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Analysis and potential of digital twins in tunnel construction

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ABSTRACT: The construction industry still requires significant advancements in digitalisation, particularly tunnel construction presents numerous challenges. Using digital twins can help. However, the current implementation is challenged by the lack of specific concepts. As data serves as the initial step towards digitalisation, implementing data management is essential. This will be demonstrated using a digital twin.

The status quo of digital twins in tunnel construction will be presented. Initially, a distinction between digital models, shadows, and twins will be made. A literature review will illustrate the current status and application of digital twins in tunnel construction. Through systematic research, all software solutions will be identified and analysed.

Finally, the current state of usage and the application areas of digital twins in tunnel construction will be presented. Also highlighting existing gaps and areas requiring further action. An outlook will indicate the necessary future developments in this field and the potential digital twins hold.

1 INTRODUCTION

Digitalisation has the potential to significantly improve the construction industry. It enables the processing of large volumes of data, which facilitates better coordination and enhances planning. Tunnel construction can profit from these opportunities. By using digital tools, projects can enhance decision-making and efficiency (Hossain and Nadeem; Li et al. 2024). Additionally, the distinction between digital models, digital shadows, and digital twins can sometimes lead to confusion, so a clearer understanding of their respective roles in managing complex projects is necessary. The question arises whether software solutions can effectively handle the large data volumes associated with tunnel projects, what existing software tools for digital twins are available, and how commonly they are already in use.

In chapter 2, the main differences between digital representations will be identified. A software analysis will present the various options in chapter 3, while chapter 4 will explore the current use in tunnel construction through a literature review. The information from these analyses will provide an overview of the current situation and implementation.

Finally, in chapter 5, existing gaps and areas requiring further action will be identified, with an outlook on the necessary future developments.

2 DISTINCTION BETWEEN DIGITAL MODELS, SHADOWS, AND TWINS

There are various concepts employed to represent and analyse physical objects. Digital models, digital shadows, and digital twins all use digital technologies to depict an object. These technologies enable the understanding and improvement of system behaviours. However, their similarities often lead to difficulties in telling them apart. Additionally, there is no standard definition for each of these terms. Various authors and papers do not consistently

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differentiate the terminology used to describe the three digital representations. To make sure to get the most appropriate definitions, the definitions used in this paper are taken from another author's systematic literature review. There are a few papers in which a systematic literature review on digital twins was conducted, with some also defining digital models and digital shadows. For instance, VanDerHorn and Mahadevan (2021) don't mention digital shadows in there literature review at all, while Liu et al. (2021) and Semeraro et al. (2021) mention digital shadows, but don't provide details about their characteristics.

2.1 *Description of digital models, shadows, and twins*

In this paper, each of the concepts is defined along with their respective properties. The literature review by Sepasgozar (2021) isn't as generalised as others, but it offers more detail on digital shadows. Serving as a source for the literature review by Jones et al. (2020), these two works are the references for the descriptions in the following chapters. These definitions are considered to be the most accurate and sufficient by the authors.

2.1.1 *Digital model*

A digital model represents a real or planned object virtually. Information and data are incorporated to depict the physical structure, this representation may vary in detail. A change in the real object does not result in a corresponding change in the digital model, the focus is on the representation itself, not on dynamic interaction. A digital model can provide the foundation for analysing data, making predictions, and optimising processes. However, it doesn't perform these tasks on its own (Sepasgozar 2021; Jones et al. 2020).

2.1.2 *Digital shadow*

A digital shadow is similar to a digital model but takes it one step further. While the model does not correspond with the real object, the shadow does. It contains data from the actual physical construction. Therefore, a change in the state of the physical object results in a corresponding change in the state of the digital shadow (Jones et al. 2020; Sepasgozar 2021).

