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Digital Twin Technologies for Smart and Sustainable Infrastructure: Recent Advances, Applications, and Future Directions

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Abstract
The Digital Twin (DT) technology is one of the digital technologies that have been developed as a means of transforming the way of planning, operation, monitoring and management of infrastructure systems. The use of Digital Twin technology along with other advanced digital technologies has facilitated the development of sustainable infrastructure systems. This study offers a review of DT technologies with emphasis on its evolution, enablers, applications in infrastructure systems, contribution to sustainability, infrastructure monitoring and asset management, and research agenda. A comprehensive literature review was done using scholarly articles collected from Google Scholar search engine. In relation to the DT evolution, enablers, infrastructure application areas, sustainability, monitoring methods, and implementation challenges, relevant studies have been comprehensively searched and analysed based on the thematic synthesis approach. It can be concluded from this review that DTs have moved from being static digital representations to being intelligent cyber-physical systems that can perform tasks such as real-time monitoring, predictive analysis, and data-driven decision-making. Applications of DTs range from building infrastructure, transport infrastructure, bridge infrastructure, water infrastructure, and cultural infrastructure, where they play a role in improving efficiency, predictive maintenance, asset lifecycle management, and sustainability. Nevertheless, challenges such as interoperability, standardisation, cybersecurity, scalability, and cost of implementation still restrict the wide use of DT technology. The DT technology is an important enabler of digital transformation towards smart and sustainable infrastructure. Further research in intelligent analysis, interoperable frameworks, and collaborative implementation approaches will enhance the adoption of DT technology.

Keywords:

- Digital Twin
- Smart Infrastructure
- Sustainable Infrastructure
- Asset Lifecycle Management
- Predictive Maintenance.

1. Introduction

The rapid digitalization of infrastructures has completely transformed the process of designing, building, operating, and maintaining physical assets. The use of digital technologies has gained rapid traction in the field of infrastructure owing to the increased rate of urbanization, the aging infrastructure, growing population size, and the need for reliable public services. The conventional techniques used in infrastructure management, which include conducting periodic inspections and documenting such information, are typically not adequate to deal with the dynamic nature of the modern infrastructure. Real-time monitoring, intelligence through analysis, and decision making using data are the qualities of digital technologies of keen interest nowadays. One such technology is Digital Twin (DT), which has proven to be one of the most interesting technologies to support efficient and intelligent infrastructure management through networking of physical assets and their digital counterparts (Liu et al., 2023).

The concept of DT has changed mere digital simulation of physical processes into intelligent virtualization of them through which they can interact continuously with the real-world assets. In comparison to the traditional simulation techniques, DT technology integrates real-time data sensing, computations, and analytics capabilities to provide accurate representations of performance of infrastructure throughout its life cycle. The development of Internet of Things (IoT), cloud computing, artificial intelligence, and communication technologies has led to this evolution, allowing infrastructure managers to track the status of assets, anticipate failures and improve the operation efficiency. DT technologies are gaining traction in terms of their implementation in the context of different fields of infrastructure, such as transportation, civil engineering, urban planning, and heritage asset management (Al-Sehrawy et al., 2021).

The increased focus on smart and sustainable infrastructure has also increased the significance of the DT technology. Smart infrastructure is an integration of digital technologies to enhance operational efficiency, resource utilisation, safety and service delivery whilst sustainable infrastructure is intended to ensure long-term economic and social benefits are maximised and environmental impacts are minimised. DTs support these goals by allowing the constant monitoring of the assets, predictive maintenance, consumption optimisation, and making evidence-based decisions during the lifecycle of the assets. They have been used in intelligent transportation systems, smart mobility, renewable energy networks, and heritage infrastructure, showing that they can be used to increase the resilience of infrastructures and facilitate sustainable urban development (Chang et al., 2024; Faliagka et al., 2024; Hou et al., 2024).

