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ADVANCING CIVIL INFRASTRUCTURE WITH DIGITAL TWINS: A REVIEW OF APPLICATIONS AND CHALLENGES

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Abstract. The digital twins (DTs) technology has emerged as a ground-breaking approach in the management and maintenance of civil infrastructure, providing a virtual representation of physical systems which are continuously updated with real-time data from IoT sensors and simulations. Initially introduced in the manufacturing sector, the concept of digital twins has been extended to civil engineering, offering a significant potential for real-time monitoring, predictive maintenance, optimized asset management, and enhanced decision-making. This paper provides a comprehensive survey of the applications of the digital twins technology in civil infrastructure, with a particular focus on structural health monitoring (SHM), predictive maintenance, smart city frameworks, and disaster response systems. By reviewing existing methodologies, case studies, and practical implementations, this paper highlights the transformative impact of DTs in improving the efficiency, safety, and sustainability of infrastructure systems, including bridges, buildings, and transportation networks. Despite the numerous advantages of DTs, several challenges impede their widespread adoption in civil engineering. These challenges include high implementation costs due to the need for sophisticated sensors, high-performance computing, and advanced simulation tools. Additionally, data integration and interoperability issues between various data sources and platforms hinder seamless adoption. Cybersecurity risks associated with real-time monitoring systems and the protection of critical infrastructure are also discussed. This survey identifies these barriers and outlines the necessary technological advancements which may help overcoming the barriers. These include standardized data formats, enhanced AI-driven predictive models, and scalable cloud solutions, among others. This paper concludes by highlighting future research directions to address the identified challenges, emphasizing the need for collaboration across academia, industry, and government to fully unlock the potential of DTs technology. With continued advancements in machine learning, edge computing, and secure data protocols, DTs are poised to revolutionize infrastructure management, contributing to smarter, safer, and more efficiently built environments.

Keywords: digital twins, civil infrastructure, structural health monitoring, AI-driven predictive model, cybersecurity.

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1. Introduction

The rapid advancement of digital technologies has paved the road for the integration of digital twin systems in civil infrastructures. A digital twin's system is a virtual representation of a physical system, continuously updated by reflecting real-time data and simulations (Grieves, 2014). Initially introduced in the manufacturing industry, the concept has evolved into a transformative approach in civil engineering, enabling real-time monitoring, predictive maintenance, and optimized asset management (Tao et al., 2018).

Civil infrastructures, including bridges, buildings, and transportation networks, require continuous monitoring and maintenance to ensure safety and efficiency. Traditional inspection methods rely on manual assessments and periodic evaluations, which are often time-consuming and prone to human error (Kapteyn & Willcox, 2021). The emergence of Digital Twins technology provides a paradigm shift by integrating real-time IoT sensor data, artificial intelligence, and computational modeling. This integration facilitates predictive maintenance, improves operational efficiency, and extends the lifecycle of structures (Fuller et al., 2020).

Despite the enumerated advantages, several challenges hinder the widespread adoption of digital twins in the civil engineering domain. The implementation costs remain high due to the need for sophisticated sensors, high- performance computing, and advanced simulation tools. Additionally, interoperability between different data sources and platforms poses a significant barrier, requiring standardized frameworks for data integration (Fuller et al., 2020). Security concerns also arise, as real-time monitoring systems may be vulnerable to cyber threats and data integrity issues.

This survey aims to provide a comprehensive overview of digital twins' applications in civil infrastructures, highlighting recent advancements, key challenges, and future research directions. By examining existing methodologies, case studies, and practical implementations, we seek to offer insights into how the digital twins technology can revolutionize civil engineering practices.

2. Related work

The concept of DTs has been extensively studied in various domains, including manufacturing, healthcare, and smart cities. In civil infrastructures, researchers have explored DTs applications for SHM, predictive maintenance, urban planning, and disaster response. This section provides an overview of the key research contributions in these areas.

2.1. Digital twins for structural health monitoring

One of the primary applications of DTs in civil engineering is real-time SHM. Kapteyn and Willcox (2021) proposed a physics-based DTs framework which integrates sensor data with finite element models for accurate bridge diagnostics.

Recent advancements have introduced machine learning (ML) techniques for SHM. Tao et al. (2018) explored how deep learning can enhance predictive maintenance by identifying structural degradation patterns. Additionally, Fuller et al. (2020) demonstrated the feasibility of using DTs combined with artificial intelligence to enhance damage assessment in bridges and tunnels.

2.2. Digital twins for predictive maintenance

Predictive maintenance is a critical component of DTs applications in infrastructure management. A recent study by Johnson and Saikia (2024) focused on emerging technologies, such as blockchain and digital ledgers to ensure data integrity in predictive maintenance systems. These advancements address one of the main challenges of DTs adoption, namely cybersecurity vulnerabilities in interconnected systems.

2.3. Digital twins for smart cities and urban planning

DTs systems have become foundational components in smart city design, enabling real-time monitoring, data-driven decision-making, and virtual prototyping of complex urban environments. The application of DTs in conjunction with 3D printing and additive manufacturing (AM) technologies introduces new capabilities in urban development, sustainability, and resilience planning.

Recent research by Prasittisopin (2024) and others underscores how 3D printing supports the smart city ecosystem by enabling rapid prototyping, customized infrastructure components, and cost-effective housing solutions (Prasittisopin, 2024). The study by Prasittisopin (2024) highlights how AM can significantly reduce construction time, material waste, and overall project costs, aligning closely with the sustainable objectives of smart city frameworks. For example, 3D printing enables the local production of infrastructure elements, minimizing transportation-related emissions and improving responsiveness during disaster recovery or rapid urban expansion.

Moreover, DTs integrated with 3D printing workflows allow urban planners to simulate and optimize construction layouts before implementation. This is particularly useful for experimental or adaptive designs in public spaces. The synthesis of DTs with AM has enabled novel applications, including smart materials for self-healing buildings, thermally adaptive facades, and sensor-embedded components that support continuous monitoring and predictive maintenance.

The use of additive manufacturing in smart city initiatives is also extending to citizen engagement. Currently, participatory planning platforms allow communities to co-design urban furniture or housing components using 3D printing, which are then modeled in DTs environments for feasibility and simulation. Such feedback loops between physical prototyping and virtual modeling enhance the transparency and efficiency of urban innovation pipelines.

To sum up, the convergence of DTs and 3D printing fosters a more agile, scalable, and inclusive approach to smart city development, aligning technological innovation with sustainability goals and community engagement. Also, Adreani et al. (2022) proposed a Smart City DTs Framework that integrates real-time traffic data, environmental monitoring, and infrastructure health analytics for improved urban management. Their case study demonstrated how DTs enhance decision-making in traffic congestion control and resource allocation.

The Virtual Singapore project (GovTech Singapore, 2020) serves as a pioneering example of city-scale DTs application in Singapore. This initiative enables policymakers to simulate urban expansion scenarios, predict environmental impacts, and optimize energy consumption patterns.

