Digital twins of bridges: notions towards a practical digital twinning framework

Kamil Korus[1], Marek Salamak[1] and Jan Winkler[2]

[1]Department of Mechanics and Bridges, Silesian University of Technology, Poland
[2]Digital Engineering Solutions, Poland
kamil.korus@polsl.pl, marek.salamak@polsl.pl, j.winkler@de-solutions.info

Abstract

Digital twins, the virtual counterparts of objects throughout their life cycle, are a crucial component of ongoing digitization. While the civil engineering community has already recognized the advantages of utilizing digital twinning, there is still a lack of comprehensive research in the field, resulting in uncertainties. This article proposes a set of notions regarding digital twins of bridges – structures of logistic and strategic importance and high demands of resilience. By stating the principles for comprehensive digital twinning, the notions can guide practical applications of digital twins of bridges and other civil engineering facilities.

Keywords –

Digital twins, Digitization, Bridges, Building Information Modeling

1 Introduction

Digital twins are virtual counterparts of objects throughout their life cycle. First implemented by NASA, today are contributing to multi-industrial digitization, reported as a crucial component of Industry 4.0. The benefits of digital twinning have been spotted by many industries, including civil engineering. It resulted in increasing research interest and work by practitioners [1]. Although ongoing works are promising, the digital twinning concept is still nascent in civil engineering practice. Both theoretical principles and practical use cases are required to push the concept of civil engineering digital twins.

1.1 Digital twins in civil engineering

At the current stage of digital twinning development, the research is double-track, also in civil engineering. Some activities focus on theoretical frameworks and principles for applying digital twins ([2], [3]); others on practical use cases.

The first civil engineering applications of digital twins utilize modern techniques like BIM (Building Information Modeling), SHM (Structural Health Monitoring), 3D reconstruction, and AI (Artificial Intelligence). The techniques are often integrated to provide additional benefits. BIM models can be used to visualize SHM sensor data [4]. FEM models can be synthesized with monitoring data to reconstruct unmonitored structure responses [5]. Artificial intelligence helps in managing the fatigue of steel bridges [6]. Point clouds can be a source for the automated generation of semantic models [7].

The use of these techniques is a positive trend. Due to the fast development (in the field of, e.g., computer vision and data acquisition equipment [8], automated model generation [9], and machine learning [10]), the techniques are increasingly popular and useful. The current applications make a foundation for complex digital twinning. Nonetheless, still more activities are required for applying complete digital twins in the form of intelligent management systems coexisting with real facilities through their entire life cycle and cooperating with other instances in the digital space.

1.2 Research motivation: the need for digital twins of bridges

Activities on digital twins of bridges are motivated by both requirements and opportunities of the nowadays world and challenges in bridge engineering. The following sections discuss why this area should be a subject of thorough research.

1.2.1 Digital twins as the enabler of effective functioning

Industries must adapt to the requirements and demands of the nowadays world to function effectively both in the business and technological sense. The process of adaptation forces applying new techniques to benefit from technical innovations. Adopting digital twinning is challenging. However, as a worldwide trend, it connects its adopters to multi-industrial cooperation, giving instant and long-term profits.

The digital era facilitates collaboration. Industries have become more interdisciplinary, adapting foreign practices and tools. The trend also leads to multi-industrial standardization. Cross-sectoral written standards and versatile data exchange formats (e.g., JSON, XML) are already used. As industries become more interdisciplinary, models of different assets will collaborate more, similar to their physical counterparts. Cooperation between digital twins will be based on standardized data exchange interfaces. The collaboration will open opportunities for the adapted – and exclude technical laggards.

Modern techniques increase the effectiveness of whole industries but are also beneficial on a smaller scale. BIM is already proven to provide commercial advantages for contractors. BIM is expected to provide "new markets, new services, new business models, new entrants. [11]" BIM, a technical innovation, is seen as an export product, increasing the competitiveness of the national market. The same reasoning, on the interdisciplinary scale, applies to digital twinning.

1.2.2 The impact and challenges of bridge engineering

Bridges, similar to other objects, have specific factors, characteristics, requirements, and context of operation. These should be regarded in conceptualizing specified frameworks, including the digital twinning framework. This section analyzes the features of bridges and the challenges of bridge engineering.

