Proceedings of CONF-FMCE 2025 Symposium: AI and Machine Learning Applications in Infrastructure Engineering
DOI: 10.54254/2755-2721/2025.MH25388

Exploring the Use of Digital Twins in Infrastructure Operations and Maintenance

Lianghe Li[1*], Yihao Sun[1], Xiyuan Tang[1]

[1]Leeds College, Southwest Jiaotong University, Chengdu, China
**Corresponding Author. Email: 1977547196@qq.com*

Abstract. Traditional infrastructure operation and maintenance (O&M) models have long been plagued by issues such as low efficiency, insufficient accuracy, and high costs, primarily due to the subjectivity of human judgment, inadequate data processing capabilities, and poor resource management. To overcome these challenges, this study proposes the integration of digital twin technology into modern O&M systems. By establishing an intelligent management platform that enables bidirectional mapping between physical and virtual domains, the study aims to achieve fine-grained management of infrastructure throughout its entire lifecycle. Multi-source data collection and fusion technology based on the Internet of Things (IoT) addresses the issue of data silos in traditional operations and maintenance. Through analyses of typical cases such as urban transportation hubs, cross-sea bridges, and nuclear power plants, this technology has demonstrated significant effectiveness in risk warning, resource optimisation, and emergency response. Research indicates that the application of digital twin technology can improve operations and maintenance efficiency by over 40%, reduce costs by approximately 30%, and significantly enhance system safety and reliability. With the integration of new technologies such as 5G and edge computing, digital twins will drive infrastructure maintenance toward advanced stages of 'predictive maintenance' and 'autonomous decision-making,' providing critical technological support for the development of smart cities. Future research will focus on areas such as digital twin model lightweighting and multi-system collaborative optimisation to further expand its engineering application value.

Keywords: Infrastructure Operation, Digital Twins, Maintenance.

1. Introduction

Infrastructure operations and maintenance are a complex and critical task, primarily aimed at ensuring the continuous availability, performance, and security of physical and virtual systems. With a large number of infrastructure assets spread across wide geographical areas, their operation and maintenance involve significant workloads. In recent years, the acceleration of global urbanisation has driven rapid infrastructure development, making the improvement of infrastructure design, construction, operational maintenance and management efficiency a pressing issue to address.

Infrastructure lifecycle management encompasses five stages: planning, design, construction, operations and maintenance, and decommissioning. However, the emergence of digital twin

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2025.MH25388

technology has addressed the limitations of traditional infrastructure operations and maintenance methods. Traditional lifecycle management models have increasingly shown inefficiencies, insufficient cost and risk control, and a lack of a holistic lifecycle perspective. Digital twin technology, as an innovative technology that deeply integrates the physical world with the digital world, creates a digital copy that serves as a fully equivalent counterpart to a specific physical object. Unlike Building Information Modeling(BIM), Cyber-Physical System(CPS), and digital shadows, digital twins possess bidirectional interaction and full lifecycle coverage characteristics [1]. By constructing dynamic, real-time virtual models of infrastructure, digital twins apply knowledge and data-driven methods to monitor, manage, and improve products throughout their entire lifecycle, thereby optimising resource allocation, reducing operational costs, and enhancing system resilience, providing a new paradigm for lifecycle management. Baek et al. explored the applicability of digital twin technology in lifecycle operations and maintenance. With the rapid development of the Internet of Things, big data, and artificial intelligence, digital twin technology has become a key driver for the construction of smart cities and intelligent infrastructure.

Based on this, this paper focuses on the application of digital twin-driven technologies in the lifecycle maintenance of infrastructure, aiming to systematically explore the application models, key technologies, and implementation pathways of digital twin technology in the maintenance phase of infrastructure. By analysing typical cases and combining technological and industry trends, this paper proposes application frameworks and optimisation strategies suitable for different types of digital twin applications.

2. Usage requirement

2.1. Traditional O&M solutions

Traditional O&M solutions have problems in perception, decision-making mechanisms, resource misallocation, and high-risk operations due to technical limitations, such as low data collection efficiency, which can only build static models, and the inability to be integrated.

First of all, in the face of such a huge workload of infrastructure operation and maintenance, manual inspection is not only inefficient but also inaccurate. In addition, because data is divided into different parts, it is easy to form data islands. As a result, the ability to respond to emergencies decreases, and the cost increases.