2.4. Digital twins for disaster response and emergency management

DTs are increasingly being explored for disaster response and emergency management. Roberts (2024) developed a DTs-based system for real-time emergency management, leveraging remote sensing data to assess infrastructure resilience following earthquakes and floods. Furthermore, White (2025) investigated predictive analytics for urban environments, demonstrating how DTs can be used for early-warning systems in natural disasters, helping authorities mitigate risks in high-density urban areas.

2.5. Challenges and gaps in related work

While previous studies highlight the potential of DTs in civil infrastructures, several challenges remain unaddressed; these include:

- Scalability issues: Many proposed frameworks struggle to be deployed at a large scale due to computational and data processing limitations (Fuller et al., 2020).
- Interoperability concerns: The lack of standardized data formats hinders integration across different platforms.
- Cybersecurity threats: Real-time data exchange introduces vulnerabilities to cyber-attacks, requiring robust encryption mechanisms (Verma et al., 2024).

This survey aims to bridge these gaps by providing a comprehensive review of DTs advancements, discussing implementation challenges, and outlining future research directions.

3. Digital Twins applications in civil infrastructures

3.1. Paper retrieval from Scopus

To conduct a comprehensive survey on the applications of DTs in civil infrastructures, we performed a systematic literature search using the Scopus database. The search query was structured as given in Table 1.

Table 1. Scopus search query for Digital Twins in civil infrastructure

Field	Search Query
Title, Abstract, Keywords	TITLE-ABS-KEY (“digital twin” AND “civil infrastructure”)
Filters Applied	LIMIT-TO (LANGUAGE, “English”)
Scope	Publications discussing Digital Twins in Civil Infrastructures

This search resulted in a total of 118 papers. After applying the inclusion criteria, including relevance, peer- reviewed status, and full-text availability, we filtered the dataset down to 60 key papers for detailed analysis. To ensure transparency and methodological rigor, we followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines in our literature selection process. The flow of information through the different phases of the review, including identification, screening, eligibility, and inclusion, is summarized in the PRISMA diagram (Figure 1).

Inclusion and Exclusion Criteria: To ensure the relevance and quality of the studies included in this review, we applied the following inclusion and exclusion criteria:

Inclusion criteria:

- Studies published in peer-reviewed journals or reputable conference proceedings;
- Publications written in English;
- Papers that explicitly discuss the application of DTs technology in the context of civil infrastructures, such as structural health monitoring, predictive maintenance, smart cities, and disaster response;
- Studies providing either theoretical frameworks, methodological approaches, or real-world case studies involving DTs in civil engineering.

Exclusion criteria:

- Papers not focusing on civil infrastructures (e.g., DT applications in manufacturing or healthcare);
- Non-peer-reviewed materials, such as editorials, white papers, and theses produced by students;
- Studies lacking sufficient technical detail or methodological clarity;
- Duplicate entries and studies with inaccessible full text.

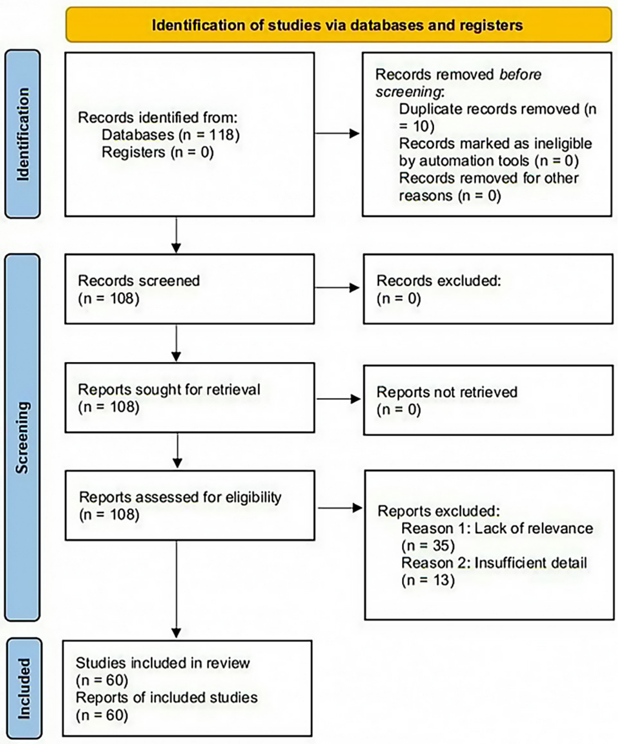

Figure 1. PRISMA flow diagram for study selection process

3.2. Analysis of retrieved publications

The selected papers were analyzed based on different attributes, including subject area, publication sources, geographic distribution, document types, and yearly trends.

Publications by country: Figure 2 shows that the majority of research contributions originated from the United States, followed by China, the United Kingdom, and Italy.

Publications by source: Figure 3 highlights the leading publication venues. The most frequently cited sources include *Automation in Construction* and *Lecture Notes in Civil Engineering*.

Publications by subject area: Figure 4 reveals that the primary disciplines contributing to DTs research in civil infrastructures are Engineering and Computer Science. These two disciplines are expected because the engineering side concentrates on the design issues while computer science researchers are involved in the analysis.

Publications by document type: Figure 5 illustrates that the largest proportion of publications are conference papers (36.4%), followed closely by journal articles (35.6%). This shows how an emerging topic attracts more interest for discussions in meetings.

Publications by year: Figure 6 demonstrates an increasing trend in DTs-related research, peaking in 2024, indicating growing interest in this field.

