Chapter

Roadmap to a Holistic Highway Digital Twin: A Why, How, & Why Framework

Ashtarout Ammar, Hala Nassereddine and Gabriel Dadi

Abstract

The advent and spread of the COVID-19 pandemic shifted the world's focus toward investing in social structure projects that would improve urbanization and enhance equity. This shift compiled with the emergence of innovative technologies namely Digital Twins, allowed for investigating new approaches for designing and delivering infrastructures, thus paving the road toward smarter infrastructures. Smart infrastructures achieved by connecting the physical aspect of the infrastructure with its digital aspect will allow for optimizing the performance of infrastructure systems by digitally enhancing the asset value and leveraging the value of asset data. Digital Twins can be applied to several civil infrastructure projects including the transportation sector. Also, Digital Twins can be implemented for different spatial scales, on a national level, on the level of the city, and for a network of assets. Few case studies described how to transfer a Digital Twin vision to practice; thus, this chapter presents the journey for a holistic Digital Twin for a highway system formed of a network of assets by discussing the Why, How, and What framework. A holistic highway Digital Twin will allow for cross-asset data analysis, conducting predictive and preventive maintenance, and efficient resource allocation based on data-driven decision-making.

Keywords: digital Twins, data management, data management system, civil infrastructure systems, highway system, transportation assets

1. Introduction

In 2019, the world witnessed a global crisis caused by the emergence and spread of COVID-19 an infectious disease that caused the death of millions of people [1]. With the emergence of the pandemic, it was evident that the lack of focus on sustainable development goals (SDGs), especially the ones related to people and the environment, played an important role in the emergence and spread of infectious diseases, including COVID-19 [2]. The resulting chaos caused by the pandemic urged a shift in goals and investments toward health and infrastructure [3]. Thus, the pandemic has accelerated the shift toward social infrastructure projects targeting urbanization, healthcare, infrastructure, and Global Water, Sanitation, & Hygiene (WASH) projects, which will help cities to face future pandemics [4, 5]. This shift motivated governments to upgrade systems to achieve a more resilient and sustainable infrastructure ecosystem and consider implementing and adopting technologies within the architectural, engineering, construction, and operation (AECO) industry [6, 7].

Some governments started this shift before the pandemic to help overcome the challenges of the AECO industry and improve the industry's digitization capability. For instance, the United Kingdom (UK) in their 2018 construction sector deal, a partnership between the government and the construction sector, dedicated £600 billion of investment in infrastructure including £31billion to boost digital construction and smart infrastructure [8]. Conversely, in the United States (US), in November 2021, the Infrastructure Investment and Jobs Act (IIJA) was officially legislated. The IIJA is a $1.2 trillion investment, representing the "largest investment in the nation's critical infrastructure systems in a generation or more" [9]. The new law will allow for the investment of $110 billion in funding for roads, bridges, and major infrastructure projects. This investment will support mitigating the impact of climate change, building resilient and sustainable infrastructure, enhancing equity, and improving safety for road users of all modes [10]. Moreover, the law dedicated $100 million to fund the digital construction management systems and related technologies program. It is anticipated that this program will support the investment in technologies and tools including visual-based inspection technologies, construction management tools, electronic ticketing (e-ticketing), Digital Twins, and unmanned aerial vehicles (UAVs) [11].

Smart infrastructure—or the combination of the physical aspect of the infrastructure with its digital aspect—is a global opportunity worth £2 trillion to £4.8 trillion [12]. Smart infrastructures will allow for a better understanding of the performance of the existing infrastructure system, thus optimizing its efficiency and supporting the design and delivery of new infrastructure systems [12]. The concept of connecting the physical aspect of assets with its digital model aligns with the concept of Digital Twins, which was defined by several researchers as the digital representation of physical assets, or a digital model created to depict either an existing, ongoing, or future construction project and linked throughout its lifecycle [13, 14]. The authors of [14] highlighted the notion of the Digital Twins for the construction project lifecycle and emphasized the different capabilities of the technology including increased transparency of information, real-time monitoring, analysis, and feedback, better stakeholder collaboration, advanced preventive measures, advanced what-if scenario analysis and simulation, real-time tracking, and higher accuracy.

The concept of Digital Twins emerged with the Fourth Industrial Revolution, known as Construction 4.0 in the AECO industry. However, among the technologies under the umbrella of Construction 4.0, Digital Twins is the least researched in the industry [15] and, while its definitions and applications vary from one sector to the other, its framework is similar [12]. For smart infrastructures, the framework of Digital Twins can be presented as a pyramid formed of a base and three layers. The base is formed of raw data collected using several tools and methods including customer billing, sensors, drone surveys, laser surveys, building information modeling (BIM), geographic information system (GIS), and control systems, among others. On top of the base, resides the data management layer such as data storage, data cleaning, data structure, and other practices related to data management. The layer above data management is data analysis and interpretation or making sense of the existing data. Finally, the crown of the pyramid (i.e., the third layer) is decision-making. As such, to leverage the process of data-driven decision-making, it is essential to lower the data volume (i.e., layer 1) and increase the data value (i.e., layer 3) where the three layers are internally and externally connected by communicating information as presented in **Figure 1** [12].

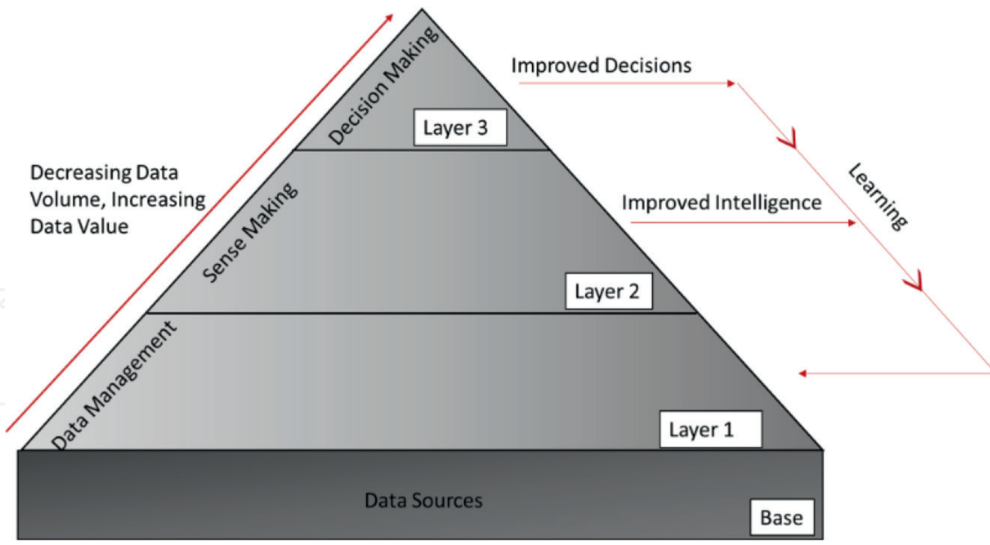


Figure 1.
Digital Twins model for smart infrastructure (adopted from [12]).

This chapter thoroughly investigates the existing research on Digital Twins in the infrastructure industry (Section 2), the applications of Digital Twins in the transportation sector (i.e., bridges, rails, tunnels, and highways) (Section 3), and the implementation of Digital Twins for different spatial scales in the civil infrastructure industry (i.e., national level, city level, and for a network of assets) (Section 4). Additionally, this chapter discusses the vision for a holistic Digital Twin for a highway system (Section 5) and summarizes major findings in a conclusion section (Section 6).