This has brought about the necessity of DT technology in the infrastructure lifecycle, which includes planning, design, construction, operation, maintenance, rehabilitation, and eventual replacement of the assets. By synchronising physical and virtual environment in real time, infrastructure owners are able to detect performance problems, optimize maintenance plans, save on operations and enhance reliability of the infrastructure. Moreover, DTs aid in proactive maintenance and predictive analytics, which promote asset management and minimise unforeseen breakdowns and service life. They are also playing a role in innovating intelligent transportation, renewable energy systems, and sustainable infrastructure management due to their integration with the emerging technologies, which emphasizes their increasing role in the future digital ecosystems (Mahmoodian et al., 2022; Gu et al., 2025; Al-Shetwi

et al., 2025).
While there have been many studies that have explored various applications of the DT technology, a systematic review on the enabling technologies, sustainability, infrastructure monitoring, and future research direction is still lacking. This review seeks to provide an overall summary on DT technologies for smart and sustainable infrastructure through exploring the evolution of DT technologies, the enabling technologies, DT applications in infrastructure, the contribution of DT towards sustainability, application of DT in infrastructure monitoring and asset management, and current challenges and future research direction. It is hoped that this review will also be able to highlight the current trends and future opportunities that could be leveraged for the design of resilient and sustainable infrastructure.

2. Methodology

A comprehensive review was performed in order to make generalizations from the scientific literature on the DT technologies for smart and sustainable infrastructure. The peer-reviewed journal articles were selected with the help of Google Scholar database according to their relevance. The systematic review focused on original research articles, review articles, and survey research related to DT technology and excluded the non-peer reviewed articles and those that were not specifically connected with infrastructure application. The keyword searching strategy was based on different combinations of keywords such as DT, smart infrastructure, sustainable infrastructure, civil infrastructure, Building Information Modelling (BIM), Internet of Things (IoT), Artificial Intelligence, structural health monitoring, and asset management. Studies selected according to the title and abstract were further screened according to their full text in order to ensure their relevance. The selected papers were subsequently categorized according to the following themes: DT technology development, DT technology possibilities, infrastructure applications, sustainability, and monitoring and management of infrastructure, as well as future research directions. Synthesis of the findings was done to determine key trends, applications and research gaps. The general outline of the review process, such as identification of literature, screening, thematic classification, and synthesis of evidence, are presented in Figure 1.

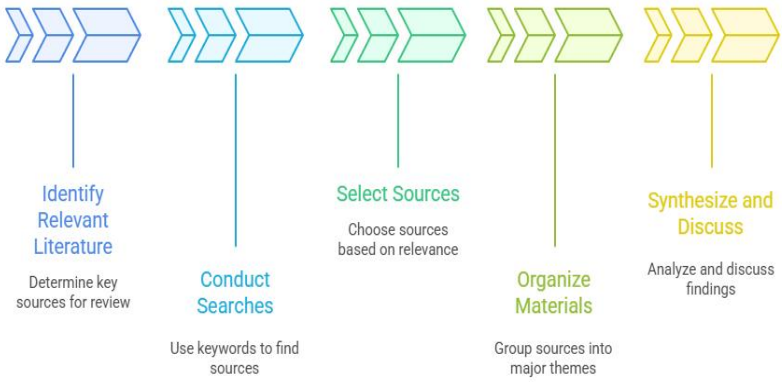

Figure 1. Overview of the Comprehensive Review Process

Figure 1 presents an overview of the comprehensive review process followed in this study. The workflow involves five steps: literature identification, screening of the retrieved literature for eligibility, selection of relevant publications, categorisation of literature in the main review domains and the synthesis of the results. The structured approach provided a comprehensive analysis of existing literature and allowed for coherent understanding of recent developments, applications, sustainability issues, infrastructure monitoring, and prospects of Digital Twin technologies for smart and sustainable infrastructure.

3. Results

3.1 Evolution and Core Concepts of DT Technology

DT technology is a development of conventional digital models, and is now described as an intelligent cyber-physical system that can continuously represent and interact with real-world infrastructure assets. Early digital models were mainly used as representations of static designs for limited analysis. Later, digital shadows added the capability of sending data from physical resources to virtual resources to monitor their conditions. With recent advancements, these systems have become full-fledged DTs with abilities to communicate in both directions, monitor in real time, simulate in the present future and make intelligent decisions during the entire lifecycle of the infrastructure. As a result, DTs are essential tools for planning, designing, constructing, operating, maintaining and asset optimising, enabling operational efficiency, resilience and sustainability. The major evolutionary stages and fundamental characteristics of DT technology are summarised in Table 1.

