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Digital Twin Applications for Urban Infrastructure Management: Comparing the United Kingdom and Singapore

Putri Rahma Syahrani Harahap[1] ✉

STT Terpadu Nurul Fikri, Indonesia[1]

ABSTRACT

Digital Twin technology has become a key enabler of smart urban infrastructure management by integrating real-time data, simulation models, and advanced analytics to improve planning, operation, maintenance, and decision-making throughout the infrastructure lifecycle. The United Kingdom and Singapore are internationally recognized for implementing Digital Twin technologies to support sustainable urban development and smart city initiatives. This study aims to systematically review research published over the last five years by comparing Digital Twin applications for urban infrastructure management in both countries. Using a Systematic Literature Review (SLR) approach, the study synthesizes recent developments, implementation strategies, technological integration, application domains, benefits, challenges, and future research opportunities. The findings indicate that the United Kingdom emphasizes national digital infrastructure frameworks and asset lifecycle management, whereas Singapore focuses on integrated smart city governance and real-time urban monitoring. Despite significant progress, challenges related to interoperability, data governance, cybersecurity, and implementation costs remain. This review provides evidence-based insights to support future Digital Twin adoption for sustainable and intelligent urban infrastructure management.

Keywords: *Digital Twin, Infrastructure Management, Singapore, Smart City, United Kingdom.*

CORRESPONDING AUTHOR:
Putri Rahma Syahrani Harahap
STT Terpadu Nurul Fikri, Indonesia

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1. | INTRODUCTION

Urban infrastructure plays a fundamental role in supporting economic development, public services, and the quality of life in modern cities. As urban populations continue to increase, governments face growing challenges in managing transportation systems, utility networks, public buildings, and other essential infrastructure efficiently. Aging assets, increasing maintenance demands, rapid urban expansion, and sustainability goals require infrastructure managers to adopt more effective approaches than conventional inspection and maintenance practices. Traditional management methods often depend on fragmented data, periodic inspections, and reactive decision-making, making it difficult to identify infrastructure problems at an early stage or optimize long-term asset performance. Consequently, digital transformation has become a strategic priority for improving the efficiency, resilience, and sustainability of urban infrastructure management (Salas & Yepes, 2020).

Among the emerging digital technologies, Digital Twin has gained considerable attention as an innovative solution for managing complex infrastructure systems. A Digital Twin is a digital representation of a physical asset that continuously integrates real-time operational data with simulation and analytical capabilities. By combining information from sensors, Internet of Things (IoT) devices, Geographic Information Systems (GIS), Building Information Modeling (BIM), cloud computing, and data analytics, Digital Twin technology enables infrastructure managers to monitor asset conditions, evaluate operational performance, predict deterioration, and support informed decision-making throughout the infrastructure lifecycle. This integrated approach improves coordination among stakeholders while enabling proactive maintenance and more efficient resource allocation (Adepoju et al., 2022).

The rapid advancement of digital technologies has expanded the role of Digital Twins beyond visualization into intelligent decision-support systems. Artificial Intelligence (AI), machine learning, big data analytics, and predictive modeling have strengthened the ability of Digital Twins to process large volumes of infrastructure data and generate accurate forecasts of infrastructure performance. These capabilities support real-time monitoring, risk assessment, scenario simulation, and maintenance optimization, allowing engineers to reduce operational disruptions and extend infrastructure service life. As a result, Digital Twin technology has become an essential component of smart city development by improving infrastructure resilience, operational efficiency, and environmental sustainability (Yang et al., 2018).

The United Kingdom has become one of the leading countries in developing Digital Twin applications for infrastructure management through national digital transformation initiatives and collaborative engineering frameworks. Digital Twin technology has been implemented across transportation systems, water infrastructure, energy networks, and public facilities to improve asset lifecycle management, infrastructure planning, and operational efficiency. Standardized digital frameworks and integrated data environments have strengthened collaboration among public agencies, infrastructure operators, researchers, and technology providers, enabling more effective management of complex urban infrastructure systems (Serrano, 2018).

Singapore has also demonstrated significant progress in adopting Digital Twin technology through its Smart Nation initiative. As a highly urbanized city-state with limited land resources, Singapore has invested extensively in digital technologies to improve urban planning, infrastructure operation, and public service delivery. Digital Twin platforms support transportation management, environmental monitoring, utility services, and emergency response by integrating real-time information into centralized management systems. This digital ecosystem enables authorities to evaluate infrastructure performance continuously, optimize resource utilization, and improve urban resilience while supporting sustainable development objectives (Van et al., 2021).