2. Existing research on Digital Twins in the infrastructure industry

Digital Twins originated in aerospace engineering; however, with the advancement in technology, the concept is no longer limited to complex systems and can be implemented to provide a digital representation of any system [16]. This feasibility encouraged several researchers from different industries to investigate the concept of Digital Twins. The increased focus on data and the opportunities created by digitization promoted the potential of the emerging phenomenon of Digital Twins in the manufacturing industry with the wave of Industry 4.0 to fulfill the requirements of smart factory [17–19]. The concept of Digital Twins then found its way to the oil and gas industry to optimize offshore operations, reduce risks to health, safety, and environment, and facilitate complex integrated processes [20]. Similarly, the construction industry began considering Digital Twins a key enabler for its digital transformation that could improve the industry's poor record in digitization [14, 21]. Moreover, the digital transformation of engineering assets increased the interest of both researchers and practitioners to investigate the implementation of the concept of Digital Twins in the civil infrastructure domain [22].

Several researchers investigated the implementation of Digital Twins in the infrastructure sector. The authors of [23] examined the current practices of implementing Digital Twins through a series of semi-structured interviews with experts and executives from the UK infrastructure industry. Their study found that the current implementations are still not mature and most of them are under development. These implementations included 3D modeling of physical assets, integration of real-time weather forecasts, asset data and information projects, integration of different information systems coming from several organizations (in the construction phase), and contract management systems throughout the supply chain (in the construction phase), procurement of a network management system and its integration with existing systems, sensor data collection, implementation of common data environments, and modeling of systems and control philosophies. Similarly, the authors of [24] conducted a comprehensive review to investigate the implementation of Digital Twins within the civil infrastructure systems (i.e., transportation, energy telecommunication, water and waste, and smart cities). They thoroughly investigated the existing literature, in addition to surveying professionals and interviewing stakeholders. It was also found that the concept of Digital Twins in the infrastructure industry is still in the early stages of development. The authors also highlighted that the major adoption of Digital Twins within the civil infrastructure system was to optimize operations. Also, they emphasized that it is critical to investigate how Digital Twins can be retrofitted into existing infrastructure systems to improve the efficiency of their operation and maintenance. More recently, the authors of [22] conducted a systematic literature review to map the applications of Digital Twins within the road and rail system, telecommunication, and electricity networks. This study showed that the available studies are scarce and that the use of Digital Twins is mainly perceived for the operation and maintenance phase. It was also noted that while Digital Twins can leverage the value of asset information and, thus, improve the process of data-driven asset management decisions, the impact of Digital Twins on the development of asset management programs within infrastructure organizations should be addressed. Since the focus of this chapter is on transportation systems, a comprehensive review of the existing studies on the application of Digital Twins for transportation systems is discussed in the following section.

3. Digital Twins applications for the transportation system

The transportation system includes the sectors of bridges, railroads, tunnels, and highways. Transportation systems are critical for the development of any jurisdiction, they represent the arteries necessary for connecting people, delivering goods, and providing services for economic development. The failure of these systems can result in considerable economic losses [25]. To mitigate the risks of failure and to improve the management of such a critical and aging system, the transportation sector followed suit and investigated the implementation of Digital Twins with a wide variety of applications.

3.1 Digital Twin applications for bridges

Bridges are complex engineering systems and are considered high-value assets with a relatively extended life span; thus, their continuous maintenance to prevent their deterioration and mitigate the risks of their failure is always a priority for infrastructure organizations. As such, the ability to conduct preventive maintenance and lifecycle monitoring of bridges became an essential strategy in the bridge industry since it can support proactive measures to maintain the structural integrity of bridges throughout their entire lifecycle. The capability of Digital Twins to aggregate real-time data and historical data, support data analysis, and enable insights on preventive maintenance captured the attention of researchers in the bridge industry to investigate the potential of implementing Digital Twins in their bridge design, construction, operation and maintenance, and deterioration [26, 27].

A Digital Twin solution to enhance bridge maintenance by integrating a maintenance information management system based on a 3D information model with a digital inspection system using image processing was proposed by the authors of [26]. The proposed model was validated for maintaining pre-stressed concrete bridges where it facilitated the detection of surface damages in a real-time manner, thus providing early warnings of any potential distress and enabling early remedial interventions. Additionally, a closed lifecycle fatigue management driven by Digital Twins for steel bridges was developed by the authors of [27]. The authors discussed the implementation mechanism of Digital Twins in the bridge design phase, the bridge construction phase, the bridge service and operation phase, and the bridge retirement phase. The authors noted that a Digital Twin-driven fatigue management system can support the integration of a diversity of fatigue data including historical fatigue information after the bridge retirement thus providing better insights for the design and management of new bridges.

3.2 Digital Twin applications for railroads

The railway system is no less important than bridges, which is also a complicated system made of several subsystems, where their maintenance and condition monitoring is critical to mitigate the risks and ensuring safety. Asset managers should have access to continuous information related to the railroad conditions to allow for the early detection of any surface abnormalities caused by temperature change, degradation, or component failure and to have the ability to automate and modify railway turnouts or railway switches automatically, in case of an emergency. In that manner, Digital Twins with its capability of integrating multi-sourced data such as data collected by sensors depicting the railroad conditions and weather conditions allows it to act as a centralized data source that can act as a traffic management and control system [28, 29]. The authors of [28] applied the concept of Digital Twins to monitor railway turnouts, a very complicated system by nature of design and construction. Sensors were used to measure the rail temperature promptly and cyclically to support the data acquisition of rail turnouts and to capture emergency conditions. This automated and continuous analysis of the rail components increased the efficiency of managing and maintaining railroad turnouts. Moreover, the concept of Digital Twins for the European Train Control System (ETCS) applications was investigated [29]. The Digital Twin served as a repository and universal simulation environment to support the automatic check and compliance of organizational and operational requirements, system requirement specifications, design principles, regulations governing railway operations, interfaces with the control-command basic layer system, and requirements for the verification process of the control-command subsystem. This resulted in a significant reduction in the duration and cost of validating the ETCS applications.

3.3 Digital Twin applications for tunnels

The development of smart cities and the advancement of available technologies enhanced the utilization of urban underground spaces to construct urban infrastructures such as tunnels. Tunnels are complicated spatial structures and have multiple electromechanical components, such as ventilation systems, necessary for their operation. Digital Twins can support the operation and maintenance of tunnels and allow for lifecycle management analysis [30, 31]. A Digital Twins prototype of noise barrier tunnels (NBTs) was implemented to predict the life and condition of the tunnel components using numerical behavior analysis. Sensors were used to link the behavior of the physical model of the NBT (i.e., a digital model created using a 3D printer) and the digital model of NBT (i.e., a shape-generation script comprised the NBT shape-generation, component-shape generation, and component mapping and layout models) [30]. The implemented Digital Twins prototype allowed for the lifecycle management analysis, which can help reduce NBT installation costs, support the use of recycled materials, and make the process of installation more sustainable by identifying components that should be replaced at the early stages of the NBT design. Moreover, the authors of [31] proposed a Digital Twins-based decision analysis framework for the operation and maintenance of tunnels. The proposed framework defined the decision analysis and an extended Construction-Operations Building information exchange COBie standard-based organization method employed to define information for assets that are delivered as part of facility construction projects and used to document the data with BIM—and integrating data using semantic web technologies. The proposed framework was validated by operating and maintaining complex electromechanical systems such as fans that are used to eliminate harmful gases and control visibility inside the tunnel. The Digital Twin framework supported the early detection of any anomalies in the operation of fans and determining the fault causes. This allowed for taking timely maintenance interventions to ensure better operation of the tunnel.