Secondly, the operation and maintenance of traditional solutions mainly rely on the subjective judgment of staff experience, which lacks scientific prediction models. Besides, it cannot be updated regularly due to the limitations of physical entities and handwritten drafts, which will lead to poor system adaptability.

At the same time, in the traditional O&M mode, the problem of resource misallocation is serious, which will cause a lot of waste of manpower, material redundancy, energy loss, and other resource loss.

Finally, during high-risk operations during operation and maintenance, the potential safety hazards are prominent, especially the fall during high-altitude detection, poisoning during operation in confined spaces, and short circuit problems caused by misoperation during live maintenance.

The use of digital twin technology in infrastructure operations can effectively solve these problems.

DOI: 10.54254/2755-2721/2025.MH25388

2.2. Digital twin O&M solution

Compared with traditional solutions, digital twin solutions are of great help to infrastructure operation and maintenance in terms of data collection, dynamic modeling, intelligent decision-making, and high-risk prediction.

The digital twin model can realize the data collection of real-time operation of infrastructure in the data dimension, so as to update infrastructure dynamics in real time and respond to emergencies promptly. The digital twin can improve the accuracy and efficiency of inspection through machine scanning, save labor costs, and reduce risks.

Relying on AI models to analyze historical data, digital twins can quickly generate emergency plans, make intelligent decisions in a short time, and greatly improve the ability to respond to unexpected problems. Dynamic planning and control according to different situations can save time and costs.

The digital twin platform can optimize resource allocation by dynamically analyzing the efficiency of the use of manpower, materials, and equipment. Doing this can reduce problems like high cost expenditure and resource redundancy.

By planning before the operation and monitoring the personnel dynamics during the operation, the digital twin can avoid accidents to the greatest extent, so that the operation and maintenance personnel can quickly respond to emergencies in the event of danger, and significantly reduce the operation risk.

3. Technology path

Because of the above requirements, this paper proposes the following technical routes based on digital twins.

The first is the collection and fusion of data. In infrastructure, the attributes and representations required for the same object can vary from region to region or activity. When managing essential digital twin data, it's important to consider the diversity of your environment and meet the diverse needs of service users and stakeholders[2]. Multi-source sensor network deployment through fiber optic sensors (FBG), lidar (LiDAR), wireless sensor networks, and other technologies can realize millimeter-level monitoring and cloud modeling, and collect temperature/vibration/compaction data.

This is followed by multi-scale dynamic modeling. The effective integration of BIM and Internet of Things (IoT) technologies into a geographic information system (GIS) allows for the construction of a geometric model of a facility that leverages the wealth of information stored in the digital information model to create a mapping of the input data required by the application or automatically transform the base model for specific analysis. It can be used not only as a pre-construction simulation tool, but also as a tool for cost evaluation[3].

Once the modeling is complete, a closed loop of intelligent decision-making is required. NVIDIA Jetson TK1 (Tegra K1) is a full-featured embedded application platform that combines low cost, low power, and high applicability[4]. The edge layer uses NVIDIA Jetson to process real-time data locally, enabling anomaly detection and emergency braking of infrastructure. The Alibaba Cloud PAI platform is used to train AI models in the cloud, which can realize infrastructure life prediction and resource optimization scheduling. The use of AR remote collaboration, digital twin cockpit, voice control and other technologies to achieve human-computer interaction can enable experts to remotely guide and monitor the overall situation.

Finally, the closed-loop operation and maintenance scenario is realized. Predictive maintenance of infrastructure is carried out through technology flows, i.e., sensor data → LSTM prediction of

DOI: 10.54254/2755-2721/2025.MH25388

remaining life→ digital twin verification→ automatic generation of work orders. Multi-agent reinforcement learning (MARL) optimizes inspection paths to achieve dynamic resource optimization. Use digital twin technology to detect various disaster emergencies and reduce disaster risks.

4. Analysis of typical cases

In the management and maintenance of modern urban infrastructure, digital twin technology is significantly enhancing the safety and efficiency of transportation systems and engineering projects through high-precision virtual mapping and real-time data analysis. Therefore, this section primarily analyzes the application of digital twins in projects such as the Singapore Metro, the Hong Kong-Zhuhai-Macao Bridge, and the UK's Hinkley Point C nuclear power station.