\Table 1. Evolution and Fundamental Characteristics of DT Technology

Aspect	Description	Reference
Digital Model	Static digital representation of a physical asset without continuous data exchange.	Shirowzhan et al. (2020)
Digital Shadow	One-way communication from physical assets to virtual models for monitoring purposes.	Sepasgozar (2021)
DT	Bidirectional real-time synchronisation between physical and virtual systems for prediction and optimisation.	Qian et al. (2022)
Core Characteristics	Real-time connectivity, simulation, interoperability, predictive analytics, and intelligent decision support.	Wang et al. (2023)
Infrastructure Lifecycle Perspective	Supports planning, construction, operation, maintenance, rehabilitation, and end-of-life asset management.	Naderi and Shojaei (2022)

3.2 DT Architecture and Enabling Technologies

The effective deployment of DT technology depends on the incorporation of different technological capabilities, which help in managing infrastructures through intelligence. The IoT devices and smart sensors constantly capture data related to operations, whereas BIM and GIS provide an accurate representation of infrastructure assets in terms of space and structure. Artificial Intelligence and Machine Learning help in making predictions about anomalies and other decisions. Cloud computing and edge computing ensure large-scale storage of data and processing at lower latency, whereas big data analytics ensures the derivation of useful insights from different data sources. Blockchain technology helps in ensuring data integrity, transparency, and security, and cyber-physical systems help in interacting with physical infrastructure by integrating with digital environment. The important enabling technologies behind DT deployment are provided in Table 2.

Table 2. Key Enabling Technologies Supporting DT Systems

Technology	Role in DT Systems	Reference
Internet of Things (IoT)	Enables continuous connectivity and real-time data acquisition from infrastructure assets.	Mihai et al. (2022)
Smart Sensors	Monitor structural, environmental, and operational conditions in real time.	Hakimi et al. (2023)
Building Information Modelling (BIM)	Provides comprehensive digital representation throughout the asset lifecycle.	Badenko et al. (2024)
Geographic Information Systems (GIS)	Supports spatial analysis and geospatial visualisation of infrastructure assets.	Shirowzhan et al. (2020)
Artificial Intelligence (AI)	Enables intelligent prediction, optimisation, and automated decision support.	Wu et al. (2022)
Machine Learning (ML)	Detects anomalies and predicts infrastructure deterioration using historical data.	Iranshahi et al. (2025)
Cloud Computing	Offers scalable storage and high-performance computational resources.	Wang et al. (2023)
Edge Computing	Facilitates low-latency processing near data sources for real-time applications.	Jafari et al. (2023)
Big Data Analytics	Processes heterogeneous datasets for infrastructure performance assessment.	Wang et al. (2023)
Blockchain	Ensures secure, transparent, and traceable data sharing across platforms.	Matei and Cocoșatu (2024)

Cyber-Physical Systems	Integrates physical infrastructure with digital environments through continuous interaction.	Qian et al. (2022)

3.3 Applications of DT Technologies in Smart Infrastructure

There have been numerous applications of DT technology across various infrastructure sectors owing to its potential to enable intelligent monitoring, maintenance, operations, and lifecycle management. In terms of built environment, there are various uses of DTs in improving building performance, facilities management, and sustainable construction. There is better traffic management, assessment, safety monitoring, and maintenance associated with transportation infrastructures such as roads, bridges, railway tracks, and airports. DTs are being used for optimizing network, leak detection, and resource management in water infrastructure, while virtual replicas of heritage infrastructures are utilized in conservation planning. More recently, the application of DT technology has extended to geotechnical engineering through real-time monitoring of subsurface structures. The major infrastructure sectors and their applications with DT technology are presented in Table 3.

Table 3. Applications of DTs Across Infrastructure Sectors

Infrastructure Sector	Major Applications	Reference
Buildings	Facility management, energy optimisation, occupancy analysis, and lifecycle management.	Omrany et al. (2023)
Bridges	Structural health monitoring, damage detection, and predictive maintenance.	Mousavi et al. (2024)
Roads	Pavement condition monitoring and maintenance planning.	Liu et al. (2023)
Transportation Systems	Traffic optimisation, intelligent mobility, and infrastructure management.	Chang et al. (2024)
Railways	Infrastructure inspection, operational efficiency, and predictive maintenance.	Gao et al. (2025)
Airports	Asset monitoring, operational management, and resource optimisation.	Wang et al. (2023)
Water Infrastructure	Leakage detection, water distribution monitoring, and resource optimisation.	Jafari et al. (2023)
Heritage Infrastructure	Digital preservation, conservation planning, and facility management.	Hou et al. (2024)
Geotechnical Infrastructure	Ground deformation monitoring, stability assessment, and geotechnical risk management.	Tan et al. (2025)

3.4 DTs for Sustainable Infrastructure Development

DT technology has emerged as a key enabler for sustainable infrastructure, and can be used to foster environmental, economic and social sustainability across the asset lifecycle. DTs increase the efficiency of infrastructure, avoid any form of wastage of resources, and provide opportunities for continuous surveillance, real-time integration of information and simulation predictions. These capabilities contribute to the optimisation of energy consumption, reduction of wastage of material, and the efficiency of the process, which all reduce greenhouse gas emissions and increase environmental performance. The combination of DTs with advanced analytics tools also makes it possible for the managers of the infrastructure to simulate various operations and make informed decisions in order to ensure sustainability (Zahedi et al., 2024; Tan & Li, 2024).