3.4 Digital Twin applications for highways

Highways are less complicated when compared to other transportation systems in terms of their structure, nevertheless due to their expansion over a vast network and the use of vast quantities of materials their lifecycle management and material durability are always a concern. Multi-sourced data integration enabled by Digital Twins facilitates the prediction of highway materials performance, allows better visualization of key performance indicators (KPIs), and supports reliable and data-driven decision-making [32, 33]. A framework combining Digital Twins and multiple time series stacking (MTSS) was employed to predict the performance of highway tunnel pavement performance [32]. The Digital Twins is formed of three key components: (1) data collection module including pavement performance data collected by performance indicators such as sensors and high precision accelerometers, main maintenance records extracted from the operation and maintenance system, tunnel highway structure, traffic flow, and tunnel environment; (2) prediction model, where a pavement performance prediction model was developed based on multiple differentiated models generated to predict the future performance of selected pavement section; and (3) parametric analysis model, established in the dynamo environment to integrate the multisource spatial-temporal data of the BIM model and the physical assets. The proposed framework was validated using a case study, and it was found that the visuals provided by Digital Twins allowed for conducting preventive maintenance. Similarly, the authors of [33] established a fully functioning Digital Twin of a road constructed using secondary raw materials (SRMs). The model included structured geometric and attribute data related to SRMs such as material data, chemical and mineralogical composition, strength, and unstructured data including real-time material characteristics collected by sensors. The developed Digital Twins supported data centralization and allowed the graphical presentation of KPIs.

3.5 Section summary

Infrastructure projects are complicated construction projects with a lifespan that might expand for a couple of decades. It is well known in the construction industry that the cost of operation and maintenance can be up to two or three times the cost of the initial construction and that it can equate from 60 to 80% of the total lifecycle cost, with the extended lifecycle of infrastructure projects this cost can be significant [34]. Infrastructure asset management constitutes several processes that are data-intensive and necessitates continuous data collection and analysis to support decision-making. The emergence of Construction 4.0 technologies, mainly Digital Twins, facilitated by the availability of powerful and cheaper sensors and cyber-physical systems (CPS) and with the aid of computational technologies such as big data analytics, semantic web-based technologies, and the Internet of Things (IoT) coupled with the drive toward digitizing infrastructure assets and transforming them into "smart infrastructures" provided a more holistic and innovative approach for managing infrastructure assets and informing decision-making.

The use of Digital Twins for transportation systems was mainly implemented to help asset managers better operate and maintain complex and interconnected sub-systems, monitor the performance of different system components, enhance the visualization of information necessary to conduct preventive maintenance and detection of abnormalities, conduct lifecycle management analysis, and take proactive interventions to mitigate failure risks and enhance the system's structural integrity. Moreover, the capability of Digital Twins to act as a centralized hub of meta-data with multiple sources supported the establishment of a universal simulation environment and data repository, thus allowing asset managers to have access to reliable information and therefore allowing them to conduct informed and quality-based decision-makings. However, the discussed studies showed that the implementation of Digital Twins for the transportation system is not mature yet. Most of the studies presented either a practical or conceptual Digital Twins framework that was driven to satisfy its purpose of solving an identified problem. No large-scale Digital Twin for transportation systems was employed where the full potential of Digital Twin is achieved, and their capabilities are optimized. Nevertheless, the proposed frameworks showed promising results toward adopting Digital Twins in the transportation sector.

4. Digital Twins for different spatial scales in the civil infrastructure industry

Sections 2 and 3 showed that Digital Twins can be used for many purposes. It can be used for potential future planning by running what-if simulations, and predictive and preventive maintenance management. Also, it can be implemented in the project's current state for operation and maintenance, real-time monitoring and control, and early detection of abnormalities to optimize the performance of assets. Moreover, it can act as an archive for historical data and provide key insights from past lessons. However, Digital Twins can be used for multiple purposes and can be employed for different spatial scales, that is, on the level of an asset, for a network of assets, for a system or city, and at a national level. As was mentioned in the previous sections, most of the applications of Digital Twins were for a specific purpose and on a small scale and this could pertain to the fact that the concept of Digital Twins in the civil infrastructure industry is not mature yet. Previous studies showed very promising results, and this encouraged several governments, institutions, and organizations to explore the practicality of the concept and build a vision toward optimizing the potential of Digital Twins on a holistic spatial scale and investigate different strategies, frameworks, and roadmaps to bring the vision into action and transform the way of planning, verifying, delivering, and operating the built environment.

4.1 Digital Twins on a national level

The case studies on envisioning the implementation of Digital Twins on a national level are very limited since this is a huge investment and requires the collaboration of several stakeholders. However, the UK is leading in this initiative and the government generated the Industrial Strategy Transforming Construction Programme and established the Center for Digital Built Britain (CDBB) at the University of Cambridge to set definitions and principles across the built environment to develop a roadmap toward a National Digital Twin (NDT); an ecosystem of connected Digital Twins of physical assets to leverage the use of asset data for the benefit of the public [35]. The vision for Digital Built Britain is to "enhance the natural and built environment, thereby driving up commercial competitiveness and productivity as well as quality of life and wellbeing for the public. This will be achieved through better planning, delivery and whole-life management of infrastructure and the wider built environment—enabled by mustering the full power of the information value chain" [13]. It is perceived that the use of an information management framework and an NDT in a coordinated and considered manner will support the release of data from isolated silos and enable the creation of a centralized data repository, resulting in an additional £7 billion/year of benefits across the UK infrastructure sectors [36]. The road map for delivering the information management framework can be addressed by answering the following questions [13]:

1. **Approach**: What is the best overall approach for realizing the benefits of information management across the built environment?

2. **Governance:** What are the best structures and processes for managing the development, adoption, and ongoing oversight of the framework?

3. **Standardization:** What principles, guidance, specifications, and formal standards are required?

4. **Enablers:** What potential blockers are there, and how should they be addressed? What cultural, behavioral, technological, commercial, or other adjustments are necessary?

5. **Change:** What should be done to get the framework adopted across the whole built environment?

To guide the development of the framework and the NDT, CDBB defined the Gemini Principle as the conscience of the framework identified by nine principles and distributed over three clusters (1) purpose, (2) trust, and (3) function [13]. The NDT should have a clear purpose and must be used to provide good to the public, enable value creation and improve performance, and must provide insights into the built environment. Additionally, it should be trustworthy to the public; otherwise it will lose value, data sharing should be open as possible but at the same time should be secured to ensure its integrity and should rely on quality data. Finally, the NDT should function effectively in support of its purpose, must be based on standards with clear data ownership and data governance, and should be flexible to develop and adopt any technological or system evolutions in the future.