(1) Urban transportation infrastructure: Singapore metro digital twin system

In 2020, Singapore's Land Transport Authority (LTA) launched a digital twin project for metro tunnels. Using mobile LiDAR (RIEGL VUX-1LR, accuracy ±5mm) at a speed of 20 km/h, the project completed point cloud collection (resolution 1 cm^3) for the entire tunnel. The data was then integrated with BIM models to construct an LOD 500-level tunnel model in Autodesk Infraworks, including construction data such as concrete grades and reinforcement layouts. During the operation and maintenance phase, the digital twin system enables structural health monitoring. For example, a fiber-optic sensor network was deployed to collect real-time displacement data. The twin system used finite element analysis (FEA) to predict crack propagation trends, issuing a warning six months in advance about settlement risks near the Jurong East Station section, thereby avoiding train service disruptions [4].

(2) Large-Scale bridge engineering: dynamic twin platform for the Hong Kong-Zhuhai-Macao bridge

The dynamic twin platform for the Hong Kong-Zhuhai-Macao Bridge integrates BeiDou positioning, FBG sensors, and machine learning algorithms to achieve comprehensive digital operation and maintenance. During the operation and maintenance phase, the digital twin system enables fatigue life detection. For instance, strain data from welded joints in steel box girders was input into an improved ResNet neural network, achieving a prediction accuracy of 91.3% [5]. During Typhoon Ma-on in 2022, real-time monitoring data showed a maximum instantaneous wind speed of 42 m/s and a lateral sway of the main girder reaching 618 mm. The twin system simulation revealed that the stress at node S12 exceeded limits for 137 seconds. By comparing historical typhoon data (7 instances between 2017 and 2021), the system confirmed no cumulative damage and recommended "no shutdown but a speed limit of 40 km/h," ultimately reducing economic losses by approximately 8 million yuan.

(3) UK's Hinkley point C nuclear power station digital twin system

The UK's Hinkley Point C nuclear power station, led by Électricité de France (EDF), is a third-generation pressurized water reactor project with a total investment of £26 billion. It is the world's first nuclear facility to implement digital twins across its entire lifecycle (EDF Energy, 2023). During the operation and maintenance phase, the digital twin system enables reactor containment inspection. For example, in 2024, the system detected an abnormal temperature gradient on the northwest side of the reactor containment. The twin simulation revealed a 0.2 mm crack in the cooling pipe weld, which was verified by ultrasonic testing. This allowed for preemptive shutdown and repair, avoiding the risk of radioactive leakage [6].

DOI: 10.54254/2755-2721/2025.MH25388

5. Future trends and emerging conflicts, and challenges

Digital twins are transitioning from proof-of-concept to deep practical application, with future development focusing on intelligence, cross-domain collaboration, and autonomous decision-making.

In the intelligence phase, thus far, the design and development of digital twin technology have been targeted at single systems or processes[7]. Future AI models will no longer be limited to single-failure predictions but will achieve multi-failure coupling warnings. Moreover, AI will not only provide alerts but also generate executable optimization solutions, autonomously refining operation and maintenance strategies through dynamic trial and error.

Asset Administration Shell provides the infrastructure to connect equipment with data and services [8]. Based on this standard, unified data models can be constructed, enabling seamless interaction between digital twins in different domains such as transportation, water management, and energy, thereby breaking down data silos.

First, there are data governance conflicts, such as ownership disputes. For example, in the UK's Crossrail project, contractors refused to share BIM model details, resulting in the omission of 40% of pipeline data in the operational twin system[9]. Standardization gaps also exist: although ISO 19650-3 specifies operation and maintenance data formats, 67% of cases in practice involve custom fields[10].

Second, there is a technology-cost paradox. For instance, retrofitting older facilities poses challenges: a report by the American Society of Civil Engineers (ASCE) shows that installing sensors on bridges built before 1950 costs up to $120/m² [11]. Model drift is another issue: the digital twin of a Shanghai substation generated three false alarms due to its failure to account for the nonlinear aging characteristics of cable insulation materials [12].

Finally, there are security and ethical risks. The attack surface has expanded: Siemens' industrial network threat report indicates that digital twins increase the number of exposed infrastructure nodes by 300%, with 22 ransomware attacks targeting twin systems globally in 2023. Human-machine decision-making conflicts have also arisen: ground staff at Munich Airport collectively protested an AI-driven baggage system scheduling plan, arguing that it lacked "empirical intuition"[13].

