adult Digital Twin, as well as Child Physical Twin and Adult Physical Twin.

Civil engineering digital twinning concepts are a domain of not only academics. National Digital Twin (NDT) is a Centre for Digital Built Britain framework [57] envisioned as an ecosystem of digital twins collaborating in data exchange. The National Digital Twin is a next-step framework focused not on creating singular digital twin instances but rather on their linkage. The UK government expects the National Digital Twin to contribute to the national economy, public good, and environment.

3.2 Use cases

Civil engineering digital twinning research provides also use cases. It is important to notice, however, that in the current stage of digital twinning maturity, the applications are not complete digital twins but rather focus on particular components: BIM, SHM, AI, point clouds, virtual, augmented, and mixed reality, automation, optimization, automated modeling, etc., sometimes mixing the components. Although partial, these applications are pushing the idea of civil engineering digital twinning. [58] describes a limited (as claimed by authors) digital twin of a building façade with sensor networks enabling an analysis of the actual light, temperature, and humidity conditions. [59] introduces an IFC-based digital twin for detecting anomalies in HVAC systems. [20] is an attempt to accountable information sharing with digital twins and blockchain, tested on prefabricated brick positioning. [60] presents a semi-automatic approach (referred to as geometric digital twinning) to generate IFC models from images and CAD drawings. [61] describes digital twins for bulk silos to manage materials' supply chains. [62] uses digital twinning for replicating hospitals (HospiT'Win framework) to monitor, analyze, and predict patients' pathways. The exemplar use cases show the variety of facility types (or their parts) and objectives on different lifecycle stages. Increasing research resulted in reviews. [63] reviews 22 publications and depicts six main research areas: BIM, structural system integrity, facilities management, monitoring, logistics processes, and energy simulation. [64] reviews 100 publications focusing on BIM features facilitating the evolution into digital twins; the study diversified research into the construction process, building energy performance, and indoor environment monitoring. [1] reviews 134 publications (diversified into the design, construction, and maintenance stages applications) and highlights differences between digital twins, BIM models, and cyber-physical systems. [65] is a review focused on digital twinning for construction workforce safety (e.g., workforce behavior monitoring, identification of risks, safety planning, and training).

The concept of smart cities is another prominent research area regarding both methodologies and specific use cases. [66] uses BIM for visualizing, estimating, and finally promoting the Net Zero Energy Buildings concept for existing facilities. [67] focuses on smart cities' disaster management. [68] processed LiDAR point clouds (with points' clustering and object recognition) for creating Digital Twin Cities. [69] describes the Digital Twin City of Atalanta, a virtual reality platform with a 3D model. [70] developed a digital twin of the West Cambridge site of the University of Cambridge as a unified data source for effective management on the city level. [71] describes the digital twin of Zurich to address the pressing requirements of the growing city. [72] introduced a digital twin of the Docklands area in Dublin, freely accessible to citizens to acquire feedback on planned changes or existing problems. [73] describes the Helsinki 3D city model for energy-related data acquisition and analysis; the study highlights the importance of the CityGML data model for the smart cities concept. [74] conceptualized a smart city architecture with machine learning and semantic modeling and tested it for Chicago buildings.

4 Conclusions: digital twins' potential exceeds academia

This article reviewed activities on digital twins in the industry and civil engineering. The research comprises both crafting theoretical backgrounds (e.g., frameworks) and proposing practical use cases. Current activities, however, are not limited only to academia. The business potential of digital twins resulted in the interest of industrial environments.

Deloitte [17], Siemens [52, 53], and Gartner [54] published their reports on digital twinning. Also, many industrial tycoons declare their implementations. Tesla, with its autonomous cars, is a prominent representative. Besides cars, Tesla uses digital twinning for smaller-scale devices, like batteries, and whole production lines to identify bottlenecks and optimize the flow of parts. Mercedes (Daimler) is another automotive industry representative. Boening, Airbus, and Rolls-Royce use digital twinning in aerospace engineering to design aircraft and optimize engines. GE Digital (General Electric subsidiary) developed the "Aviation Digital Twin". Siemens creates digital twins of power plants, wind farms, and buildings; Shell – of offshore platforms and refineries. Microsoft developed the "Azure Digital Twins" platform, intended to be a multi-industrial simulation environment. These examples show that digital twins have already transformed from scientific vision into industrial practice.

As for outside-academia civil engineering activities, the government of the United Kingdom founded the Centre for Digital Built Britain and initiated the Industrial Strategy Transforming Construction Programme with the National Digital Twin as its component [57]. The United Kingdom perceives digital twins as beneficial for the internal economy and export business, opening new markets and business models. Digital twinning in infrastructure is a subject of white papers of industrial organizations (e.g., Digital Twin Consortium [75]) and business companies. Deloitte published "New Technologies Case Study: Data Sharing in Infrastructure" [76], stating predictions and business opportunities. Siemens published "Digital twin – Driving business value throughout the building life cycle" [52]. This dedicated interest of technological, non-civil engineering companies reveals a new potential trend in the construction industry – an industry of enormous economic and social impact, which still has a vast margin of increasing its efficiency (resulting in accountable benefits for the optimizers).

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