4.2 Digital Twins on a city level

Historically, Singapore faced several challenges while planning its built environment to provide a better quality of life to its residents considering that its area is 728.6 km^2 and its urban density is the third worldwide. To face these challenges, the government of Singapore with the aid of several authorities and research foundations developed "Virtual Singapore: A Digital Twin for Planning," a platform providing a dynamic 3D virtual model of the urban areas of Singapore. The government used 2D maps to solve urban challenges; however, with the emergence of 3D models they realized the potential of 3D data in offering planners a more comprehensive platform to design and pilot urban solutions. This innovative program was operated with three strategic objectives, (1) to consolidate research in 3D data, (2) to develop an operational 3D city model and data platform that integrates BIM, 3D GIS, and simulation for planning use by researchers, citizens, and authorities, and (3) develop a 2D/3D Digital Twin for Singapore that offers planners and citizens tools to examine spatial data and test-bed concepts, and observe the impacts of projects in a "Virtual Singapore" before delivery in the real world [37]. The applications of Virtual Singapore include flood risk analysis, the potential for solar panels and green roofs, and monitoring the impact of wind load on vegetation [37].

Similar to Singapore, the city of Vienna has been experiencing continued growth and demand for new buildings, pressuring the city to issue thousands of new building permits every year. The process of building validation and verification is sophisticated and prone to the loss of information between the building authority and the planners and investors. Digitizing this process and using BIM at the early stages of design and being aware of the benefits of Digital Twins will allow building owners to have a Digital Twin model for their facility that they can use throughout the facility lifecycle and will provide authorities with an efficient building verification and a permission process. For that purpose, the city of Vienna worked with TU Wein and experts from different engineering and architectural firms and consultants on a project titled BRISE-Vienna, an openBIM-based building submission process aiming to integrate the building authority into the Digital Twin of a construction project throughout its lifecycle [14]. The development and maintenance of a Digital Twin for all buildings provide the building authority access to up-to-date Digital Twins throughout the phases of the building lifecycle. The sum of the Digital Twins of all buildings results in a Digital Twin of the city, named an Urban Digital Twin (UDT). UDT creates new opportunities for strategic considerations (urban mining, area analysis, and fire protection analysis) and further research activities (data basis for AI training and thermal simulation). Hence, UDT allows the city to perform advanced what-if scenario analysis and simulations to simulate the change of power supply or heating systems in a whole area for instance (i.e., change to district heating) [14].

4.3 Digital Twins for a network of assets

The government in the UK is very ambitious about being the world leader in shaping the future of infrastructure; for that purpose, they set their vision for Digital

Themes	Subthemes	Description
 *Created by Iconstock from Noun project* Digital Design & Construction	Digitally enabled design Modular & standardized approaches Automated construction	Activities will be automated, modular, and conducted off-site, resulting in safer production, reduced disruption, increased productivity, and smoother journeys
 *Created by Aficons from Noun project* Digital Operations	Intelligent Asset Management Enhanced operational capability Digitally enabled workers	Operations will leverage data to drive increasingly pre-emptive interventions - resulting in improved asset resilience, increased asset life, and a safer, smoother-running network
 *Created by Sunardi from Noun project* Digital for Customers	Information Provision Customer engagement Partnerships & alliances	Customers will be better informed and have trust in the journey information they access, ensuring that they feel safe and in control of their journeys.

Table 1.
Core themes for UK Digital Road Vision 2025.

Roads from 2020 to 2025 and are working on the longer vision of 2050. It is perceived that Digital Roads will harness data, technology, and connectivity to enhance the way the strategic road network (SRN) is designed, constructed, operated, and used. This will allow for safer traveling, faster delivery, and an optimized customer experience [38]. The vision toward Digital Roads is built based upon three core themes as presented in **Table 1** [39].

By the same token, several state Departments of Transportation (DOTs) in the US followed suit and investigated how they can embrace Digital Twins to leverage the value of enterprise asset information to conduct daily operations, monitor performance, and provide transparency to the public. For instance, Utah DOT (UDOT) envisioned Digital Twins as an information management strategy to connect enterprise asset information to a geospatial model of individual physical assets. Digital Twins is foreseen to support the documentation of the planned and as-constructed (as-built) updates and therefore to fill the gap in the information across project development for priority assets, thus ensuring the collection of the necessary information to document asset histories and proper governance of the asset current state [40, 41]. Moreover, at the organizational level, the Digital Twins of the transportation asset systems will provide a single source of reliable, real-time information that will be used across different divisions of the department and the public enabling UDOT to perform complex analyses and make holistic decisions to improve safety, enhance mobility, and preserve the transportation infrastructure [41]. Additionally, UDOT identified several tactical goals with a two-year horizon considered high-value activities with no pre-requisites, and strategic goals with a five-year horizon which are also considered high-value activities with pre-requisites and requires further collaboration. The identified tactical and strategic goals required for the achievement of the overarching objective of adopting Digital Twins for infrastructure assets are summarized in **Table 2** [41].

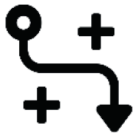
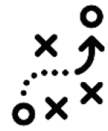
	**Tactical goals (2 years horizon)**		**Strategic goals (5 years horizon)**
Created by Ayub Irawan from Noun project		*Created by Gregor Cresnar from Noun project*	
Analyze the business architecture. Find ways to improve how to develop projects,		Use automation to harvest asset information from project data.	
Govern project data, define the rules, roles, and responsibilities for data.		Simplify how information is collected to increase consistency and focus on priority activities in construction.	
Finalize the model development standards manual and use it on all design projects.		Roll out the policies, tools, and roles for data governance in the development of projects.	
Use a repeatable process in construction to update the asset information created in the design.		Use the two prototype Digital Twins on all projects with those assets. Create Digital Twins for other assets.	
Build a prototype Digital Twin for two assets (examples, single post signs and barrier). Pilot the Digital Twins on projects.		Make the Digital Twin program sustainable. Invest in Digital Twins to bring value to UDOT as technology changes.	
		Adopt the concept of Digital Twin across all groups within the Department.	

Table 2.
Tactical and strategic goals identified by the Utah Department of Transportation for a successful implementation of Digital Twins for infrastructure assets.

4.4 Section summary

Envisioning Digital Twins on a large spatial scale is starting to sound appealing among governments, institutions, and organizations. Few envisioned implementing Digital Twins on a national level, others proposed its implementation to face the challenges associated with planning urban environments in developed cities, while some intended to use it for a network of infrastructure assets to digitize the design, construction, and operation of transportation networks or to manage the data of priority assets and fill the gap of the enterprise information.

Each presented vision started by identifying the purpose behind adopting Digital Twins for infrastructures and they established a set of certain principles, themes, strategic objectives, or goals that they considered necessary for achieving the overarching objective of this adoption. Also, they discussed the expected benefits resulting from this implementation. However, there is a lack of pilot projects or actual studies that implemented Digital Twins and explained the transition from vision to action. In the next section, we are going to discuss the vision toward a holistic Digital Twin for a highway system and to further understand how to move from concept to practice, a case study is presented.