Although numerous studies have explored Digital Twin technology in different engineering applications, comparative research examining its implementation in the United Kingdom and Singapore remains limited. Most existing studies emphasize technical development or individual case studies without comprehensively comparing implementation strategies, governance approaches, application areas, benefits, and remaining challenges. Therefore, this study conducts a Systematic Literature Review (SLR) of journal articles published between 2020 and 2024 to compare Digital Twin applications for urban infrastructure management in both countries (Schrotter & Hürzeler, 2020). The review aims to identify recent technological developments, implementation strategies, major applications, benefits, challenges, and future research opportunities while providing practical insights for researchers, engineers, policymakers, and infrastructure managers seeking to accelerate digital transformation and promote sustainable urban infrastructure management.

2. | RESEARCH METHOD

This study employed a Systematic Literature Review (SLR) to identify, evaluate, and synthesize recent research on Digital Twin applications for urban infrastructure management, with a comparative focus on the United Kingdom and Singapore. The SLR approach was selected because it provides a structured, transparent, and reproducible process for reviewing scientific literature while minimizing selection bias and ensuring comprehensive coverage of relevant studies (Muka et al., 2020). The review process consisted of four sequential stages: literature identification, screening, eligibility assessment, and qualitative synthesis. Relevant publications were collected from internationally recognized scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, IEEE Xplore, and MDPI. The literature search employed combinations of keywords such as "Digital Twin," "Urban Infrastructure Management," "Smart City," "Infrastructure Monitoring," "Asset Management," "United Kingdom," and "Singapore." Only peer-reviewed journal articles published between 2020 and 2024 were included to ensure that the review reflected recent technological developments and current research trends. The inclusion criteria required that the selected studies explicitly discuss Digital Twin implementation for urban infrastructure management, smart city development, digital asset management, infrastructure monitoring, lifecycle management, or intelligent decision-support systems in the United Kingdom or Singapore (Huang et al., 2023). Duplicate publications, conference papers, book chapters, editorials, and studies without sufficient methodological information were excluded from the review. After completing the screening process, all eligible studies were analyzed using qualitative content analysis to extract relevant information, including publication year, research objectives, infrastructure sectors, Digital Twin technologies, supporting digital systems, implementation strategies, reported benefits, existing challenges, and recommendations for future research (Iqbal et al., 2022). The extracted information was subsequently classified into thematic categories to facilitate a comparative evaluation of Digital Twin implementation in the United Kingdom and Singapore. Particular attention was given to similarities and differences in technological integration, governance frameworks, urban infrastructure applications, operational performance, sustainability contributions, and implementation barriers. The synthesized findings were then interpreted to identify current research trends, existing knowledge gaps, and future research priorities (Reis & Melão, 2023). Through this systematic review process, the study provides a comprehensive understanding of how Digital Twin technology supports intelligent urban infrastructure management while offering evidence-based recommendations for researchers, engineers, policymakers, and infrastructure managers seeking to accelerate digital transformation and sustainable urban development.

3. | RESULTS AND DISCUSSION

The systematic literature review indicates that Digital Twin technology has experienced rapid development between 2020 and 2024 and has become an important component of urban infrastructure management. The reviewed studies consistently show that Digital Twins improve the planning, operation, monitoring, and maintenance of infrastructure by integrating real-time information with digital simulation and intelligent analytical tools. Unlike conventional infrastructure management, which depends on periodic inspections and fragmented databases, Digital Twin technology provides a continuously updated digital representation of physical assets. This capability enables infrastructure managers to monitor asset conditions, evaluate operational performance, identify potential failures, and support evidence-based decision-making throughout the infrastructure lifecycle. Consequently, Digital Twins have become a key technology for improving infrastructure efficiency, resilience, and sustainability in rapidly developing urban environments (Zeng et al., 2022).