Besides being environmentally sustainable, DTs can also have a great impact on the economic and social sustainability of assets, through optimizing their life span, reducing their maintenance expenses, and increasing their service reliability. The implementation of predictive maintenance practices leads to decreasing the probability of unexpected failures and allows optimizing resource utilization and becoming cost-effective for managing the infrastructure. Also, DTs contribute to applying circular economy principles, by optimizing the asset's usage, recycling information about its construction and planning future rehabilitations. Besides that, DTs help in increasing social sustainability due to the following factors: infrastructure resilience, safety of public and decision making of stakeholders for improving society infrastructure systems (Omrany et al., 2024; Badenko et al., 2024; Al-Shetwi et al., 2025).

3.5 DT for Infrastructure Monitoring and Asset Management

DT technology has brought about a change in the way that infrastructure is monitored as it enables continuous monitoring of the state of the assets through integration with sensors, real-time data acquisition and intelligent analytical models. DTs ensure that there is synchronisation between the physical asset and the virtual counterpart, thereby providing a true reflection of how the infrastructure is behaving. This feature can enable timely maintenance actions which will result in minimal disruption and enhance the reliability and safety of the infrastructure systems. The use of DT technology allows infrastructure managers to shift from maintenance to predictive maintenance of the infrastructure, enhancing its efficiency (Mahmoodian et al., 2022; Sakr & Sadhu, 2024; Sun et al., 2024).
DTs also facilitate full asset lifecycle management, combining inspection history, past maintenance information, environmental influences, and predictive models within a single decision support system for assets. This integration can help to enhance risk assessment, maintenance scheduling and simulating potential failure scenarios prior to them occurring. In addition, DTs can help with disaster preparedness and infrastructure resilience, enabling engineers to simulate the effect of disasters and take proactive measures to mitigate them. As infrastructure networks are increasingly complex, DTs continue to serve as an important tool for the efficient management of infrastructure assets, increasing their lifespan, and enabling data-driven infrastructure governance (Liu et al., 2023; Mousavi et al., 2024; Wang et al., 2023).

3.6 Challenges and Future Directions

Although the development of DT has been progressing rapidly, there are some technical and organisational issues that act as bottlenecks in implementing this technology in infrastructure systems. The main issues in implementing the DT technology include data interoperability, the absence of standards of framework, cybersecurity, privacy, high computing power, high costs of implementation, and scalability. These issues need to be tackled by collaboration among researchers, the industry, and policy makers. Future research will most likely focus on autonomous DTs using AI, cloud-edge collaboration computing, data interoperability, resilient cyber physical systems, and sustainable digital infrastructures. The major issues and future research directions have been described in Table 4 below.

Table 4. Challenges, Limitations, and Future Research Directions

Challenge	Future Research Direction	Reference
Data interoperability	Development of unified data exchange standards and interoperable platforms	Naderi & Shojaei (2022)
Standardisation	Establishment of internationally accepted DT frameworks and protocols	Mihai et al. (2022)
Cybersecurity	Development of secure communication architectures and cyber-resilient DT systems	Wang et al. (2023)
Privacy	Privacy-preserving data governance and secure information management	Matei & Cocoşatu (2024)
High computational requirements	Integration of cloud-edge computing and high-performance AI algorithms	Qian et al. (2022)
High implementation cost	Development of modular and cost-effective DT solutions	Omrany et al. (2023)
Scalability	Scalable DT architectures for large infrastructure networks	Iranshahi et al. (2025)
Regulatory issues	Policy development, governance frameworks, and ethical guidelines	Mazzetto (2024)
Future opportunities	Autonomous DTs, Generative AI integration, digital sustainability, and intelligent infrastructure ecosystems	Kim et al. (2025)