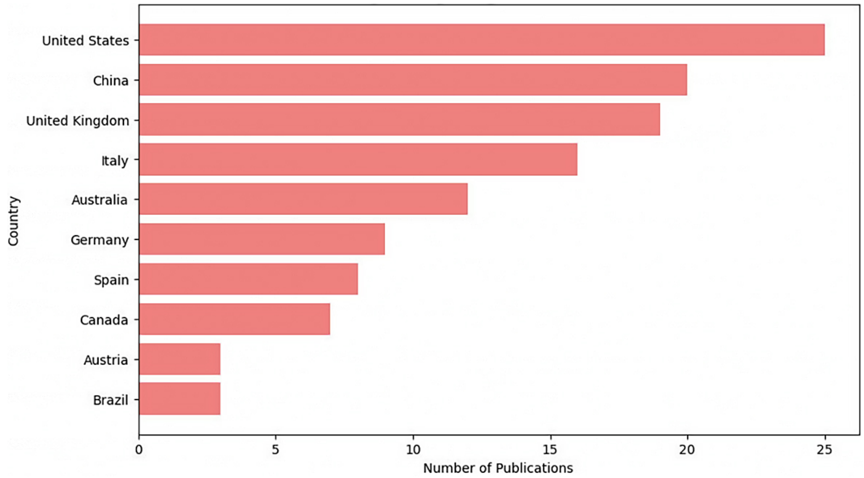

Figure 2. Publications by country in Digital Twins for civil infrastructures

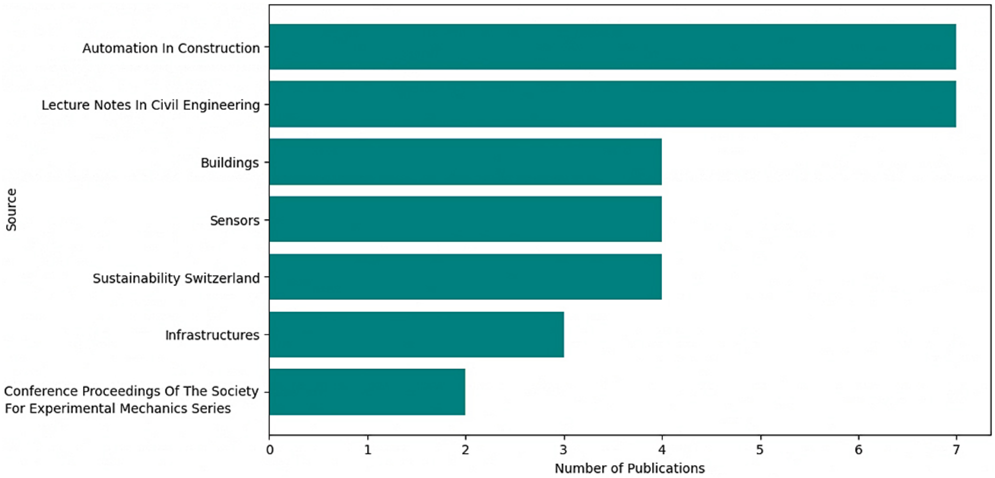

Figure 3. Top publication sources for Digital Twins in civil infrastructures

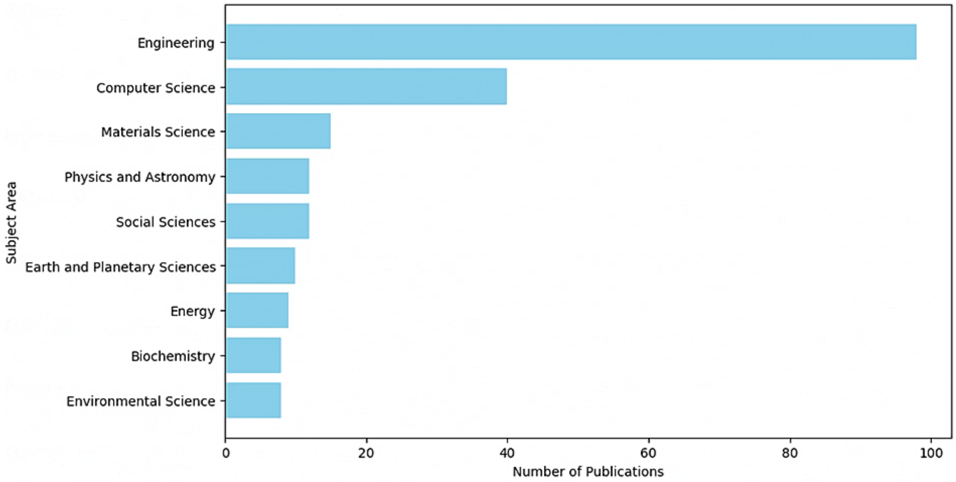

Figure 4. Publications by subject area

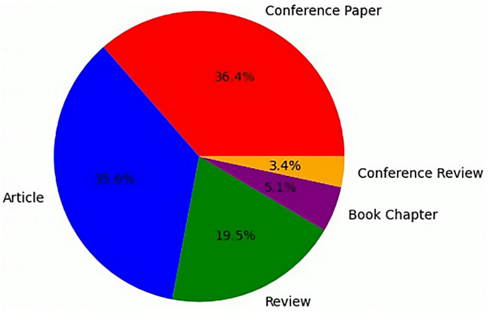

Figure 5. Publications by document type

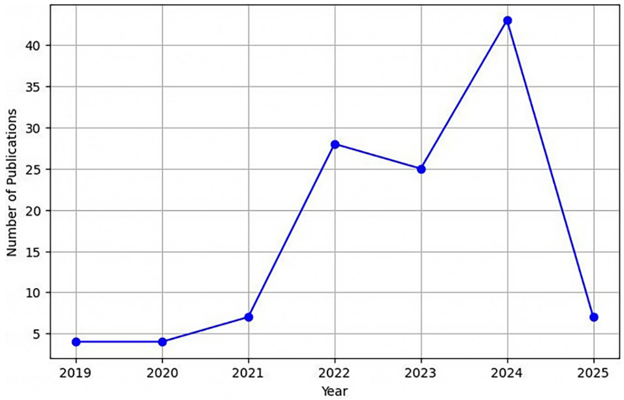

Figure 6. Number of publications by year (2019–2025)

3.3. Keyword relationship analysis using VOSviewer

The co-occurrence of keywords was analyzed using VOSviewer, as shown in Figure 7.

This network visualization highlights strong connections between DTs, civil infrastructures, structural health monitoring, machine learning, and decision making. These relationships indicate that DTs research is increasingly focused on predictive maintenance, real-time analytics, and smart city applications.

4. Detailed review of papers

To provide clarity and coherence, the 60 selected studies are grouped and discussed based on their primary thematic contributions, including DTs for bridge monitoring, integration with BIM and IoT, risk and asset management, and sustainability-driven infrastructure planning.

4.1. Digital Twins applications for bridge monitoring and SHM

Several studies focused on real-time monitoring and health assessment of bridge structures. For instance, Romanello et al. (2024) and Zirpoli and Sattamino (2024) developed IoT- and BIM-integrated DTs frameworks to collect actionable, real-time structural health data. Pregnolato et al. (2022) and Kong and Hucks (2023) explored DT implementations for legacy and historic structures, leveraging photogrammetry and structured workflows. Sun et al. (2025b), H. Hosamo and M. Hosamo (2022), and Shokravi et al. (2024) showed how continuous SHM can be enabled through 3D scanning, remote sensing, and connected vehicle data. Additionally, Scianna et al. (2022) and Zinke et al. (2023) introduced modular DT architectures using semantic or linked data to improve predictive accuracy and scalability. Other efforts like Mufti and Thomson (2024), Callcut et al. (2021), and Bado et al. (2022) examined distributed sensing and real-time updates for monitoring structural performance. Machine learning techniques within DTs platforms were applied by Liu et al. (2022b), Sun et al. (2025a), and Malekloo et al. (2021) to enhance the detection of failure conditions and extend service life.