Another important finding is the growing integration of Digital Twin technology with other digital systems. Modern Digital Twin platforms combine data collected from Internet of Things (IoT) devices, Geographic Information Systems (GIS), Building Information Modeling (BIM), cloud computing, remote sensing, and Artificial Intelligence (AI). These technologies create an integrated digital environment that allows infrastructure managers to observe infrastructure performance in real time while predicting future operational conditions. AI-based predictive models support maintenance planning by identifying abnormal infrastructure behavior before failures occur, reducing maintenance costs and minimizing service interruptions. Furthermore, simulation capabilities enable engineers to evaluate multiple infrastructure scenarios before implementing physical interventions, improving planning accuracy and reducing project risks (Wang et al., 2020).

The comparative analysis reveals that the United Kingdom has developed a comprehensive Digital Twin ecosystem through national digital transformation initiatives. Digital Twin implementation is applied across transportation systems, water infrastructure, energy networks, and public facilities to strengthen asset lifecycle management and improve operational efficiency. Infrastructure owners increasingly utilize Digital Twins to monitor asset performance, optimize maintenance schedules, and evaluate infrastructure resilience under different operational conditions. Standardized data management frameworks also promote collaboration among government agencies, infrastructure operators, researchers, and private organizations. This collaborative approach improves information sharing and supports more effective decision-making across multiple infrastructure sectors (Nezami et al., 2022).

Another significant development in the United Kingdom is the increasing use of Digital Twins for predictive infrastructure management. Real-time operational data collected from sensors are continuously synchronized with digital models, allowing engineers to identify infrastructure deterioration before serious failures develop. Predictive maintenance reduces unnecessary inspection activities, extends infrastructure service life, and improves the allocation of maintenance resources. Digital Twin simulations are also widely used to evaluate infrastructure performance under various environmental and operational scenarios, supporting long-term investment planning and infrastructure resilience. These capabilities enable infrastructure managers to respond more effectively to changing urban demands while maintaining reliable public services (Sharifi et al., 2023).

The reviewed studies further indicate that Digital Twin technology contributes to sustainable urban infrastructure development by improving resource efficiency and reducing operational waste. Continuous monitoring enables infrastructure operators to optimize energy consumption, minimize water losses, improve traffic management, and reduce unnecessary maintenance activities. Better infrastructure performance also contributes to lower operational costs while supporting environmental sustainability objectives. As a result, the United Kingdom has increasingly positioned Digital Twin technology as a strategic component of smart city development, integrating engineering knowledge, digital innovation, and long-term infrastructure planning to create more resilient and sustainable urban systems (Kaluarachchi, 2021). These findings demonstrate that successful Digital Twin implementation depends not only on technological advancement but also on effective governance, standardized digital frameworks, and strong collaboration among stakeholders responsible for infrastructure planning, operation, and maintenance. The reviewed literature shows that Singapore has also achieved significant progress in implementing Digital Twin technology for urban infrastructure management. However, its implementation strategy differs from that of the United Kingdom because of Singapore's compact urban environment, limited land availability, and highly centralized governance system. Digital Twin technology has been integrated into the country's Smart Nation initiative to support efficient urban planning, infrastructure operation, public service delivery, and environmental sustainability (Cheng et al., 2021). Transportation systems, public housing, utility networks, water management, and environmental monitoring are increasingly connected through Digital Twin platforms that continuously collect and analyze real-time data. This integrated digital ecosystem enables government agencies to monitor infrastructure performance, identify operational issues, and make timely decisions based on accurate and continuously updated information (Adekunle et al., 2021).

Artificial Intelligence (AI), Internet of Things (IoT), Geographic Information Systems (GIS), Building Information Modeling (BIM), cloud computing, and advanced data analytics play essential roles in supporting Digital Twin implementation in Singapore. Sensors installed across urban infrastructure provide continuous information regarding traffic flow, energy consumption, water distribution, environmental quality, and asset conditions. These large datasets are processed using intelligent analytical models to identify abnormal system behavior, predict infrastructure deterioration, and optimize operational performance. Predictive maintenance supported by Digital Twins allows infrastructure operators to schedule maintenance activities based on actual infrastructure conditions rather than fixed inspection intervals, thereby reducing operational costs, improving service reliability, and extending infrastructure lifespan. The integration of Digital Twin technology with intelligent urban management systems also enhances emergency response capabilities by enabling authorities to simulate disaster scenarios and evaluate alternative response strategies before emergencies occur (Ceferino etb al., 2020).