5. Journey for a holistic Digital Twin for a highway system—the why, what, and how

A vision for a holistic Digital Twin is initiated by identifying the purpose by answering the *Why* component, or in other words, *Why is a holistic Digital Twin for a*

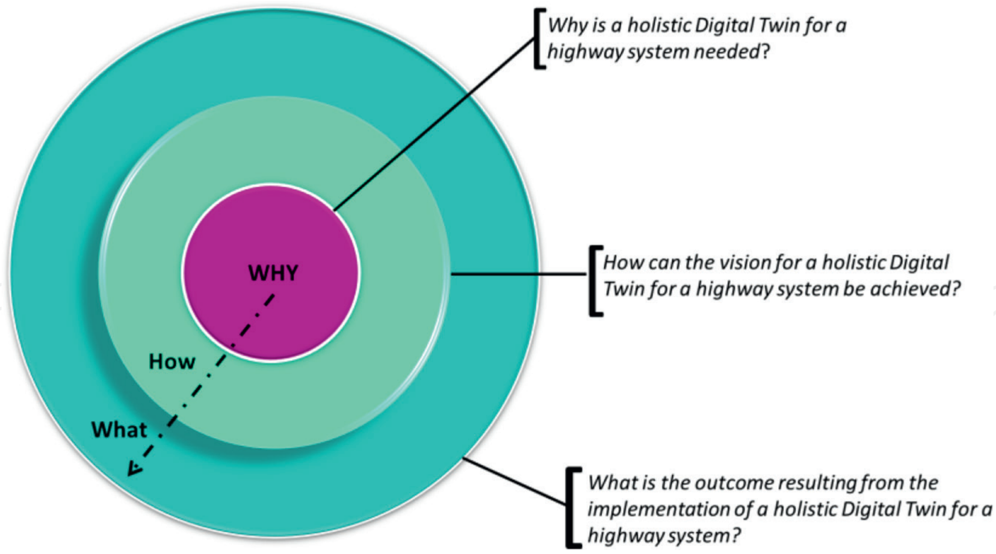


Figure 2.
The why, how, and what components of a holistic Digital Twin for a highway system.

highway system needed? where a clear statement describing the purpose is generated. After declaring the overall purpose, a set of principles, themes, strategies, or goals are formed for setting the *How* component, that is, the process, or in other words, *How can the vision for a holistic Digital Twin for a highway system be achieved?*, which can be described by setting short- and long-term objectives that should be achieved to fulfill the overarching objective for adopting a holistic Digital Twin. Finally, *What* component should be investigated, that is, *What is the outcome resulting from the implementation of a holistic Digital Twin for a highway system?* The Why, How, and What components of a holistic Digital Twin for a highway system are presented in **Figure 2**. In the following sub-sections, the three research questions will be addressed.

5.1 Why the need for a holistic Digital Twin for a highway system

A highway asset system within a state Department of Transportation (DOT) can be classified into three categories: bridges, pavements, and ancillary assets. Usually, state DOTs prioritize the management of high-value assets and highly-visible ones such as pavements and bridges. However, transportation systems extend beyond pavement and bridges to include a wide variety of ancillary assets [42]. Ancillary assets represent a significant investment of public funds and many are essential for the safe and efficient operation of highway facilities including, for instance, access ramps, guardrail end treatments, pavement markings, signs, culverts, drain inlets and outlets, communication systems, and intelligent transportation system (ITS), among others. DOTs are responsible for managing highway assets; thus, they are responsible for collecting, storing, managing, and analyzing vast amounts of asset data to support the process of transportation asset management (TAM) [43]. Every year state DOTs conduct hundreds of projects and make changes to existing ones. New construction projects require the generation of new sets of data to be included in the current database. On the other hand, reconstruction, rehabilitation, asset demolition, or other major maintenance activities require revising and updating the database. All changes conducted for assets through the project execution and its whole lifecycle should be collected accurately and promptly to ensure effective TAM and proper operation and maintenance (O&M) [44]. However, state DOTs are facing several challenges integrating data across systems and throughout the asset lifecycle [45], and they need to focus on six major data management practices that are data collection, data handling, data flow, data transfer, data governance, and data integration to achieve a seamless data management approach and improve the value of data to enable informed decision-making [46].

Conversely, with the emergence of technologies and the notion of data-driven decision-making, where data itself is considered a high-value asset, state DOTs changed their perspective on operational performance where they focused more on operating and maintaining the existing transportation system instead of expanding it, and thus, they are investigating new approaches to manage and operate their transportation assets [47]. However, operating and maintaining existing assets is a sophisticated process and requires complicated decision-making since state DOTs need to identify for each asset a defined management strategy, select priority assets, and make cross-asset resource allocation decisions that would consider multiple objectives [42]. Moreover, transportation asset management requires the existence of spatial metadata with heterogeneous data features coming from multi-sources, in addition to data throughout the asset lifecycle, that is, asset history (e.g., as planned asset data), the current state of the asset (e.g., as-constructed asset data), and real-time data about the asset condition to allow for asset condition monitoring and control. Given the relatively extended life of assets, state DOTs need to use tools and technologies that will enable them to access reliable and informative data to support a lifecycle management approach and adopt data management approaches that can evolve with the evolution of technologies and future data requirements.

Furthermore, asset management can be explained as the task of connecting the fundamental mission of an organization of operating the infrastructure, that is, connecting the digital aspect of the asset and its physical aspect to ensure better asset operation and maintenance and support decision making [48]. This concept of asset management of connecting the physical and digital aspects of assets intersects with the concept of Digital Twins for infrastructure [40]. As such, with the capabilities of Digital Twins in supporting decision-making by providing one source of data registry and a simulation environment to allow for the conduction of prognostic and diagnostic maintenance, in addition to its ability to integrate multi-sourced data and provide enhanced data visualizations, the concept of Digital Twins can be adopted by state DOTs to transform their way of designing, delivering, and operating and maintaining their transportation assets. However, to optimize the use of the concept of Digital Twins, a holistic Digital Twin for the highway system is necessary, since a globalized highway Digital Twin includes informative data about all assets constituting a highway ecosystem and how they interact with each other and with the surrounding environment, thus allowing state DOTs to have better insights toward managing cross-asset systems and make decisions on resource allocation to optimize the performance of cross-asset systems, and the overall highway system.

5.2 How to achieve the vision for a holistic Digital Twin for a highway system

After identifying *Why* is a holistic Digital Twin for a highway system is needed, it is important to understand how the vision can be translated into action. The best way to fulfill this understanding is to learn from leading organizations that succeeded in putting visions into practice. A case study is a form of qualitative research that offers an in-depth examination of the topic [48]. The case study presented in this section started as a vision where the facility management department within the Sydney

Opera House imagined having a 3D model of the facility where they can fly around, select different assets, and view all the related information in one system. This vision was put into practice, where a Digital Twin providing a single source of information for regular building operational requirements and ongoing projects was created.

5.2.1 Digital Twins from vision to action: a facility management case study

The Sydney Opera House was added to UNESCO's World Heritage List in 2007 and is a multi-venue performing art center located at Sydney Harbor in Sydney, New South Wales, Australia. It is one of the country's most iconic and distinctive buildings. The building welcomes more than 8.2 million visitors a year, presenting more than 2000 shows 363 days a year for more than 1.5 million people [49]. The management and maintenance of the building are very challenging because of the special purpose that the building serves and the required technicalities, for instance, when the Sydney Symphony Orchestra is on stage in the concert hall, the room temperature must be maintained at 22.5 degrees to ensure the instruments stay in tune [50]. The building has more than 1000 rooms and managing the use of spaces is dynamic. For instance, spaces might be used for other purposes such as using lifts as dressing rooms for certain shows, partitioning different rooms, or merging spaces to expand the capacity and make use of the added space. The budget for the yearly maintenance of the Sydney Opera House amounts to $30 million AUS (equivalent to £16.5 million or $20.7 million) [51], thus aiming to reduce this high cost, the managers of the Sydney Opera House started investigating innovative solutions to support them in achieving their objective.