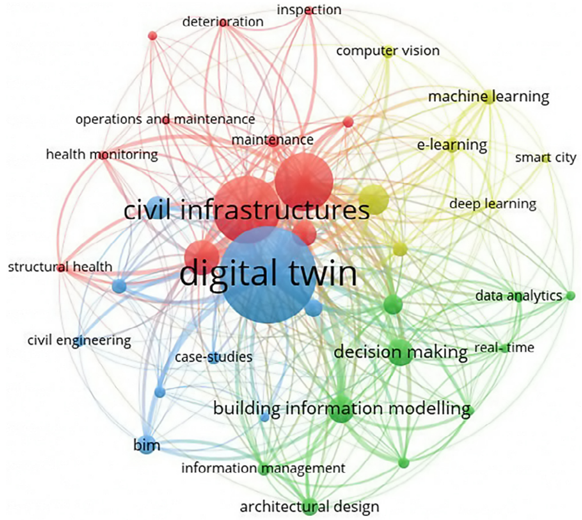

Figure 7. Keyword co-occurrence network from VOSviewer

4.2. Integration of BIM, GIS, and IoT in digital twins

Studies in this category explored the synergy between Building Information Modeling (BIM), Geographic In- formation Systems (GIS), and IoT in DTs. Muñoz Pavón et al. (2024) and Sakr and Sadhu (2023) integrated BIM with IoT sensor networks for campus management and structural monitoring. Khan et al. (2023) and Ramonell et al. (2023) developed voxel-based models and knowledge graphs, respectively, to enable multi- source integration and spatial reasoning. Li et al. (2024) and Li et al. (2022) offered bibliometric and technical overviews of BIM integration trends, while Naderi and Shojaei (2022) proposed a multi-level knowledge map to unify BIM-GIS data for DTs development. Sacks et al. (2020) coined the term "Digital Twins Construction" for systems combining BIM, AI, and real-time tracking, and Lozano-Galant et al. (2024) automated sustainability assessments using BIM and parametric modeling.

4.3. Risk assessment and asset management frameworks

This group includes studies focused on improving decision-making, safety, and lifecycle optimization. Candón et al. (2024) introduced an IoT-enabled Asset Health Index model for real-time condition monitoring. Broo and Schooling (2021) summarized common DT deployment barriers, especially around integration and governance. Lozano-Galant et al. (2024) integrated BIM with the MIVES framework to evaluate infrastructure sustainability. For risk-specific contexts, Providakis et al. (2022) proposed an AHP-based DTs system to assess tunneling-induced settlements. Osunsanmi et al. (2025) conducted a bibliometric review of success factors in smart maintenance during the Fourth Industrial Revolution. Bado et al. (2022) focused on using DTs to facilitate distributed condition monitoring and long-term data collection.

4.4. Smart cities and emergency response

DT applications in urban planning and disaster resilience were addressed by Huzzat et al. (2025), who proposed a Smart City Digital Twins Framework by integrating traffic and environmental monitoring. The large-scale "Virtual Singapore" project (GovTech Singapore, 2020) highlighted policy simulation and energy forecasting capabilities of city-scale DTs. Cheng et al. (2023) synthesized how DTs can be used across mitigation, response, and recovery phases of civil emergencies. Roberts (2024) and White (2025) proposed predictive analytics for natural disasters and hazard management. Emergency coordination and real-time scenario modeling were covered in Raviolo et al. (2023) and Schreiber et al. (2024). Other research effort, e.g., Pang et al. (2024), reviewed self-powered sensing solutions such as Triboelectric Nanogenerators for powering urban DTs in smart infrastructure.

4.5. Review and methodology-oriented studies

Review-focused works such as Liu et al. (2023), Sakr and Sadhu (2024), and Naderi and Shojaei (2022) provided high-level analyses of the current landscape, research trends, and methodological gaps in DTs adoption for civil infrastructures. Raviolo et al. (2023), Malekloo et al. (2021), and Liu et al. (2022b) proposed optimization, ML-enhanced failure prediction, and structural modeling techniques tailored for DTs frameworks. Liu et al. (2022a) emphasized the importance of cybersecurity, blockchain, and trustworthiness in DTs deployment. Early conceptual foundations and enabling technologies for DTs were presented by Grieves (2014), Tao et al. (2018), and Fuller et al. (2020). Finally, Kapteyn and Willcox (2021) contributed physics-based and real-time data–driven DT models which bridged simulation with real-world monitoring systems.

Table A1 in the Appendix gives the information of these papers in a table format, for better understanding.

5. Challenges and future directions

The integration of DTs technology in civil infrastructures systems has shown significant promise, yet several challenges must be addressed for its widespread adoption and optimal utilization. These challenges span technical, organizational, and policy dimensions, and overcoming them will require both technological innovations and a coordinated effort across various stakeholders, including government agencies, private industry, and academia.

5.1. Data integration and interoperability

One of the most pressing challenges in the implementation of DTs in civil infrastructures is the integration of diverse data sources. Civil infrastructure systems typically involve heterogeneous data from various domains, such as SHM, environmental monitoring, geographical information systems (GIS), and BIM. The seamless integration of these data sources into a unified DT model is complex due to differences in data formats, standards, and communication protocols. Furthermore, the integration of real-time data streams from IoT sensors, with historical data stored in different systems, often requires the development of sophisticated middleware platforms.

Research has highlighted the need for standardized frameworks to enable data interoperability between different platforms and technologies (Fuller et al., 2020). While some progress has been made in integrating BIM and GIS, challenges remain in achieving full interoperability among various systems used in civil infrastructures management.

5.2. Scalability and computational power

Scalability is another significant challenge when implementing DTs at the level of large-scale civil infrastructures. DTs, by their very nature, require real-time processing and analysis of vast amounts of data. As the number of sensors and the amount of collected data increases, the computational power required to process this data grows exponentially. Traditional computing resources may not be sufficient to handle the growing demands of DT models in large cities or across national infrastructure networks.

Cloud computing, edge computing, and high-performance computing (HPC) are potential solutions to these issues, but their deployment comes with challenges in terms of cost, complexity, and the need for robust cybersecurity measures. Furthermore, balancing the trade-off between computational cost and model accuracy is a critical challenge, especially in real-time monitoring applications (Osunsanmi et al., 2025).

5.3. Cybersecurity risks

The real-time nature of DTs and the integration of various data sources, including IoT sensors, introduce significant cybersecurity risks. Infrastructures which are heavily reliant on interconnected systems may be vulnerable to cyberattacks that could compromise data integrity, disrupt operations, or even endanger public safety. Ensuring the security of DTs and the data they rely on is a critical challenge. The development of secure communication protocols, encryption methods, and robust cybersecurity frameworks is essential to mitigate these risks.