2.1.3 *Digital twin*

A digital twin is defined as consisting of three elements: the physical reality, the virtual representation, and the connection. The physical reality includes all parameters that can influence the physical object. To achieve a virtual representation, the physical environment is measured and modelled within a virtual environment. The connections operate via integrated data using sensors and Internet of Things (IoT) technologies. Through this integration, the digital twin replicates reality in real-time, allowing continuous monitoring and analysis. Some key characteristics are fidelity (the degree to which the virtual representation accurately reflects the physical object's characteristics and behaviours), real-time control, and real-time optimisation (Jones et al. 2020; Sepasgozar 2021).

2.2 *Comparison*

Figure 1 shows the characteristics of the three digital representations. A three-step model is used to illustrate that the digital twin builds on the characteristics of the previous digital representations. Each step shows the increasing complexity and demands needed to go from a digital model, to a digital shadow, and to a digital twin, and demonstrates the development from each step.

Figure 2 shows the differences between the digital representations regarding the data flow. The dashed line shows that it is a manual data flow and indicates that the information is only transferred through manual input. The continuous line shows automatic data flow, which enables real-time data exchange.

While the digital model has no automatic data flow, the digital shadow has an automatic data flow from the physical object to the digital object. The digital twin has a two-way data flow, allowing for real-time updates between the physical and digital objects, resulting in a continuous data exchange.

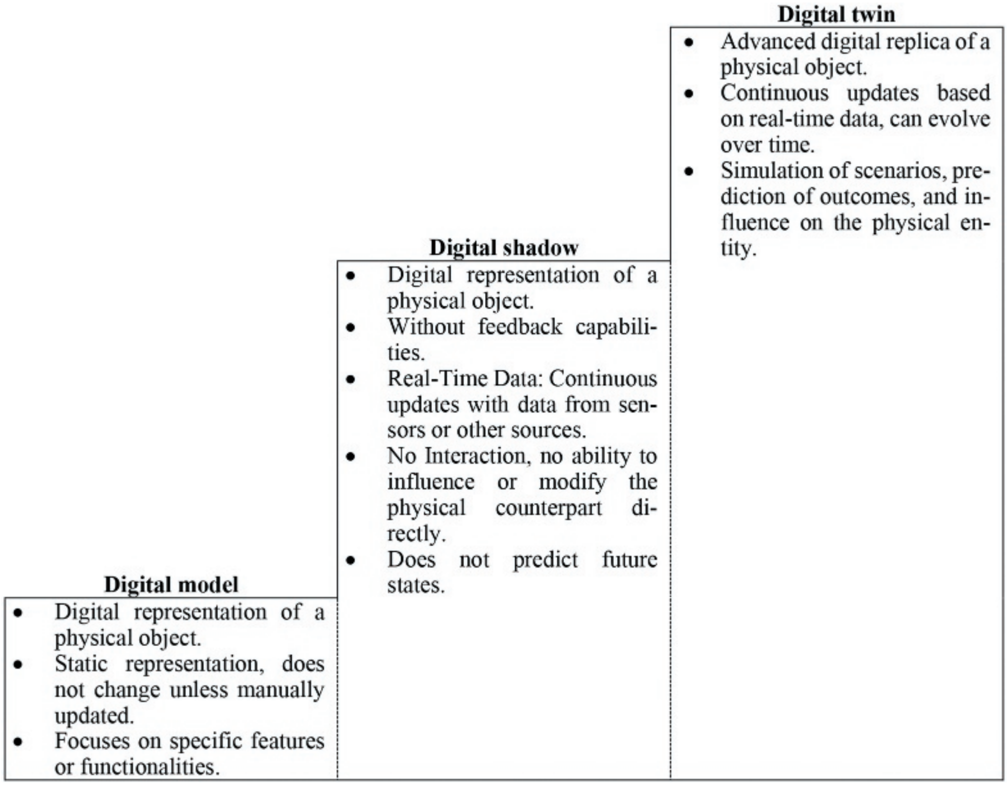

Figure 1. The characteristics of the different kinds of digital representations.