As such, in 2013 the BIM Academy (one of the world's leading research and strategic consultants in the global digital built environment established by Northumbria University and Ryder Architecture) won a worldwide tender for the contract to write a detailed BIM strategy to support the facility management (FM) of the Sydney Opera House. Writing the technical piece of the BIM-based facility management required a comprehensive review and thorough investigation of the existing disparate systems that were used to operate the building, methods of documentation, and the current approaches to information modeling. More than 350 interviews with the Sydney Opera House facility managers and employees were conducted to establish a roadmap and write a detailed technical specification for the BIM for FM interface that would connect the facility existing data and future data to the BIM model. The technical specification identified the requirements, developed a model management plan describing the process of developing the 3D models on site, and identified the information that should be included. This phase of the project facilitated the achievement of the second phase which is delivering the Digital Twins platform of the Sydney Opera House.

For the second phase of the project, the BIM Academy collaborated with AECOM (a global multidisciplinary consultancy), and EcoDomus (a leading software developer), to tender and subsequently win the delivery of a Digital Twin-enabled facility management platform for the Sydney Opera House. Alongside that, they won a bid to reformat their documentation system and their spatial management system by expanding their capacity to support the newly developed system. This phase of the project was executed in two stages. The first stage involved recouping and integrating information from the existing database with the newly established database within the 3D model. The second stage introduced a broader range of functional systems that can be added to the BIM interface over time. The aim was to improve the existing Technical Document database (TDOC) and develop a new spatial record management system. The new system encompasses the 3D model and will act as a parent system for all other sub-systems such as the document management system, spatial management system, asset register, and condition management system, and will support the establishment of one source of true data. TDOC will improve efficiency by eliminating wasted efforts and providing usability improvements. Changes such as updating the types of information that could be added to a document, editing information, adding functionalities to edit significant numbers of documents in bulk, and updating the system became more feasible and can be done promptly.

The vision of delivering a Digital Twin platform for the Sydney Opera House was thus achieved over two phases where each phase had several stages. Business analysis was first conducted, followed by comprehensive, structured research and a review of existing information systems and technical and IT infrastructure. Next, integration for systems was designed and innovative potential solutions were solicited. Then, model management was planned and a technical specification with a road map was established. Finally, Digital Twin delivery and implementation were achieved, and user approval, training, and testing were accomplished. The created Digital Twin platform enabled facility managers to have access to reliable geometry and to operate the building easily. Moreover, the platform is not only used by facility managers, but it can also be used by marketing teams to organize events and design and plan seats; security teams to plan logistics around new events; and site management, for instance, removing large bits of equipment and implementing others. The Sydney Opera House implemented the Digital Twin platform as an innovative solution to have better access to asset information, so they can have a diagnostic approach and solve problems promptly. It is expected that the feasible access to information would save on average 30 minutes per work order, for instance, if they have 20,000 work orders per year with an average cost of $50 per hour, they can save up to $500,000 per year. In the future, the Sydney Opera House is envisioning optimizing the use of the Digital Twin platform to support solving any future problems that they might face and keep updating the platform to manage any additional subsystems or any future advancement in data and technologies.

5.2.2 Digital Twins from vision to action: case of a highway system

State DOTs, responsible for managing and maintaining highway assets, have created, collected, and stored transportation asset data; however, the available data structures are not consistent, and they are either unstructured data (e.g., documents), semi-structured (e.g., excel data sheets), or structured data (e.g., databases). State DOTs are trying to improve their digitization capacity by collecting data in digital formats and abandoning the use of papers, improving the quality of collected data, and using automated and remote techniques to collect asset data [40]. However, data exist in isolated silos, with no further understanding of how these data should be integrated and managed. Therefore, to achieve the vision of Digital Twins for a highway system, state DOTs need to put a set of objectives and goals as a roadmap toward a holistic highway Digital Twin. Based on key takeaways from the presented Sydney Opera House case study and previous studies, state DOTs need to consider the following proposed objectives that should be considered for a successful implementation of Digital Twins for a highway system. These objectives include the following:

1. **Improving digital capacity.** State DOTs need to consider having a full data digitization lifecycle from “cradle to cradle” by enhancing digital design and construction, digital operation, and digital data integration with users. Designs should be enabled digitally, integrate automated construction when possible,

and adopt modular design and construction approaches. Moreover, enhancing the digital skills of workers to allow for smart asset management and support customer engagement by improving the digital capabilities of operations.

2. **Understand data architecture**. For each asset, state DOTs need to identify data sources and data requirements, identify the gaps in existing data, and look for additional resources to fill the information gaps.

3. **Set data management plans**. Data specifications and standards, and data governance (i.e., data rules, roles, and responsibilities) should be identified.

4. **Integrate existing management systems**. Structured research and review of any existing information system, such as asset management information systems (AMIS) or any other existing in-house management system whether it is used by the planning division or the maintenance division, should be considered for integration. Additionally, the use of existing databases should be planned for where the newly adopted Digital Twin platform should be designed to support this data integration.

5.3 What is the outcome resulting from the implementation of a holistic Digital Twin for a highway system

Implementing Digital Twins for the highway system will provide an innovative smart management system that integrates asset semantic and geometric data, in addition to spatial data based on the asset location and the surrounding environment. This based Digital Twin management system can support the monitoring and control of the asset condition promptly, employ an advanced machine-learning algorithm to predict the asset condition, and allow for conducting preventive and predictive maintenance.

The developed Digital Twin-based management system will allow for the integration of data extracted from BIM and GIS. BIM can provide rich geometric and semantic asset data including but not limited to asset models (i.e., available 2D models or 3D models), asset specifications, required level of details, asset documentation, data schemes, and ontologies. Additionally, GIS can integrate many types of data while analyzing the spatial location of the asset and organizing layers of information into visualizations using maps and 3D scenes. Moreover, GIS can handle and process spatial data of the individual physical asset, system of assets, and the surrounding environment. The integration of asset data extracted from BIM and GIS can provide a digital representation of the asset architectural entity and will support the management of spatial information of the asset and the surrounding environment, thus providing a better understanding of how the individual physical asset or system of assets interacts with its surrounding [52].

A Digital Twin can reflect the asset condition in a real-time manner; data collected using sensors or cyber-physical-systems (CPS) can also be integrated to allow for comprehensive control and monitoring of the asset or system of assets condition, thus allowing for the early detection of abnormalities and therefore enhancing preventive maintenance. Moreover, the Digital Twin platform can enable the conduction of what-if simulations by utilizing the digitally enhanced asset models, aggregated asset historical data, real-time data, and data related to factors that might affect the asset performance, for instance, data related to the temperature of the surrounding environment, thus allowing for predictive maintenance by simulating the future asset condition based on multi-sourced high quality and reliable data.