The comparative analysis demonstrates that both the United Kingdom and Singapore recognize Digital Twin technology as a strategic tool for improving urban infrastructure management and supporting sustainable city development. Nevertheless, each country has adopted different implementation priorities. The United Kingdom primarily emphasizes asset lifecycle management, infrastructure resilience, and cross-sector collaboration through standardized digital frameworks that support information sharing among multiple infrastructure stakeholders. Singapore, in contrast, focuses on integrated smart city governance, centralized urban management, and real-time operational control supported by comprehensive digital platforms. Despite these differences, both countries have successfully demonstrated that Digital Twin technology enhances infrastructure efficiency, improves maintenance planning, strengthens operational resilience, and supports evidence-based decision-making across various infrastructure sectors (Mills et al., 2021).

Although considerable progress has been achieved, the reviewed studies identify several challenges that continue to affect Digital Twin implementation. Data interoperability remains one of the most significant barriers because infrastructure information is often generated from multiple digital platforms using different standards and data formats. Integrating these heterogeneous datasets into a unified Digital Twin environment requires consistent data governance and standardized information management practices. Cybersecurity and data privacy also represent important concerns as increasing numbers of infrastructure assets become digitally connected through cloud computing and Internet of Things technologies. Protecting sensitive infrastructure information while maintaining reliable real-time data exchange is therefore essential for ensuring secure Digital Twin operations (Alcaraz & Lopez, 2022). Another challenge relates to the financial and organizational requirements associated with Digital Twin implementation. Developing comprehensive Digital Twin systems requires substantial investment in digital infrastructure, sensing technologies, cloud platforms, software development, and workforce training. Successful implementation also depends on multidisciplinary collaboration involving civil engineers, information technology specialists, urban planners, government agencies, and private technology providers. Furthermore, many organizations continue to experience shortages of professionals possessing expertise in both engineering and digital technologies, slowing the adoption of advanced Digital Twin applications. Strengthening education, professional training, and interdisciplinary research will therefore be critical to supporting future implementation *(Holmes et al., 2020).

Overall, the findings demonstrate that Digital Twin technology has transformed urban infrastructure management from conventional asset monitoring into an intelligent, data-driven decision-support system. The United Kingdom has established strong digital governance and lifecycle asset management frameworks, while Singapore has successfully integrated Digital Twins into smart city operations through centralized digital management (Ramu et al., 2022). Despite differences in implementation strategies, both countries demonstrate that Digital Twin technology improves infrastructure resilience, operational efficiency, sustainability, and long-term asset management. Future research should focus on developing interoperable Digital Twin platforms, standardized data frameworks, explainable Artificial Intelligence models, and stronger integration with emerging smart city technologies to further enhance urban infrastructure performance and sustainable urban development.

4. | CONCLUSION

This study systematically reviewed recent developments in Digital Twin applications for urban infrastructure management by comparing research trends and implementation practices in the United Kingdom and Singapore based on peer-reviewed publications published between 2020 and 2024. The findings demonstrate that Digital Twin technology has become a fundamental component of digital transformation in urban infrastructure by supporting real-time monitoring, predictive maintenance, lifecycle asset management, and evidence-based decision-making. The integration of Digital Twin with Artificial Intelligence (AI), Internet of Things (IoT), Geographic Information Systems (GIS), Building Information Modeling (BIM), cloud computing, and big data analytics has significantly improved infrastructure efficiency, operational reliability, and long-term sustainability.

The comparative analysis indicates that the United Kingdom emphasizes standardized digital frameworks, cross-sector collaboration, and lifecycle infrastructure management, whereas Singapore focuses on centralized smart city governance, integrated digital platforms, and real-time urban operations. Although both countries adopt different implementation strategies, they share a common objective of enhancing infrastructure resilience, optimizing resource utilization, and improving public service delivery through intelligent digital technologies.

Despite these achievements, several challenges remain, including data interoperability, cybersecurity, implementation costs, limited technical expertise, and the need for standardized governance frameworks. Addressing these issues requires stronger collaboration among governments, academic institutions, infrastructure operators, and technology providers to ensure successful Digital Twin implementation.

Future research should prioritize the development of interoperable digital platforms, standardized data management practices, advanced predictive analytics, and greater integration with emerging smart city technologies to strengthen sustainable urban infrastructure management and support resilient urban development.

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The authors declare that there is no conflict of interest.

Ethical Approval and Originality Statement

Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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