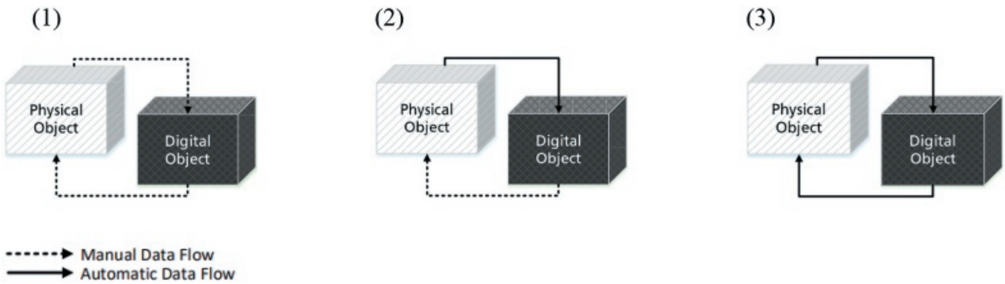

Figure 2. Data flow in (1) digital model, (2) digital shadow, and (3) digital twin (Kritzinger et al. 2018).

3 ANALYSIS OF SOFTWARE SOLUTIONS

To identify the status quo regarding the software solutions, an exploratory market analysis was conducted using various search engines. The market analysis illustrates the current landscape of the procurement market. Within tunnel construction, there are subcategories like tunnel equipment and MEP (Mechanical, Electrical, Plumbing) systems. This article takes a holistic view of tunnel construction to analyse the available software solutions, without differentiating between these subcategories. The software tools that will be analysed may be specific to these subcategories or applicable to tunnel construction in general.

For the analysis, the following search engines were used: Google, Google Scholar, Bing, and Yahoo.

Three search strings were formulated for finding the software solutions. These are:

- Search String 1: tunnel AND software AND digital model
- Search String 2: tunnel AND software AND digital shadow
- Search String 3: tunnel AND software AND digital twin

The number of results returned by the three search strings are displayed in Table 1.

Table 1. Number of results for search strings.

Search engine	Search String 1	Search String 2	Search String 3
Google.com	43,300,000	2,710,000	2,080,000
Scholar.google.com	353,000	28,400	27,900
Bing.com	909,000	321,000	560,000
Yahoo.com	909,000	320,000	563,000

While there is a significant difference in the number of results from Google compared to other search engines, Google does not provide a correspondingly greater number of high-quality results. Although many software solutions were discovered through it, Yahoo also proved to be a reliable source of usable results. The results obtained through Bing included a large number of research papers, without naming actual software. This trend was generally observed across various search engines when conducting searches for search string 2.

The software solutions were evaluated objectively in terms of their functionalities during the market analysis. This independent assessment, conducted by two individuals, aimed to minimise errors in tool evaluation. The results were subsequently validated to ensure accuracy.

The analysis shows the following software functionalities:

- Static representation
- Dynamic updates
- Real-time data
- Predictive analytics (using statistical algorithms)
- Simulation capabilities (behaviour under different scenarios)
- Real-time simulation
- Data exchange (automatic)
- Bidirectional data exchange (automatic, between the digital tool and the physical object)
- Monitoring capability
- Impacts physical object

Table 2 shows the results of the analysis of software tools for the digital representations. It is important to note that there was no direct access to the software. The findings are based solely on the information provided by the vendors on their websites.

A "+" indicates that a tool meets the specified criteria, while a "-" signifies that it does not.

Figure 3 presents the results of the analysis in a bar chart, providing a clear visualisation of the characteristics of the analysed software tools, allowing for an easy comparison. Additionally, Figure 4 illustrates in a pie chart the percentage distribution of these features, offering insights into their relative prevalence. A second pie chart in the same figure illustrates the frequency of the digital representations.

As discussed in Table 1 in Section 2.2, digital models represent the object, while digital shadows utilise real-time data, and digital twins additionally influence the physical entity (bidirectional data exchange). Most software tools advertised as digital models align with our definition. However, this does not apply to digital twins. Their webpages can lead to confusion. Vendors often advertise data exchange, but this does not refer to bidirectional exchange. They rather indicate a data exchange to the model, but not to the physical object. In the end, the software identified in the search for digital twins can be characterised as digital shadows. However, neither of the companies claimed this term. Thus, digital twins are currently underrepresented in software solutions.