The first factor is the strategic role of bridges. Infrastructure systems provide essential services for the proper functioning of societies [12]. As links between the infrastructure, bridges are indispensable for logistics. Historically, they have also been crucial from a military perspective. Due to these, bridges have always been a strategic component of societies' wealth. This wealth is not easy to assess, but some numbers are helping in the realization of scale. Only in the USA are there 619 thousand bridges [13]. One of them, the San Francisco Oakland Bay Bridge, appears in the Guinness Book as the most expensive bridge. Just the restoration in 2002 is estimated at 6.3 billion USD.

Safety is – or should be – an indispensable characteristic of bridges. Bridges need to be resilient due to their strategic role and the impact of their malfunctions, which can have a direct influence on people's lives and an indirect influence on economies. The infamous catastrophes of Ponte Morandi in Genua in 2018 (with 43 killed), the Mexico City Metro overpass in 2021 (with 26 killed), and the Julto Pul pedestrian bridge in Morbi, India, in 2022 (with 135 killed) convince that bridges' collapses are not just an imaginary black scenario.

A nontrivial part of the civil infrastructure is aging and suffering from alarming deterioration [12]. It also regards bridges. Of the mentioned USA bridges, 224 thousand require major repair work or replacement [13]. Due to the need for safety, bridges must be adequately monitored and maintained. Nonetheless, bridges' condition assessment still relies mostly on periodic human inspections. The aging bridges require holistic management solutions, especially given their assumed lifespan: many bridges are designed for 100 years.

The modern world aims at new goals; one of them is ecology. The construction and operation of buildings were responsible for 36% of global energy demand and 37% of energy-related CO_2 emissions in 2020 [14]. The ecological factors already influence civil engineering – advanced Life Cycle Assessment (LCA) regarding economic, social, and environmental costs are already being required.

Civil engineering makes up around 15% of the world's Gross Domestic Product [15]. Although of high impact, civil engineering is ineffective compared to other sectors: since World War II, productivity in manufacturing, retail, and agriculture has grown by around 1500%, but productivity in civil engineering has nearly not changed [16]. As estimated, civil engineering productivity can be increased by 50-60% [16]. This margin is a business motivation for the implementation of modern solutions.

Bridges are complex and unique. The need for liaison with the environment results in various structural, material, and manufacturing solutions. Even if bridges are of typical structure, their uniqueness comes from the different conditions in which they operate – the same structure influenced by different phenomena throughout its life cycle can have noticeably different characteristics. The uniqueness and complexity of bridges demand thorough monitoring and analysis.

1.3 Scope of the article

Activities on digital twins of bridges must be based on principles regarding the general concepts of digital twins and the specificity of bridges and civil engineering. Therefore, this article proposes a set of notions regarding digital twins of bridges. By stating the principles for comprehensive digital twinning, the notions can guide practical applications for bridges and other civil engineering facilities. The notions have been formulated based on the literature study, as well as the original research and experience of the authors. The studied articles regard general concepts of digital twins and their practical applications in various fields, with a particular focus on civil engineering and bridges. The studied articles also regard accompanying techniques (e.g., computer vision, artificial intelligence, data analysis, Internet of Things). The study also comprised reports of industrial companies and associations.

2 Notions towards digital twinning of bridges

2.1 Digital twins' frameworks should be object-specific

Digital twinning encompasses various industries and types of objects – such different as bridges and livers [17]. Various industries have different requirements and aims; various objects have different characteristics. Digital twins need to be based on general standards to enable cooperation. At the same time, the standards must be flexible enough to enable reflecting the specificity of the twinned object. It resulted in the specified digital twinning frameworks for, e.g., shop floors [18], air force [19], and cities [20].

The frameworks are attempts to adapt digital twinning principles to serve specific objects. The frameworks also discuss the strategy of implementation. The strategy is crucial because digital twins need to be industry applicable to develop as a concept (section 2.10). Therefore, the digital twin frameworks should regard not only the specificity of the object but also its industrial environment – for example, the industry's ability and willingness to implement new techniques. All industries, including civil engineering, must declare dedicated digital twinning frameworks based on general principles but suited to the specificity.