The Digital Twin-based management system will result in creating one source of true data, and the generation of a repository environment with simulation capabilities by making use of existing databases and systems. This data management system will release data from isolated silos, improve visualizations, enhance safety, optimize asset performance, allow for better resource allocation, and support data-driven decision-making.

6. Conclusions

Governments and organizations worldwide are investigating innovative approaches to change the design and delivery of civil infrastructure systems, with the ultimate objective of constructing and operating more resilient and sustainable infrastructure that would support equity, enhance safety, and target urbanization. This aim was further emphasized with the shift toward digitizing assets to leverage the value of asset data and optimize the performance of infrastructure assets. As such, the concept of smart infrastructure emerged, that is, connecting the physical aspect of the assets with its digital aspect by the bidirectional communication of information. Smart infrastructure also aligns with the concept of Digital Twins, or the digital representation of physical assets. Given the potential of Digital Twins, several organizations, researchers, and practitioners investigated the implementation of the concept in the civil infrastructure industry.

The concept of Digital Twins in the civil infrastructure industry is not mature yet; however, the adoption of the concept was investigated to address several problems related mainly to the operation and management of infrastructure systems. Few studies have investigated the implementation of Digital Twins throughout the lifecycle of infrastructure projects, but these studies mainly presented a framework for implementation. Additionally, Digital Twins can be applied at different spatial scales including the national level such as the National Digital Twin (NDT) initiative by the UK, on the city level to help with urban planning such as Virtual Singapore and BRISE-Vienna, or for a network of assets such as the vision for Digital Roads or the implementation of Digital Twins as a management information system.

This chapter also presented the journey toward a holistic Digital Twin for a highway system. The Why, How, and What components were investigated. A holistic Digital Twin will support managing cross-asset systems, and how they interact with each other and with the surrounding environment. Moreover, to understand how to translate the vision to practice, a case study related to the implementation of BIM for facility management of the Sydney Opera House was presented and recommendations on implementing a holistic Digital Twin for a highway system were discussed. Finally, data integration between BIM and GIS with the aid of the integration of real-time data about the asset condition, and employment of machine learning algorithm was proposed for a successful implementation of a Digital Twin-based management system that can integrate existing subsystems and make use of existing databases. The proposed smart data management system will allow for conducting preventive and predictive maintenance, support visualization, release data from isolated silos, allow for feasible access to data by creating one source of true data, and enhance decision-making to optimize the overall performance of the highway system.

Acknowledgements

The authors would like to thank Dr. Graham Kelly, director at BIM Academy for providing information about the presented case study.

Author details

Ashtarout Ammar*, Hala Nassereddine and Gabriel Dadi
University of Kentucky, Lexington, KY, USA

*Address all correspondence to: ashtrout.ammar@uky.edu

References

[1] WHO Coronavirus (COVID-19) Dashboard [Internet]. World Health Organization. 2022. Available from: https://covid19. who.int/ [Accessed: 8 August 2022]

[2] Tonne C. Lessons from the COVID-19 pandemic for accelerating sustainable development. Environmental Research. 2021;**193**:110482

[3] Ogunbiyi D. Opinion: Power in a pandemic—Why energy access matters during coronavirus [Internet]. 2020. Available from: https://news.trust.org/item/20200331134807-w6a0h/ [Accessed: 8 August 2022]

[4] Saldinger A. AIIB launches health infrastructure investments in response to COVID-19 [Internet]. 2020. Available from: https://www.devex.com/news/aiib-launches-health-infrastructure-investments-in-response-to-covid-19-96958 [Accessed: 8 August 2022]

[5] Cheshmehzangi A. Revisiting the built environment: 10 potential development changes and paradigm shifts due to COVID-19. Journal of Urban Management. 2021;**10**(2):166-175

[6] Balasubramanian S, Shukla V, Islam N, Manghat S. Construction industry 4.0 and sustainability: An enabling framework. IEEE Transactions on Engineering Management. 2021:1-19. DOI: 10.1109/TEM.2021.3110427

[7] Forcael E, Ferrari I, Opazo-Vega A, Pulido-Arcas JA. Construction 4.0: A literature review. Sustainability. 2020;**12**(22):9755

[8] HM Government. Industrial Strategy Construction Sector Deal [Internet]. London, United Kingdom. 2018. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/731871/construction-sector-deal-print-single.pdf

[9] ASCE. ASCE Statement on President Biden Signing the Infrastructure Investment and Jobs Act into Law [Internet]. American Society of Civil Engineers. Washington, DC, United States. 2021. Available from: https://www.asce.org/publications-and-news/civil-engineering-source/society-news/article/2021/11/15/asce-statement-on-president-biden-signing-the-infrastructure-investment-and-jobs-act-into-law?utm_campaign=GR-2022-5-20-TWiW%20Email%20Short&utm_medium=email&utm_source=Eloqua [Accessed: 20 July 2021]

[10] Updated Fact Sheet: Bipartisan infrastructure investment and jobs act [Internet]. The White House. 2021. Available from: https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/02/updated-fact-sheet-bipartisan-infrastructure-investment-and-jobs-act/#:~:text=The%20bipartisan%20%20Infrastructure%20Investment%20%20and%20Jobs%20Act%20will%20%20invest%20%24110,of%20committee%20%20earlier%20this%20year [Accessed: 20 July 2021]

[11] Obando S. Construction Techies Laud $100M in Infrastructure Act, Push for More [Internet]. Construction Dive. Washington, D.C., United States. 2021. Available from: https://www.constructiondive.com/news/construction-tech-praise-110-million-infrastructure-bill-push-for-more/610126/

[12] Bowers KA, Buscher, Dentten R, Edwards MB, England J, Enzer M, et al. Smart Infrastructure Getting more from strategic assets. [Internet]. Centre for Smart Infrastructure and Construction. 2016. Available from: https://www-smartinfrastructure.eng.cam.ac.uk/system/files/documents/the-smart-infrastructure-paper.pdf

[13] Bolton A, Butler L, Dabson I, Enzer M, Evans M, Fenemore T, et al. Gemini principles [Internet]. Apollo—University of Cambridge Repository. 2018. Available from: https://www.repository.cam.ac.uk/handle/1810/284889 [Accessed: 11 December 2021]

[14] Ammar A, Nassereddine H, AbdulBakyN, AbouKansourA, TannouryJ, Urban H, et al. Digital Twins in the construction industry: A perspective of practitioners and building authority. Frontiers in Built Environment. 2022;**8**:834671

[15] Ammar A, Nassereddine H. Blueprint for construction 4.0 technologies: A bibliometric analysis. IOP Conference Series: Materials Science and Engineering. 2022;**1218**(1):012011

[16] Niederer SA, Sacks MS, Girolami M, Willcox K. Scaling Digital Twins from the artisanal to the industrial. Nature Computational Science. 2021;**1**(5):313-320

[17] Negri E, Fumagalli L, Macchi M. A review of the roles of Digital Twin in CPS-based production systems. Procedia Manufacturing. 2017;**11**:939-948

[18] Kritzinger W, Karner M, Traar G, Henjes J, Sihn W. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine. 2018;**51**(11):1016-1022

[19] Tao F, Qi Q, Wang L, Nee AYC. Digital Twins and cyber-physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. Engineering. 2019;**5**(4):653-661