5.4. High implementation costs

One of the most frequently cited and tangible barriers to the adoption of DTs systems in civil infrastructures is the high implementation costs. These costs are not limited to initial hardware and sensor procurement, but span across modeling software, skilled labor, data integration, cloud computing, and long-term system maintenance. For instance, Abugu et al. (2024) conducted a cost-benefit investigation in the construction industry and reported that DTs adoption typically requires major capital investment in custom software tools, sensor networks, and workforce training, particularly during early deployment phases. The study also noted that for small-to-medium-sized construction firms, these costs often exceed available project budgets, discouraging experimentation and uptake.

Jahangir et al. (2024) further supported this concern through a systematic review of DTs barriers in the building sector. Their research emphasized that high implementation costs, including those related to data interoperability and the lack of affordable commercial platforms, remain among the most cited adoption challenges in international projects. The financial burden is amplified when legacy infrastructure must be retrofitted with IoT and BIM systems to accommodate real-time monitoring.

In addition, Haron and Zafir (2025) investigated DTs usage in construction cost management and found that although DTs have the potential to improve budget forecasting and cost control, the upfront expenditures on technology acquisition and staff upskilling remain critical hurdles to practical adoption. The authors emphasized that public sector projects, in particular, face procurement delays and cost justification issues, especially when long-term return on investment (ROI) remain uncertain or unquantified.

Together, these studies reinforce the view that while DTs provide long-term cost savings through proactive maintenance and lifecycle optimization, the initial capital investment poses a significant barrier, especially for public infrastructure owners, small firms, and projects in developing regions.

The initial cost of implementing DTs technology remains high, which constitutes a barrier to its adoption, particularly in developing economies. The costs of deploying sensors, high-performance computing systems, and digital modeling software can be prohibitive, especially when considering the need for long-term maintenance and upgrades. Additionally, the costs of personnel training and developing new organizational processes to fully exploit DTs technology contribute to the high entry barriers.

To reduce these costs, the current research efforts are focusing on the development of low-cost sensors and more efficient computing techniques. Moreover, as the adoption of DTs grows, economies of scale may help bring down costs over time, making the technology more accessible for widespread use (Fuller et al., 2020).

5.5. Cultural and organizational barriers

The adoption of DTs technology also faces cultural and organizational barriers, particularly within the construction and infrastructure management sectors. Many organizations have traditionally relied on manual inspection and routine maintenance practices, which can be difficult to change. Resistance to new technologies, lack of digital literacy, and the need for significant organizational change are key obstacles to the successful integration of DTs in infrastructure systems. Furthermore, the lack of a clear framework for the collaboration between different stakeholders, including engineers, IT professionals, and policy makers, hinders the development and implementation of DTs solutions. Developing training programs, standards, and best practices will be critical in fostering a culture that embraces the use of DTs in civil infrastructures management (Wynne et al., 2022).

5.6. Real-time monitoring and predictive maintenance

Machine learning models play a pivotal role in enhancing the predictive maintenance capabilities of DTs. While traditional approaches rely heavily on physics-based modeling and sensor feedback, the integration of data- driven models significantly improves early fault detection, anomaly classification, and lifespan prediction of civil infrastructure systems.

Recent studies have extended these capabilities into the domain of seismic vulnerability assessment, particularly for buildings located in high seismic risk zones. For instance, Zain et al. (2024b) developed a hybrid machine learning framework incorporating artificial neural networks and genetic algorithms to assess seismic fragility in high-rise tubular structures. Their model demonstrated high accuracy and computational efficiency, offering practical integration within a real-time DTs platform.

Similarly, Zain et al. (2024a) applied various ML algorithms, including Random Forest, Extreme Randomized Trees, and XGBoost, for seismic vulnerability prediction in low-rise school buildings, achieving reliable classification of damage states in high-intensity seismic zones. These methods serve as critical tools in DTs-based early warning systems, especially for public infrastructure requiring stringent safety measures. Furthermore, an earlier study by Zain et al. (2022) conducted seismic fragility analysis using AI-driven methods for reinforced concrete buildings, providing insights into the integration of AI within DTs frameworks to support earthquake-resilient infrastructure design and retrofit strategies (Zain et al., 2022).

These contributions highlight how machine learning enhances seismic risk prediction in both low-rise and high-rise infrastructure systems, making DTs not only a tool for monitoring, but also for proactive risk mitigation in disaster-prone environments.

While DTs offer the ability to monitor infrastructure in real-time and predict future failures, there remain significant challenges in developing robust predictive models. Predictive maintenance using DTs relies heavily on the quality of data collected and the ability to process this data in real-time to detect early signs of wear and tear or potential failure. The accuracy and reliability of predictive algorithms are still evolving, with many models requiring large volumes of historical data to train effectively.

The development of more advanced machine learning algorithms and the integration of AI technologies can significantly enhance the capabilities of predictive maintenance systems. However, these systems must be able to handle the inherent uncertainty and variability in data from real-world infrastructures; this presents additional challenges for DTs (Tao et al., 2018).

5.7. Regulatory and policy challenges

As DTs are deployed in critical infrastructure, regulatory frameworks must evolve to address new challenges related to data privacy, security, and liability. Governments and regulatory bodies must develop standards for the use of DTs, ensuring that data privacy and security are maintained while also enabling the efficient use of real-time data. Moreover, policies must be in place to ensure that the adoption of DTs is equitable and that their benefits are widely distributed. Furthermore, the role of digital twins in the decision-making process must be clearly defined, as DTs models may influence critical infrastructure management decisions. The legal and ethical implications of using DTs to monitor and manage infrastructures must be carefully considered (Thonhofer et al., 2023).

5.8. Future directions

To address these challenges, several future research directions can be pursued:

- Standardization of Data Formats and Protocols: Efforts must continue to develop standardized frameworks for data interoperability across different platforms. This includes the development of universal data formats and APIs that enable seamless integration between DTs systems, BIM, GIS, and other technologies.
- Advanced AI and Machine Learning: The application of AI and machine learning can enhance the predictive capabilities of DTs. The research should focus on developing more accurate models that can handle uncertainty in real-time data, improving the reliability of predictive maintenance systems.
- Cloud and Edge Computing Solutions: To address scalability issues, future research should explore the use of cloud and edge computing for processing large volumes of data. These solutions can provide the computational power required to run DTs models at scale, while also reducing the associated costs.
- Cybersecurity Frameworks: Developing robust cybersecurity frameworks tailored to DTs will be essential to protect critical infrastructures from cyber threats. Research in this area should focus on developing secure communication protocols, data encryption techniques, and real-time threat detection systems.
- Cost Reduction and Accessibility: To make DTs technology more accessible, future research should focus on developing cost-effective sensors, data storage solutions, and more affordable modeling software. As the technology matures, economies of scale will likely reduce implementation costs, making DTs more widely adopted.
- Collaborative Research and Industry Partnerships: Collaborative research efforts between academia, industry, and government agencies are crucial for overcoming the organizational and cultural barriers to DTs adoption. The development of training programs, best practices, and standards will play a vital role in ensuring the successful integration of DTs into civil infrastructure systems.