The specificity of frameworks should also be considered on a more granular level. Bridges can be classified regarding many features, e.g., structural solution (e.g., beam, arch, suspension), material (e.g., concrete, steel, timber), and function (e.g., road, rail, pedestrian). These aspects influence the bridge's response to loads, resilience to environmental factors, risks, damages, and maintenance during its life cycle. A bridge's complexity, costs, and logistic importance also influence its management. Therefore, the digital twinning frameworks should be flexible to enable attaching functionalities serving particular needs (e.g., complex numerical analysis for bridges under dynamic loads, extended maintenance planning for bridges of high costs and logistics importance). This is especially important in the initial stage of implementing digital twins when, due to practical obstacles and implementation costs, instances are not fully-functional digital twins but have selected functionalities.

Many current digital twin applications focus on bridges of high complexity (e.g., cable-stayed bridges with a span of 950 m length [21]) or under unusual conditions (e.g., strong earthquakes [22]). This is a positive trend. Nonetheless, also the structures of common types can benefit from digital twinning. Additionally, the idea of smart cities demands the virtualization of most infrastructure. Therefore, creating frameworks for typical structures (like concrete beam and slab bridges (one of the most popular solutions for existing and planned bridges [23]) should be a priority.

2.2 Ultra-high fidelity is not always required

The early digital twins' definitions envisioned "ultra-high fidelity" [24] simulations of the physical counterpart; the physical object was to be reflected starting from the "micro atomic level" [25]. The definitions were established when digital twin was just an idea, unable to be implemented due to technical limitations. More recent definitions are less strict, orienting on practice.

Undoubtedly, micro-atomic fidelity opens new scientific possibilities; e.g., the simulations regarding the micro-atomic structure of a material, instead of its averaged properties, may clarify unexplainable phenomena. But current modeling techniques are not prepared for such fidelity, nor simulation tools to consume such data. BIM methodology describes model accuracy with the Level of Detail or Level of Development (LOD). BIM projects in practice are in LOD 200-350, frequently starting on a lower level to gradually increase during the project. It would be hard – and unproductive – to demand the highest LOD 500 if a lower one enables effective performance.

"A digital twin must represent a physical reality at a level of accuracy suited to its purpose [11]." Ultra-high fidelity is the ultimate aim for the future. However, the approach of gradually increasing the fidelity of digital twins, following the abilities of modeling and simulation tools, is practically beneficial today.

2.3 Data synchronization does not need to be perfect

Similarly to "ultra-high fidelity", the early digital twin visions demanded "real-time synchronization" [26]. Indeed, latency is crucial in some cases, but others may operate properly with a lower synchronization rate. In practice, the synchronization rate should be established regarding how dynamically the decisions based on in-time data must be made.

Consider examples of an autonomous car and a bridge. The car is continually affected by its environment: the temperature affects tire pressure and the windshield misting. The environment also drives the car's operating parameters: the weather and road conditions are factors for setting the driving speed. Most importantly, for the car, dynamic changes in the environment require dynamic decision-making. When a pedestrian unexpectedly enters the road, the one-second latency between registering the event and making a decision can result in a crash. The bridge is also continually affected by its environment. Although the changes are typically not observable with a bare eye, bridges continually respond to the loads from vehicles, wind, or temperature. However, the bridge is not adjusting its parameters to the dynamic events – decisions about bridges are typically not made in an in-time fashion. Thus, synchronization latency can be higher.

A digital twin comprises different sources of data, e.g., SHM sensors and point clouds. These sources of data vary in their acquisition rate. The sensors can collect data almost continually, so the digital twin can be continually updated with its data. On the other hand, acquiring point clouds is a periodical task – given the pace of geometry changes in civil engineering facilities, typically, annual actualization is sufficient. The source and type of data affect the synchronization rate.

Undoubtedly, the lower latency, the better since it gives new opportunities. Considering the future communication between digital twins, an approaching car sends an introductory data package to the bridge; if the car is suspected of causing damage to the structure, the bridge may obstruct the car's passage. In-time decision-making, possible with in-time data, is beneficial for all kinds of objects. But, in some cases, it is not essential. The synchronization rate affects the digital twin's implementation costs. High upfront costs of in-time synchronization may result in neglecting the digital twinning concept. Therefore, starting with lower synchronization is acceptable from a practical perspective.