[20] Wanasinghe TR, Wroblewski L, Petersen BK, Gosine RG, James LA, De Silva O, et al. Digital Twin for the oil and gas industry: Overview, research trends, opportunities, and challenges. IEEE Access. 2020;**8**:104175-104197

[21] Brilakis I, Pan Y, Borrmann A, Mayer HG, Rhein F, Vos C, et al. Built environment Digital Twinning. In: Report of the International Workshop on Built Environment Digital Twinning Presented by TUM Institute for Advanced Study and Siemens AG. Germany: Technical University of Munich; 2019

[22] Vieira J, Poças Martins J, Marques de Almeida N, Patrício H, Gomes MJ. Towards resilient and sustainable rail and road networks: A systematic literature review on Digital Twins. Sustainability. 2022;**14**(12):7060

[23] Broo DG, Schooling J. Digital Twins in infrastructure: Definitions, current practices, challenges and strategies. International Journal of Construction Management. 2021:1-10. DOI: 10.1080/15623599.2021.1966980

[24] Callcut M, Cerceau Agliozzo JP, Varga L, McMillan L. Digital Twins in civil infrastructure systems. Sustainability. 2021;**13**(20):11549

[25] Costin A, Adibfar A, Hu H, Chen SS. Building information modeling (BIM) for transportation infrastructure—Literature review, applications, challenges, and recommendations. Automation in Construction. 2018;**94**:257-281

[26] Shim CS, Dang NS, Lon S, Jeon CH. Development of a bridge maintenance

system for prestressed concrete bridges using 3D Digital Twin model. Structure and Infrastructure Engineering. 2019;**15**(10):1319-1332

[27] Jiang F, Ding Y, Song Y, Geng F, Wang Z. An architecture of lifecycle fatigue management of steel bridges driven by Digital Twin. Structural Monitoring and Maintenance. 2021;**8**(2):187-201

[28] Kampczyk A, Dybeł K. The fundamental approach of the Digital Twin application in railway turnouts with innovative monitoring of weather conditions. Sensors. 2021;**21**(17):5757

[29] Kochan A. Digital Twin concept of the ETCS application. WUT Journal of Transportation Engineering. 2020;**131**: 87-98

[30] Kim J, Kim SA. Lifespan prediction technique for Digital Twin-based noise barrier tunnels. Sustainability. 2020;**12**(7):2940

[31] Yu G, Wang Y, Mao Z, Hu M, Sugumaran V, Wang YK. A Digital Twin-based decision analysis framework for operation and maintenance of tunnels. Tunnelling and Underground Space Technology. 2021;**116**:104125

[32] Yu G, Zhang S, Hu M, Wang YK. Prediction of highway tunnel pavement performance based on Digital Twin and multiple time series stacking. Lin JR, editor. Advances in Civil Engineering. 2020;**2020**:1-21

[33] Meža S, Mauko Pranjić A, Vezočnik R, Osmokrović I, Lenart S. Digital Twins and road construction using secondary raw materials. Biancardo SA, editor. Journal of Advanced Transportation. 2021;**2021**:1-12

[34] Rounds D. Design for maintainability: The importance of operations and maintenance considerations during the design phase of construction projects [Internet]. Whole Building Design Guide. 2018. Available from: https://www.wbdg.org/resources/design-for-maintainability [Accessed: 20 August 2022]

[35] National Infrastructure Commission. Data for the Public Good [Internet]. London, United Kingdom. 2017. Available from: https://nic.org.uk/app/uploads/Data-for-the-Public-Good-NIC-Report.pdf

[36] Deloitte. New technologies case study: Data sharing in infrastructure [Internet]. London, United Kingdom. 2017. Available from: https://nic.org.uk/app/uploads//Data-sharing-in-infrastructure.pdf

[37] Ider Batbayar. Virtual Singapore: A Digital "Twin" For Planning [Internet]. 2022. Available from: https://city2city.network/virtual-singapore-digital-twin-planning-innovation-type-institutional-pioneer [Accessed: 10 August 2022]

[38] National Highways. Digital Roads [Internet]. Birmingham, United Kingdom. 2021. Available from: https://nationalhighways.co.uk/media/2chotw13/introducing-digital-roads.pdf

[39] National Highways.Digital Roads 2025 Roadmap [Internet]. Birmingham, United Kingdom. 2021. Available from: https://nationalhighways.co.uk/media/r3nn1h3m/digital-roads-2025-interactive-roadmap_final.pdf

[40] Ammar A, Nassereddine H, Dadi G. State departments of transportation's vision toward Digital Twins: Investigation of roadside asset data management current practices and future requirements. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. 2022;**V-4-2022**:319-327

[41] Utah Department of Transporation (UDOT). Digital Twin Strategic Plan [Internet]. Taylorsville, Utah, United States. 2021

[42] AASHTO TAM Guide [Internet]. American Association of State Highway Transportation Officials (AASHTO). Washington, D.C., United States. 2022 Available from: https://www.tamguide.com/guide/

[43] Federal Highway Administration (FHWA). Handbook for Including Ancillary Assets in Transportation Asset Management Programs [Internet]. Washington, DC, United States. 2019. Available from: https://www.fhwa.dot.gov/publications/research/infrastructure/19068/19068.pdf

[44] Le T, Le C, David Jeong H. Lifecycle data modeling to support transferring project-oriented data to asset-oriented systems in transportation projects. Journal of Management in Engineering. 2018;**34**(4):04018024

[45] National Academies of Sciences, Engineering, and Medicine. Guidebook for Data and Information Systems for Transportation Asset Management. Washington, DC, United States: The National Academies Press; 2021. DOI: 10.17226/26126

[46] Ammar A, Dadi G, Nassereddine H. Transportation asset data management: BIM as a holistic data management approach. In: Construction Research Congress 2022 [Internet]. Arlington, Virginia: American Society of Civil Engineers; 2022. pp. 208-217. Available from: http://ascelibrary.org/doi/10.1061/9780784483954.022 [Accessed: 8 August 2022]

[47] Rahn PK. State DOT Mission Evolution. American Association of State Highway and Transportation Officials (AASHTO). Washington, DC, United States. 2013. p. 30 Report No.: NCHRP Project 20-24 (84)

[48] Marczyk GR, DeMatteo D, Festinger D. Essentials of research design and methodology. Hoboken, New Jersey, United States: John Wiley & Sons; 2010

[49] Sydney Opera House [Internet]. 2022. Available from: https://www.gatherlearning.com/institutions/sydney-opera-house [Accessed: 12 August 2022]

[50] Interesting Facts About the Sydney Opera House [Internet]. 2022. Available from: https://www.sydneyoperahouse.com/our-story/sydney-opera-house-facts.html [Accessed: 12 August 2022]

[51] Elaine Knutt. Sydney Opera House Trials New BIM for F.M. Service [Internet]. 2014. Available from: https://www.bimplus.co.uk/sydney-ope5ra-hous2e-tria1ls-new-bim-fm-service/ [Accessed: 12 August 2022]

[52] Ammar A, Dadi G. Towards an integrated Building Information Modeling (BIM) and Geographic Information System (GIS) platform for infrastructure. In: Feng C, Linner T, Brilakis I, Castro D, Chen PH, Cho Y, et al., editors. Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC). Dubai, UAE: International Association for Automation and Robotics in Construction (IAARC); 2021. pp. 129-136