In conclusion, while the DTs technology offers significant potential for revolutionizing the management of civil infrastructure, a concerted effort is required to address the technical, financial, and organizational challenges that currently limit its widespread use. By focusing on data integration, scalability, cybersecurity, and cost reduction, the benefits of DTs can be realized in the near future.

6. Conclusions

DTs technology represents a transformative shift in the management and maintenance of civil infrastructure, offering numerous advantages such as real-time monitoring, predictive maintenance, and improved operational efficiency. As demonstrated throughout this review, the integration of DT can significantly enhance the sustainability, safety, and performance of infrastructure systems, from bridges and buildings to transportation networks.

Despite the potential benefits, several challenges remain that hinder the widespread adoption of DT technology in civil engineering. These challenges span technical, organizational, and financial domains, including issues related to data integration, interoperability between different platforms, high implementation costs, and cybersecurity risks. Addressing these challenges requires collaboration between industry stakeholders, including researchers, engineers, and policymakers, as well as further technological advancements in areas such as machine learning, cloud computing, and secure data protocols.

The future of DT in civil infrastructure lies in overcoming these barriers and fully realizing their potential. Future research should prioritize the development of standardized data frameworks, advanced AI models for predictive maintenance, scalable cloud solutions, and cost-effective hardware. Furthermore, efforts to improve cybersecurity measures and foster a culture of digital literacy in infrastructure management will be critical to ensuring the sustainable and secure implementation of DT.

Ultimately, with continued advancements and collaboration across disciplines, DT technology has the potential to revolutionize the way we monitor, maintain, and optimize civil infrastructure, leading to smarter, safer, and more efficient built environments.

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Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article. All the authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

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APPENDIX

Table A1. Comprehensive analysis of the papers

Paper	Main Focus	Methodology/ Approach	Strengths	Weaknesses	Contribution to the Field	Key Findings/ Results	Relevance for Future Research
Romanello et al. (2024)	IoT-based bridge monitoring	Real-time IoT sensor network for monitoring bridge parameters	Advanced real-time monitoring of bridge parameters	Lack of validation with multiple real-world scenarios	Real-time monitoring of bridge health through IoT sensors	Real-time monitoring with IoT improves understanding of structural health	Research on sensor reliability and scaling for other infrastructure types
Zirpoli and Sattamino (2024)	Bridge safety monitoring with BIM and digital twins	BIM-based system for real-time bridge safety monitoring	Real-time monitoring and adherence to national guidelines	Focus on single infrastructure type (bridges)	Provides a Digital twin framework for monitoring and maintaining bridges	Successful integration of BIM and IoT for improved bridge safety	Future expansion to other infrastructure types for safety monitoring
Pregnolato et al. (2022)	Digital twins for the Clifton Suspension Bridge	Case study on applying digital twins to monitor bridge conditions	Focus on historic infrastructure and structural monitoring	Limited to the Clifton Suspension Bridge	Demonstrates how digital twins can monitor iconic historic infrastructure	Real-time monitoring of the Clifton Suspension Bridge's condition	Expand the digital twin approach to other historic structures
Kong and Hucks (2023)	Historic structure monitoring	Photogrammetry-based monitoring and digital twin modeling	Non-invasive, cost-effective solution for historic structures	Focused only on historic structures (stone arch bridge)	Demonstrates how digital twins can monitor the deterioration of historic structures	Validated on a historic stone arch bridge to detect structural deterioration	Future applications to include various types of historic structures
Sun et al. (2025b)	Bridge digital twin modeling	Knowledge-driven framework for bridge digital twin modeling	Integrates real-time data with spatiotemporal modeling	Lack of real-world validation with multiple bridge types	Proposes an innovative approach to bridge monitoring and maintenance	Improved bridge health assessments and proactive maintenance	Expanding the framework to other types of civil infrastructure
H. Hosamo and M. Hosamo (2022)	3D laser scanning for bridge maintenance	Application of 3D laser scanning for bridge inspections	Efficient and accurate data collection for bridge maintenance	Focused only on bridge infrastructure	Demonstrates the use of 3D laser scanning for more accurate bridge inspections	Improved accuracy and efficiency in monitoring bridge conditions	Expanding laser scanning technology for use in other infrastructure types
Shokravi et al. (2024)	SHM with autonomous vehicles for bridges	Using connected and autonomous vehicles (CAVs) for SHM	Real-time monitoring of bridges using data from CAVs	Limited to bridges, needs validation in other infrastructures	Introduces CAVs for continuous SHM of bridges	Provides real-time bridge monitoring through CAVs	Expansion of CAV-based SHM to other infrastructure types
Scianna et al. (2022)	BIM and IoT for real-time SHM in bridges	Real-time deflection monitoring of a bridge beam using IoT	Real-world validation and experimental use case	Limited scope (only one bridge beam)	Integrates IoT and BIM for enhanced bridge health monitoring	Real-time deflection and strain monitoring using IoT	Future work on integrating with more bridge types and IoT sensor networks
Zinke et al. (2023)	Modular digital twin for bridge structures	Linked data approach for modular digital twin models for bridges	Scalable and adaptable approach for bridge monitoring	Needs more testing in real-world applications	Proposes modular DTs for bridges to improve predictive maintenance	Enhanced life-cycle management with scalable digital twin models	Application of modular DTs to other infrastructure types
Mufti and Thomson (2024)	Civionics in SHM	Integration of civionics and IoT in structural health monitoring	Innovative integration of civionics for real-time data analysis	Lack of real-world testing	Highlights the role of civionics in infrastructure maintenance	Reduced maintenance costs and optimized system performance	Expand civionics use for other infrastructure types like dams
Callcut et al. (2021)	Digital twin applications in civil infrastructure systems	Use of digital twins in transportation, energy, and water systems	Focus on sustainability and efficiency in civil infrastructure	Limited empirical research outside theoretical frameworks	Explores digital twins for sustainability in civil infrastructure	Identifies key areas where DTs enhance resilience and sustainability	Expanding the use of DTs in other infrastructure sectors for sustainability
Bado et al. (2022)	Digital twins in distributed sensing	Role of digital twins in civil infrastructure monitoring	Enhances real-time data collection for infrastructure systems	Lack of real-world validation	Optimizes infrastructure management using real- time sensing	Improved data collection and monitoring efficiency	Future work on applying DTs to environmental infrastructure monitoring