4. Discussion

It is evident from the outcomes of this review that DT has rapidly evolved into a fully functional digital framework capable of aiding the management of intelligent infrastructure through the entire asset life cycle. From the literature reviewed, it can be concluded that DTs are not limited to being virtual models but also serve as platforms for real-time monitoring, predictive analysis, and decision-making. The wide adoption of applications in various infrastructure sectors indicates the versatility and capability of DTs in optimizing resource management, enhancing infrastructure resilience, and increasing operational efficiency. Moreover, the facilitating technologies such as Internet of Things, artificial intelligence, building information modeling, cloud computing, and geographic information systems add to the capabilities of DT systems. Overall, these technologies imply that DTs are likely to play an important role in the future of infrastructure management by facilitating proactive maintenance and improved performance of systems.

This review is consistent with previous studies that show that DT is being increasingly utilized in the constructed world. Another aspect that Mousavi et al. (2024) observed was that the DTs are not merely monitoring instruments anymore but rather smart lifecycle management platforms, predictive maintenance, and infrastructure optimisation. The results of the current review are also in line with the findings of Sepasgozar et al. (2023), who emphasized the role of integration of BIM and DT in the future of digital construction and enhanced information management throughout the life cycles of projects. Equally, the review has also noted the increasing use of DTs in the transportation infrastructure, which has been complemented by the comprehensive analysis conducted by Wu et al. (2025), which indicated their usefulness in optimising traffic, monitoring transportation infrastructure, and smart transportation management. In this regard, the Omrany and Al-Obaidi (2025) research offers another justification of the usefulness of DTs in meeting the sustainability targets, e.g., maximising the urban environmental performance through Urban Heat Island mitigation applications. Moreover, the focus on predictive maintenance and structural health monitoring noted in this review aligns with the findings of Riffat et al. (2025), which indicated that DT-based monitoring can greatly improve the reliability, safety, and maintenance efficiency of infrastructure.

The findings have a tremendous practical significance not only for the scientists but also for those who deal with the issues of infrastructure management, engineering and policymaking. In addition, DTs may be helpful in proving the need for the planning of infrastructure, optimization of the maintenance schedule, making the best use of assets and ensuring sustainability through efficient management of resources at a much bigger scale. Moreover, DTs have substantial application potential in the area of resilient infrastructure that is able to cope with changes in environmental and operating conditions.

However, there are still some drawbacks. Many current applications focus on a particular sector of infrastructure or are in a pilot phase and therefore the results cannot be transferred to other applications. Data interoperability and cyber security are technical issues still hampering the widespread adoption; also, the high costs of implementation, the need for computation, and the lack of universally accepted standards. Moreover, the models of DTs and approaches to their evaluation vary among studies, making it hard to compare these studies and increasing the need for standardization in future studies.

Future research needs to be directed towards creating interoperable DT frameworks that can integrate multiple infrastructure systems with heterogeneous data sources. However, there's a need for more focus on scalable architectures, robust Data Governance, autonomous decision-support systems, and the integration of new technologies like Generative Artificial Intelligence, edge intelligence, and sophisticated predictive analytics. Further validation over the longer term across real-world implementations in various infrastructure sectors will help to build the evidence base and accelerate the uptake of DT technology in the development of smart and sustainable infrastructure.

5. Conclusion

The emergence of DT technology can be considered a revolutionary step towards development of smart and sustainable infrastructure through continuous interaction between the physical entity and its virtual counterpart. In this context, the current study has presented a synthesis of recent advancements of DT technology, emphasizing the advancement from simple digital models to advanced cyber-physical systems through enabling technologies such as Internet of Things, Artificial Intelligence, Building Information Modelling, Geographic Information System, cloud computing, and data analytics. It is also evident from the current review that DT technology is being applied extensively in the domain of buildings, transportation systems, bridges, water distribution systems, heritage infrastructure, and civil infrastructure among others. One of the conclusions from this review is the use of DTs in the creation of sustainable infrastructure through resource optimization, better decision-making, lower operating costs, and enhanced environmental sustainability. In spite of these benefits, interoperability issues, standardization problems, cyber security threats, scalability concerns, and high implementation costs hinder the broader application of DTs. These obstacles must be overcome if one wants to unlock all potentials offered by the technology for future infrastructures. On the whole, it can be concluded that DTs are a crucial technology that enables digital transformation in the field of infrastructure. Further technological innovations, multi-disciplinary efforts, and creation of standardized frameworks for implementation are bound to promote DTs' application for creation of sustainable infrastructure.

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