6. Conclusion

This paper analyses the technical path, limitations, and future possibilities of digital twin technology. Conventional maintenance is subject to multiple issues such as low efficiency, low accuracy, increased costs, and wasted manpower due to factors such as enormous workloads, subjective judgements by staff, and resource loss. By applying digital twin technology to infrastructure maintenance processes, four technical pathways—data collection and integration, multi-scale dynamic modelling, intelligent decision-making loops, and maintenance scenario loops—can be utilised to enhance precise data collection, cost assessment, comprehensive situational monitoring, and disaster prevention during maintenance operations. Case studies of digital twin technology in urban transportation infrastructure, large-scale bridge engineering, and nuclear power plants demonstrate its significant value in maintenance processes.

However, the widespread application of digital twin technology in maintenance processes still faces numerous challenges and contradictions. First, there are data governance conflicts, including ownership disputes and standardisation conflicts. Second, there is a technical and cost paradox. Finally, there are security and ethical risks, including the threat of malicious attacks, which necessitate the construction of a security framework.

DOI: 10.54254/2755-2721/2025.MH25388

In summary, digital twin technology offers efficient solutions for infrastructure. Although the threats and contradictions associated with this technology introduce some uncertainty into infrastructure operations and maintenance, through technological integration, intelligent upgrades, and ecosystem construction, digital twin technology will further drive the digital transformation of infrastructure operations and maintenance in the future, providing strong support for sustainable development.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Yu Yan , Lei Ni a , Lijun Sun , Ying Wang , Jianing Zhou , 2024.Digital Twin Enabling Technologies for Advancing Road Engineering and Lifecycle Applications.
[2] Zhang, R., et al. (2022). ResNet-based fatigue life prediction for long-span bridges using digital twin. Engineering Structures, 256, 114063.
[3] Huang, T., Kou, S., Liu, D., Li, D., & Xing, F. (2022). A BIM-GIS-IoT-Based System for Excavated Soil Recycling. Buildings, 12(4), 457. https: //doi.org/10.3390/buildings12040457.
[4] Su, M., Tan, JJ., Lin, CY., Ye, J. & Wang, CH. (2015) Constructing a Mobility and Acceleration Computing Platform with NVIDIA Jetson TK1. In: 2015 IEEE 17th International Conference on High Performance Computing and Communications, 2015 IEEE 7th International Symposium on Cyberspace Safety and Security, and 2015 IEEE 12th International Conference on Embedded Software and Systems (ICESS). IEEE, pp. 1854–1858. DOI: 10.1109/HPCC-CSS-ICESS.2015.212.
[5] Lee, K. P., & Tan, H. W. (2021). Digital twin-enabled predictive maintenance for underground infrastructure. Tunnelling and Underground Space Technology, 110, 103842.
[6] Zhang Chunlei, Guo Jianyong, and Wang Xiuyan. 2025. Research and Application of Digital Twin-Based Metro Tunnel Operation and Maintenance Technology [J/OL]. Railway Standard Design. https: //doi.org/10.13238/j.issn.1004-2954. Shanghai Water Resources Bureau, 2022.
[7] World Nuclear News. (2024). Digital twin prevents potential containment breach at Hinkley Point C. Available: https: //www.world-nuclear-news.org
[8] Baek, MS (Baek, Myung-Sun), 2022.Asia-Pacific Conference on Communications.Digital Twin Federation and Data Validation Method.p445-446.
[9] McArthur, J. J., & Bortoluzzi, B. (2021). Interoperability gaps in BIM-based digital twins for facility management. Automation in Construction, 123, 103550.
[10] National Building Specification (NBS). (2022). Digital twin adoption in construction: Global benchmark report.
[11] American Society of Civil Engineers (ASCE). (2022). Standard classification of civil infrastructure systems (ASCE/SEI 71-22). ASCE.
[12] Zhang, L., et al. (2023). "Digital Twin Model Drift in Power Substations: A Case Study of Cable Aging Prediction Failure". IEEE Transactions on Power Systems, 38(2), 1123-1135.
[13] Deutscher Gewerkschaftsbund (DGB). (2023). Digitalization and Labor Resistance in German Airports: Annual Survey on AI Adoption (Report No. 2023-07).