2.4 Digital twin should not neglect any data freely

After two notions lightening the strict rules ("ultra-high fidelity is not always required" and "data synchronization does not need to be perfect"), this one is to balance into complex implementations.

Data is the raw material of the XXI century [27] and gives advantages to its possessors. Data-driven techniques have vast applications in business and industrial practice. In science, they complement or displace traditional calculating theories. The data-driven algorithms need data to be trained and tuned. But not only the amount and quality of data affect algorithms operation – also the diversity of data features. GPT-3, a natural language processing algorithm, is based on 175 billion input features [28]. Many AI practitioners are even stating that proper data from various sources and of various characteristics are more important for the effectiveness of the AI systems than the algorithms architectures [29] (i.e., a weak algorithm trained on strong data is preferred from a strong algorithm trained on weak data).

Existing calculating theories enable engineering practice, but it is arrogant to think that we already have understood the majority of phenomenons. Perhaps new calculating theories based on data-driven techniques will disclose new, currently omitted patterns. Perhaps the new theories will be based on data that today seem useless.

Digital twinning prepares to solve engineering tasks in the future phases of the object life cycles. Due to stored data and learned patterns, the questions can be of a type that has not been initially thought of [30]. Therefore, data prepares for the expansibility of digital twins' features to match future industrial requirements.

Storing all data is practically not possible, but continually cheaper storage and new filtering algorithms help in extensive data-collecting. In the design of the digital twins' systems, data should not be neglected freely – if it is possible to collect additional data with the designed methods, it should be done.

2.5 Digital twin should provide interfaces to work with the data

The multitude of data is beneficial for data-driven algorithms but can be overwhelming for humans. The famous Buckminster Fuller's knowledge-doubling curve predicted the increasing pace of knowledge production, eventually leading to knowledge doubling every 12 hours [31]. Humans are not adapted to that pace. The "drowning in data" [32] syndrome affects people's effectiveness.

Digital twins are data-rich models. The multitude of data is utilized by the algorithms, but people also should have access to the insights. It should be provided with proper user interfaces.

Interfaces are essential in industrial practice. They are the linkers between users and complicated systems. User interfaces perform various roles: on commercial websites, they attract visitors to convert them into customers; in specialized systems, they provide access to operation details and enable management. In digital twins, the interfaces should present historical, current, and predicted performance in an easily interpretable way. Due to data-processing techniques, the performance can be presented not as raw data but as more consumable information or knowledge. Based on the data, intelligent algorithms may even suggest a decision – this is the ultimate step of automating data interpretation.

Also, data interfaces allow segregating data access. Different users of digital twins are focused on different areas, e.g., not the same data should be provided for designers, construction site workers, managers, or users of bridges. This is important both for security and productivity.

A digital twin is a data-rich system that must provide benefits from data rather than just store it. Therefore, properly designed user interfaces – in various forms –

are essential in digital twinning.

2.6 Digital twin includes processes

Models are typically expected to store data about objects. The data-richness depends on the model type: CAD models store geometric data, while BIM models also include semantics. The semantics enable advanced analysis but are insufficient for a thorough description of a reflected object. For civil engineering facilities, knowledge about the expected response to loads or environmental factors is crucial for management. But just like the behavior of a person cannot be predicted based merely on his/her appearance, the response of an object cannot be predicted based only on semantic data. To utilize its potential, a digital twin must include not only semantics but also processes.

Digital twins include past processes by storing historical performance data. The data is processed by machine learning algorithms to distill patterns. The patterns represent the object's behavior and act as the "process knowledge" – based on that, the algorithms predict future performance.

The historical performance of a bridge is driven not only by explicit parameters (e.g., geometry, materials) but also by elusive factors (e.g., environment) – the one-object-dedicated patterns implicitly comprise also this elusive data. Such a dedicated approach leads to more accurate predictions than those based on generalizations [33]. Eventually, the developing sensing techniques will enable measuring the today-elusive factors and implement them as explicit features of global machine learning algorithms, perhaps displacing the dedicated solutions. However, even then, the dedicated patterns will be beneficial to understand the responses of an object. Processes – both historical performance, represented by data, and future expectations, represented by patterns - are indispensable components of digital twins.