Continue of Table A1

Paper	Main Focus	Methodology/ Approach	Strengths	Weaknesses	Contribution to the Field	Key Findings/ Results	Relevance for Future Research
Liu et al. (2022b)	Prestressed steel impact prediction using digital twins	Use of digital twins and machine learning for impact prediction	Improved predictive capabilities for structural health	Limited to a specific type of structure (prestressed steel)	Introduces predictive capabilities for prestressed steel structures	Machine learning improves impact prediction in structural health	Further application to other types of infrastructure for predictive maintenance
Sun et al. (2025a)	Digital twin applications for SHM in civil infrastructure	Use of digital twins for structural health monitoring	Integration of IoT and BIM for real-time monitoring of infrastructure	Limited to infrastructure maintenance systems	Reviews digital twin applications in SHM for civil infrastructure	Enhances SHM practices with real-time monitoring capabilities	Expanding the DT approach to other types of civil infrastructure
Malekloo et al. (2021)	Machine learning in structural health monitoring	Integration of machine learning with IoT and UAVs for SHM	Novel integration of machine learning with SHM	Limited validation in real-world infrastructure applications	Introduces machine learning to enhance predictive capabilities of SHM	Machine learning enhances damage prediction and real-time monitoring accuracy	Expanding machine learning applications to various infrastructure types
Muñoz Pavón et al. (2024)	BIM-based digital twin for university campus management	Integration of BIM with IoT for real-time space and asset management	Practical real-world application for campus infrastructure	High initial costs and data interoperability issues	Digital twin system for managing campus space and assets in real-time	Improved campus management, especially for space reservation and asset tracking	Research into reducing the costs of setting up digital twin systems
Sakr and Sadhu (2023)	IoT and BIM integration for SHM	Real-time deflection and strain monitoring of a bridge beam using IoT sensors	Provides real-world case study for SHM application	Limited to a single bridge beam for analysis	Highlights feasibility of continuous SHM using IoT-BIM integration	Real-time monitoring of a bridge beam's deflection and strain	Expanding the IoT-BIM integration to more infrastructure types
Khan et al. (2023)	Geological data management using 3D models	Boundary and voxel-based 3D model integrated with BIM and GIS	Combines BIM and GIS for efficient geological data management	High computational cost for modeling and integration	New approach for managing geological data in civil engineering	Efficient data exchange and visualization of geological data	Future work to reduce computational costs and allow for real-time integration
Ramonell et al. (2023)	Integration of data from multiple sources into digital twins	Knowledge graph integration with BIM, IoT, and process-related data	Modular, flexible/ integration system	Complexity in managing and integrating diverse data sources	Uses knowledge graphs to improve asset management by integrating multiple data types	Knowledge graphs enhance decision- making and data integration	Further research into automating the integration process
Li et al. (2024)	BIM and digital twins in civil infrastructure	Review of BIM applications integrated with digital twins	Comprehensive review of BIM-DT integration for lifecycle management	Focus on BIM-specific infrastructure rather than broader DT adoption	Proposes BIM-DT integration as a solution for infrastructure lifecycle management	BIM-DT integration improves lifecycle management and sustainability of infrastructure	Expanding BIM-DT integration to larger-scale infrastructure projects
Li et al. (2022)	WSN, BIM, IoT, and Digital Twins in construction	Review of advanced technologies for smart infrastructure maintenance	Focus on integrating emerging technologies like WSN and IoT	Needs more case study data for validation	Identifies the role of WSN, BIM, IoT in improving infrastructure SHM	Highlighted the integration challenges for real-time monitoring	Future research on overcoming challenges in data integration and standardization
Naderi and Shojaei (2022)	Knowledge map for civil infrastructure digital twins	Bibliometric and social network analysis of digital twin adoption	Provides a structured foundation for decision-makers and researchers	General focus without specific technological applications	Proposes a foundation for digital twin adoption in infrastructure	Identifies research gaps in digital twin adoption for infrastructure	Further research on practical applications of digital twins in construction
Sacks et al. (2020)	Digital twin construction for project management	BIM and digital twin integration for construction project management	Optimizes construction phases with real-time data	Limited real-world validation of the system	Uses digital twins and BIM for optimizing construction management	Improved management and outcomes through digital twin integration	Research on digital twin applications in larger construction projects
Lozano-Galant et al. (2024)	BIM and sustainability in civil infrastructure	BIM and MIVES for sustainability assessment of infrastructure	Focus on sustainability factors in infrastructure projects	Focused on specific infrastructure types (viaducts)	Introduces a methodology for sustainability assessment with BIM	Improved sustainability decision- making in infrastructure projects	Expand use of MIVES for sustainability assessment in other infrastructure types

Continue of Table A1

Paper	Main Focus	Methodology/ Approach	Strengths	Weaknesses	Contribution to the Field	Key Findings/ Results	Relevance for Future Research
Candón et al. (2024)	IoT-based asset health index for infrastructure	Integration of IoT with Asset Health Index for asset monitoring	Real-time monitoring of asset conditions	Lack of validation over a long period	Proposes IoT-based health monitoring for infrastructure assets	Improved insights into asset performance and decision-making	Future research into real-time IoT monitoring for long-term asset management
Broo and Schooling (2021)	Digital twins in infrastructure definitions	Examining digital twin definitions and practices in infrastructure	Provides a comprehensive overview of digital twin practices	General focus with theoretical applications	Highlights key barriers and proposes solutions for digital twin implementation	Identifies key barriers to digital twin implementation	Future work on standardizing digital twin practices across sectors
Providakis et al. (2022)	Risk assessment for tunneling-induced settlement	BIM-based risk assessment for tunneling-induced settlement in urban areas	Application of AHP for spatial and temporal risk analysis	Limited to tunneling projects	Proposes a risk assessment model for tunneling- related settlement	More accurate risk assessment of tunneling projects in urban areas	Application to other urban construction projects with similar risks
Osunsanmi et al. (2025)	Smart maintenance success factors in infrastructure	Bibliometric analysis of critical success factors in smart maintenance	Systematic analysis of success factors in smart maintenance	Lack of real-world case studies for application	Identifies key success factors for smart maintenance in infrastructure	Collaboration, digital twin design, and energy management are critical	Future research on applying success factors in large-scale infrastructure projects
Cheng et al. (2023)	Digital twins in emergency management	Application of digital twins for disaster response and recovery	Framework for disaster mitigation, preparedness, and recovery	Theoretical focus, lacks real-world application data	Provides a framework for applying digital twins in disaster management	Digital twins improve disaster response, preparedness, and recovery	Research into real-world disaster management applications
Raviolo et al. (2023)	FEMU algorithms for model updating	Comparison of various FEMU algorithms for SHM applications	Comprehensive comparison of optimization algorithms	Lack of empirical validation with real-world infrastructure data	Evaluates the most efficient FEMU algorithms for digital twin applications	Demonstrates optimal FEMU algorithms for real-time SHM	Application of best algorithms in real-world SHM systems for digital twins
Schreiber et al. (2024)	ESIT simulation tool for air traffic control	Development of ESIT digital twin for air traffic surveillance	Real-time management of air traffic loads in surveillance	Limited to air traffic infrastructure	Introduces ESIT tool for real-time air traffic load management	ESIT improves surveillance and management of transponder loads	Expanding ESIT to other infrastructure sectors requiring real-time monitoring
Pang et al. (2024)	Triboelectric nanogenerators for smart infrastructure	Review of TENGs for enabling self-powered sensing in digital twins	Focus on energy-efficient, self-powered systems	Limited experimental data for large-scale applications	Introduces TENGs as self-powered sensors for smart civil infrastructure	TENGs enable self-powered sensing for monitoring infrastructure health	Future work on scaling TENG applications across civil infrastructure
Liu et al. (2023)	Literature review on digital twins in infrastructure	Comprehensive review of challenges in infrastructure health monitoring	Detailed summary of challenges in digital twin adoption	No experimental or case study data included	Highlights challenges in digital twin adoption for infrastructure health	Identifies gaps in infrastructure health monitoring and digital twin integration	Future work to overcome barriers to digital twin adoption in health monitoring
Sakr and Sadhu (2024)	Digital twins in SHM of civil infrastructure	Survey of progress in digital twin technology for SHM	Comprehensive review of SHM digital twins and IoT integration	Focus only on SHM in civil infrastructure	Reviews the role of digital twins in enhancing SHM practices	Digital twins improve real-time monitoring and predictive maintenance	Expansion of DT applications to other civil infrastructure types
Abugu et al. (2024)	Cost-benefit analysis of Digital Twins in construction	Case-based investigation of DT deployment costs and benefits using industry survey and expert interviews	Offers real-world quantitative and qualitative insight into implementation costs	Limited geographic scope; focus primarily on U.S.-based construction firms	Highlights practical financial considerations for DT adoption in civil projects	Confirms high upfront costs for software, hardware, and training as major barriers	Can inform decision-making and ROI evaluations in future DT infrastructure deployments
Jahangir et al. (2024)	Drivers and barriers to DT adoption in building projects	Systematic literature review of internal/external drivers and barriers across project stages	Well-structured framework covering planning through operation phases	Generalized findings not validated against live implementations	Comprehensive identification of adoption bottlenecks including cost, interoperability, and skills	Finds high initial investment as a top deterrent across surveyed organizations	Framework can guide strategic adoption policies for cost-effective DT rollouts
Haron and Zafir (2025)	Cost management implications of DT use in construction	Exploratory study using interviews and case projects in Malaysia	Direct focus on financial planning and cost control enabled by DTs	Limited to regional projects; lacks international benchmarking	Explores how DT can improve construction budget accuracy and control	Finds that implementation costs (tech + training) hinder adoption among small firms	Supports future models that integrate DT into preconstruction cost planning and risk forecasting