Table 2. Analysis of software tools for digital twins.

Nr.	Tool	Vendor's Terminology	Static representation	Dynamic updates	Real-time data	Predictive analytics	Simulation capabilities	Real-time simulation	Data exchange	Bidirec. data exchange	Monitoring capability	Impacts physical object	Search string	Search engines	Reference
1	MOVE	model	+	-	-	-	+	-	-	-	-	-	1	Google Scholar, Google	(Erharter et al. 2023; Petroleum Experts)
2	Airshaper	model	+	-	-	-	+	-	-	-	-	-	1	Google Scholar	(AirShaper)
3	Bentley	model	+	-	-	-	+	-	-	-	-	-	1	Google	(Bentley Software)
4	FEM – Tunnel	model	+	-	-	+	+	-	-	-	-	-	1	Google	(Geotechnical Software GEO5)
5	IDA Tunnel	model	+	-	-	-	+	-	-	-	-	-	1	Yahoo	(EQUA Simulation AB)
6	TcpTUNNEL CAD	model	+	-	+	-	-	-	+	-	+	-	1	Bing	(Aplitop)
7	Proqio	model/ twin	-	+	+	+	-	-	+	-	+	-	1	Google	(Proqio)
8	Wasko	model	+	-	-	-	+	-	-	-	-	-	2	Bing	(WASKO Joint Stock Company)
9	Revit	model	+	-	-	-	+	-	-	-	-	-	1, 2	Yahoo	(Yuan et al. 2022; Autodesk Inc.)
10	Tunnelsoft TPC		-	+	-	-	-	-	+	-	+	-	2	Bing	(Tunnelsoft)
11	Tunnel boring 4.0	model	+	-	-	-	+	+	+	-	+	-	1, 3	Google	(Tunnelware)
12	KYP	twin	-	+	+	+	+	+	+	-	+	-	3	Google	(Digitalnology)
13	usBIM. geotwin	twin	-	+	+	-	-	-	+	-	+	-	3	Google	(ACCA software)
13	Ansys Twin builder	twin	-	+	+	+	+	+	+	-	+	-	3	Yahoo	(ANSYS, Inc.)
15	Aize	twin	+	-	-	-	-	-	-	-	-	-	3	Yahoo	(Aize)
16	Digital Twin Technology for Tunnels	twin	+	-	-	+	+	-	-	-	-	-	3	Bing	(Digital Twin Tech)
17	Honeywell Process Digital Twin	twin	-	+	+	+	+	+	+	-	+	-	3	Bing	(Honeywell International)

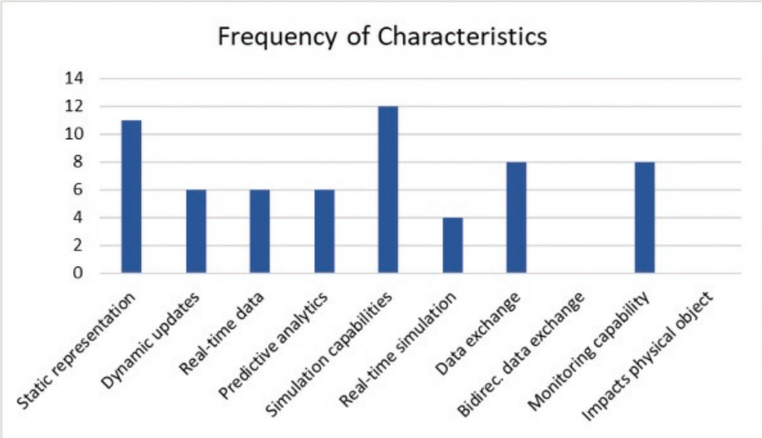

Figure 3. Bar chart for the frequency of the characteristics of the analysed software tools.