2.7 Digital twin is intelligent, autonomous

Artificial intelligence is becoming a standard automation solution, also in civil engineering [10]. Digital twins are compatible with various machine learning algorithms. As a big data system, the digital twin allows the training of supervised algorithms, the most common type of ML algorithms so far. As a simulation environment, the digital twin also allows the development of unsupervised algorithms, e.g., reinforcement learning types, that are increasingly more popular and powerful.

With intelligent algorithms, the digital twin gains autonomy. Autonomy can be on various levels. The first is giving suggestions. A digital twin can analyze physical counterpart conditions and present improving suggestions, e.g., a bridge digital twin may report a need for additional inspection or maintenance works. On this first level, the suggestions enhance human decision-making. On the next autonomy level, the suggestions are transformed into executable decisions. A digital twin of an autonomous car interprets data from its physical counterpart's sensors. The decisions resulting from actual conditions must be executed instantly and autonomously, with no human operator confirmation.

The digital twinning concept reveals an additional level of autonomy. A digital twin cooperates with other digital twins (Social Internet of Things [34], Web-of-things [35], or Social Internet of Vehicles [36] attempt to establish rules for this cooperation). With such partnership abilities, intelligent algorithms may consider the actual conditions of the collective, not only a single instance. This is beneficial for the whole group – if two cars spot a danger, but both choose the same escape path, the crash is inevitable. Therefore, digital twins communicate to make shared decisions. This is another level of autonomy when a digital twin, besides managing itself, influences others.

2.8 Digital twin is a system

A digital twin is often perceived as a single model. In civil engineering, this perception may emerge from BIM. BIM shares many features with digital twinning, so the digital twin is sometimes incorrectly perceived as a more advanced version of the BIM model. But although the model is the center of the digital twinning concept, a digital twin is more than a model – it is a system. This statement is validated on various levels.

Modularity is one of the digital twins' characteristics. The digital twin's modules are chosen regarding the specificity of the object and technical maturity. The modules may require specific submodels to perform analyses (e.g., a bridge structural response module may need a FEM model). The submodels derive from the central model and data storage, so they are based on concise, actual data. The submodels are used for specific tasks (e.g., structural analysis, scheduling, cost estimations, visualization) and, therefore, expand the abilities of the whole digital twin. The digital twin is a system of modules, while the central model and its derivates form a complementary system of models.

Digital twins operate on data beyond the typical model-stored type (e.g., big data from SHM sensors is likely to be stored in dedicated databases). Digital twins also include interfaces (section 2.5). Digital twins' submodels cooperate with themselves and the central model. All of these factors lead to extensive infrastructure orchestrating digital twins functioning. The infrastructure links the digital twining components and establishes the digital twin system.

Digital twins, with their interoperable abilities, establish systems with other digital twins. The cooperation can be at parallel or subordinate levels. A digital twin can represent an object big as a planet [37] or small as a microchip. The complex digital twins comprise subordinate digital twins: a digital twin of a smart city may contain a bridge digital twin, which may contain digital twins of its sensors. The complexity of these connections transforms a digital twin into a system of systems.

2.9 Digital twins enable dedicated approaches

Currently, data about bridges' behavior (e.g., load responses) is rarely collected in their normal state; monitoring is usually applied when a structure already shows signs of malfunctioning. Having insufficient data about the particular object, we cannot establish dedicated patterns – the object's state is assessed based on a generalization determined by other objects' data. But the normality of one object does not necessarily match the normality of the other. This statement is a basis for the digital twinning approach of personalized medicine: discovering individual patterns, varying with biophysical and lifestyle factors, allows determining optimal ranges of health indicators (e.g., blood pressure), which may differ from standard population-based values [38]. Bridges, even of similar parameters (geometry, materials), are affected by different conditions (environment, climate, soil, loads). Relying on generalizations may lead to omitting factors and dependencies affecting the particular object.