End of Table A1

Paper	Main Focus	Methodology/ Approach	Strengths	Weaknesses	Contribution to the Field	Key Findings/ Results	Relevance for Future Research
Wynne et al. (2022)	Engineer perceptions on long-term monitoring integration	Survey-based study on engineer opinions about digital twin integration	Large survey sample size (146 participants)	Subjectivity of survey-based analysis	Provides insights into barriers and benefits of long-term monitoring integration	Broad support for long-term monitoring, though barriers to use remain	Overcoming cultural and organizational barriers to adoption of long-term monitoring
Zain et al. (2024b)	Seismic vulnerability of high-rise buildings using ML	Hybrid ML framework using ANN and GA for seismic fragility modeling	High predictive accuracy and efficient computation for large structures	Limited to simulated case studies, lacks real-time DT integration demonstration	Bridges AI and DT for assessing seismic performance of high-rise tubular buildings	Demonstrated high accuracy in seismic vulnerability prediction under various ground motions	Future work can focus on integrating this framework into live DT platforms for real-time seismic hazard forecasting
Zain et al. (2024a)	ML-based seismic assessment of low-rise school buildings	Comparison of RF, ERTR, XGBoost, and ANN on seismic vulnerability classification	Broad ML model evaluation, practical application to schools in high seismic zones	Real-world validation limited to a specific building typology and region	Advances DT application in public infrastructure by supporting safety-centric predictive modeling	Found RF and XGBoost as most effective classifiers for damage state prediction	Encourages development of DT-driven seismic early warning systems for educational buildings
Zain et al. (2022)	AI-driven seismic fragility for RC buildings	Application of ANN and feature selection for fragility curve generation	Robust AI-based fragility prediction with low computational cost	Generalized RC typology without structural system specificity	Demonstrates feasibility of AI integration into DT for seismic resilience	Effective fragility estimation from minimal structural inputs	Future DT platforms can embed this AI layer for scalable structural risk modeling
ElSayed et al. (2024)	UAV airspace policies and energy consumption	Simulation of UAV trajectories in a digital twin model	Realistic simulation of policy effects on delivery cost	Lack of real-world data validation	Examines the impact of UAV policies on energy consumption and charging infrastructure	Strict policies increase charging station requirements, raising costs	Testing with real UAVs in real-world environments and other constraints
He et al. (2022)	Intelligent construction technologies and digital twins	Review of intelligent construction technologies integrated with digital twins	Comprehensive review of IC technologies for infrastructure management	Focus primarily on transportation infrastructure	Comprehensive review of IC technologies and their application to civil infrastructure	Identifies how IC technologies optimize infrastructure management	Further research into integrating IC technologies with other infrastructure types
Radopoulou and Brilakis (2016)	Parking camera calibration for road defect detection	Camera calibration for automated road defect detection	Improved accuracy in road monitoring systems	Limited to road infrastructure	Enhances automated defect detection with parking camera calibration	Improved road defect detection accuracy	Expand to other types of infrastructure using computer vision technologies
Pregnolato et al. (2023)	Digital twin framework for existing infrastructure	Step-by-step workflow for integrating physical and virtual infrastructure	Focus on legacy structures and providing a workflow for DT implementation	Standardization across infrastructure types is challenging	Framework for integrating digital twins in legacy infrastructure	Step-by-step approach to creating digital twins for existing structures	Research into standardizing processes across various infrastructure types
Taheri and Sobanjo (2024)	CIM for transportation infrastructure	Civil Integrated Management for transportation infrastructure	Focus on lifecycle management using CIM technologies	Focus limited to transportation infrastructure	Proposes CIM for improving transportation infrastructure management	Optimized lifecycle management for transportation projects	Expand CIM to other civil infrastructure types and sectors
Vieira et al. (2022)	Digital twins in rail and road infrastructure	Review of digital twin applications in transportation infrastructure	Comprehensive review of DTs in rail and road infrastructure	Limited research on sustainability and resilience impact	Reviews DT applications for sustainability in transportation	Identifies key areas where DTs enhance resilience and sustainability	Future work on integrating DTs with asset and risk management strategies
Mahmoodian et al. (2022)	Intelligent infrastructure maintenance	Novel digital twin architecture for bridge maintenance	Use of semantic modeling for real-time performance monitoring	Needs more testing with diverse infrastructure types	Proposes a digital twin architecture for improving infrastructure maintenance	Reduced maintenance costs and improved efficiency	Expansion to other infrastructure types like tunnels and dams