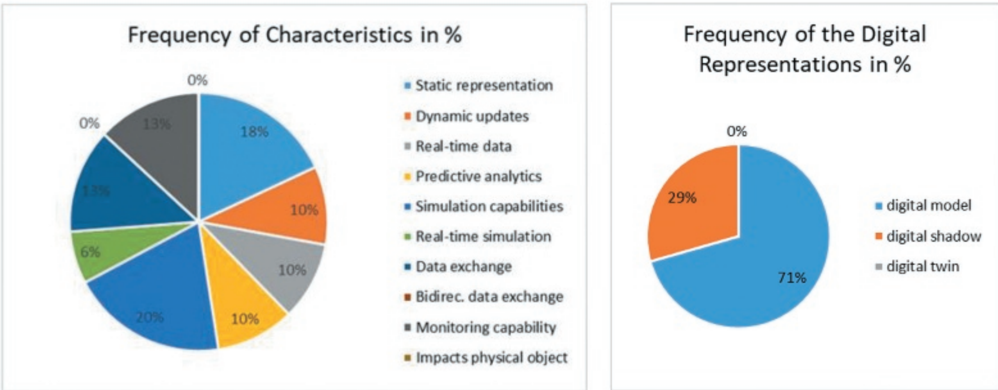

Figure 4. Pie chart of the percentage distribution of the analysed software tools.

Some software was identified only through search terms related to shadows, yet they ultimately were digital models, as also advertised by the vendors.

Digital twins also present the most challenges regarding customer confusion. The webpages frequently use both terms—model and twin. While a digital model is a necessary foundation for creating a digital twin, the term is sometimes used interchangeably, which is incorrect.

During the software analysis, it became apparent that the terminology is not important to all software providers. 'Aize' advertises its software as a digital twin, while it is, by our definition, clearly a model. Upon taking a deeper look into their webpage, they state that it may not actually be a digital twin. This indicates that they are aware of the distinction but do not seem to prioritise it.

4 CURRENT STATE OF USAGE

Digital models, especially Building Information Modelling (BIM), are already widely used in tunnel construction. Several countries, such as Norway, Singapore, Canada, the US, and the UK, have implemented public administration incentives to increase BIM adoption. Surveys conducted by McGraw-Hill Construction revealed that North America had a BIM adoption rate of 49%, compared to just over a third in Western Europe (Bradley et al. 2016).

While there are many promising case studies for digital twins, specific statistics on the percentage of tunnels or underground projects utilising digital twins are not widely available. However, experts agree that as the technology matures, its adoption is likely to increase, driven by the need for improved safety, cost efficiency, and construction speed (Tuhaise et al. 2023). Digital twins can bring positive aspects in this regard due to their characteristics. To holistically use these potentials, the tunnel construction industry needs to advance digitalisation and face the challenges of data management. Establishing frameworks for data capture and analysis will be important for effective implementation, ultimately driving the digitalisation of tunnel engineering and improving overall project success. Digital twins are a promising technology with the potential to reduce risks in tunnel engineering, leading to greater efficiency, cost-effectiveness, and environmental sustainability. By integrating their capabilities, digital twins can significantly improve outcomes in tunnel projects and overall infrastructure management (Li et al. 2024; Wang et al. 2024).

5 SUMMARY AND OUTLOOK

A separation between digital model, shadow, and twin is important, as this approach provides much more clarity in their use. The software analysis revealed that most software solutions do not clearly differentiate between the three digital representations.

The lack of definition and differentiation in terminology between digital models, shadows and twin could ultimately lead to confusion and inefficient use of the software solutions. A clear distinction could be crucial to prevent this and improve the efficiency of the software. In future developments, it would be beneficial to ensure this differentiation is considered, in order to enhance the functionality and, consequently, the positive aspects of digital twins. A standard should be defined for characteristics so that all digital twins fulfil the same criteria. This would ensure that anyone can work with them uniformly, regardless of the specific software or application being used.

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