Digital twinning establishes unique big-data systems for every object. It enables a dual approach. Individualized intelligent algorithms, looking for dependencies and patterns of the particular object, enable analyzing and forecasting. Global algorithms, operating on multiple objects' data, are an additional layer of security. If the normality of one object strongly differs from the global pattern, it will be detected; it can be an indicator of the initial malfunction. Digital twinning enables learning objects empirically – observing how inputs affect outputs and understanding better the processes.

2.10 Digital twins must provide practical benefits

Siemens's report on digital twins in buildings' life cycle states: "a pressing concern for possibly any company that starts on the journey to digitization could be the clear ability to show benefits and realize value from its investment in creating a digital twin [1]." The report focuses on the importance of the transparent benefits resulting from the implementation of digital twins. The ways to provide benefits must be addressed in establishing digital twinning frameworks.

Digital twins have been born and raised in the scientific environment [25], but only wide industrial applications can reveal their full potential. Digital twinning frameworks should address scientific requirements (e.g., proper fidelity and synchronization rate) while also balance them with implementation costs. Indeed, there is no point in demanding ultra-high detailing if it will lead to only scientific applications and neglecting the digital twinning concept in industrial practice.

Digital twinning frameworks must show clear premises of returns on implementation investment. The returns can be in various forms: limiting economic and social costs in the life cycle; automating design, manufacturing, and maintenance; increasing the effectiveness of management. Also, the human factor should be considered: digital twinning will be demanded if it will enhance the day-to-day tasks of designers, construction site workers and engineers, and managers. Therefore, besides theories and standards, digital twinning research – both scientific and industrial – must provide practical use cases, e.g., advanced simulation and modeling, automation of manufacturing, and effective management decision-making. This bottom-up approach fuels the practical development of the digital twinning concept.

3 Conclusions

Technical advances come from demand and opportunities. Digital twins originated as a concept for handling the pressing requirements of digitization, but initially, due to technological limitations, the concept was impossible to implement. Today, however, technical advances open gates for digital twinning practice. It requires thorough digital twinning research. This article states notions towards digital twinning focusing on bridges, applicable also to other civil engineering facilities. The notions form foundations for establishing frameworks for civil engineering digital twins.

Civil engineering is still in the early stages of digital transformation. Nonetheless, BIM, one of the main civil engineering transformation representatives, is already utilized. BIM implementation comes from both top-down and bottom-up approaches. In top-down, BIM is required by national laws (often for public investments, as in the United Kingdom, Norway, or Singapore), and companies must adapt. In the bottom-up approach, BIM is not required, but its benefits are spotted by commercial companies and implemented to increase effectiveness. This trend is increasingly popular. Potentially, technological possibilities coming from digital twinning may convince practitioners to complex digital twinning and fuel digital twins' implementations.

The need for the technological step – from BIM to digital twins – has been spotted by countries leading in civil engineering digitization. Centre for Digital Built Britain announced the idea of National Digital Twin [11], an ecosystem of digital twins connected to share data. The motivation for The National Digital Twin are expected benefits: data-sharing in construction will save 20-30% industrial costs; holistic management will strengthen infrastructure resilience; an increase in innovations will open new markets. Centre for Digital Built Britain forecasts almost 100 million IoT (Internet of Things) connections in the infrastructure sectors by 2024; these devices will need to cooperate based on multi-industrial standards, like digital twinning.

Civil engineering needs digital twinning to not stay a technical laggard. Digital twinning will open civil engineering to the best multi-industrial practices and enables the digital partnership of civil engineering facilities and other objects. This is especially important for bridges that in the smart cities will act as connectors of smart infrastructure. Therefore, it is the right time to research possibilities, form practices, and establish frameworks for civil engineering digital twinning.

3.1 Limitations and resulting future work

The proposed notions regard the foundations for the digital twinning of bridges but do not resolve all the issues of practical implementations. It leads to the identification of future work paths. Future research should aim to concretize the recommendations to answer specific questions. What should be synchronization rates for various data sources? How should the user interfaces be designed? Which new and emerging technologies should be integrated? Digital twinning encompasses broad multi-domain areas; every aspect requires thorough, interdisciplinary research. The next step is the creation of practical use cases based on the proposed principles to induce designers, engineers, and managers of infrastructure to adopt digital twinning.

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