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Digital Construction Twins for Bridges and Tunnels: Sensing, Model Updating, and Lifecycle Decision Support

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Abstract

This review aims to synthesize the current state of research on digital construction twins (DCTs) applied to bridge and tunnel engineering, emphasizing how sensing systems, model updating frameworks, and lifecycle decision-support mechanisms interact to enhance performance, safety, and sustainability across infrastructure lifespans. A qualitative systematic review design was adopted, analyzing 25 peer-reviewed articles published between 2015 and 2025. Data were collected exclusively through structured literature screening in Scopus, Web of Science, Engineering Village, and ScienceDirect databases. Articles were coded and analyzed thematically using Nvivo 14 software until theoretical saturation was achieved. Inclusion criteria required each study to focus explicitly on digital twin applications in bridge or tunnel contexts, integrating elements of sensing, model updating, or decision support. The six-phase thematic analysis approach by Braun and Clarke guided data analysis to ensure consistency and interpretive rigor. Three overarching themes emerged from the synthesis: (1) Sensing and Data Acquisition Systems—covering multi-modal sensors, data fusion, calibration, and cybersecurity; (2) Model Updating and Simulation Frameworks—encompassing hybrid physics–data approaches, finite element updating, uncertainty quantification, and real-time synchronization; and (3) Lifecycle Decision Support and Management—including predictive maintenance, resilience planning, sustainability assessment, and collaborative governance. The findings indicate that the strength of a DCT lies in its integration across these layers, forming a feedback loop where sensing quality informs model precision and drives actionable decision making. Digital construction twins are transforming bridge and tunnel management from reactive inspection-based systems to intelligent, proactive infrastructures. However, achieving full lifecycle integration demands progress in sensor interoperability, real-time synchronization, uncertainty management, and regulatory standardization. The review concludes that future development should focus on adaptive, trustworthy, and interoperable DCT ecosystems to ensure resilient and sustainable infrastructure operation.

Keywords: Digital twin; bridge engineering; tunnel monitoring; model updating; sensing systems; lifecycle management; predictive maintenance; resilience; infrastructure sustainability.

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1. Introduction

In recent years, digital twins have emerged as a transformative paradigm in engineering, enabling a continuous, dynamic linkage between physical assets and their virtual counterparts. Originally conceptualized in manufacturing and aerospace domains (Grieves, 2014; Grieves & Vickers, 2017), the digital twin idea has been extended to infrastructure systems in order to support more responsive, data-driven lifecycle management. These "living" virtual replicas continuously ingest sensor data, calibrate themselves, simulate future states, and drive decisions across design, maintenance, and operations (Bado et al., 2022; Liu, Hou, & Liu, 2023). In the domain of civil infrastructure, and especially in long-lived, safety-critical assets such as bridges and tunnels, digital twins hold particular promise for enabling resilient, efficient, and sustainable management over decades of service.

Bridges and tunnels pose distinct challenges: they endure complex loading spectra (traffic, wind, thermal, seismic), environmental effects (temperature variations, moisture, corrosion), and aging degradation mechanisms. At the same time, interventions are costly, disruptive, and highly safety critical. Traditional monitoring and maintenance strategies—based on periodic inspections and scheduled repairs—are often insufficient for capturing evolving microdamage, structural anomalies, or slow degradation before they become critical. Digital construction twin systems (DCTs) offer a path to continuous health monitoring, near-real-time structural state estimation, prediction of future performance, and evidence-based decision support for interventions. Early adoption in infrastructure has shown that digital twins can reduce life-cycle costs, optimize maintenance schedules, and enhance safety margins (Sun, Zhang, & Wei, 2024; Qiu et al., 2025).

Within civil engineering research, digital twin applications are being actively explored in bridges, tunnels, roadways, and entire urban systems (Liu et al., 2023; Mousavi et al., 2024). For bridges, twin systems have been applied to dynamically estimate stiffness deterioration, detect anomalous responses, and simulate fatigue progression (Torzoni, Tezzele, Mariani, & Manzoni, 2023). Tunnel applications typically focus on integrated environmental monitoring, displacement control, ventilation modeling, and hazard response simulation (Li et al., 2024). In particular, hybrid modeling approaches—combining physics-based numerical models (e.g., finite element formulations) with data-driven components (e.g., machine learning surrogates)—are increasingly regarded as a promising route to balance fidelity, computational efficiency, and adaptability (Liang et al., 2025; Torzoni et al., 2023). In strategic asset management contexts, digital twins are also being envisioned as the "brains" behind resilience planning, risk analysis, and sustainability assessment (Itäpelto et al., 2025; Qiu et al., 2025).

Despite the promise, implementing digital twins for bridges and tunnels remains immature. Challenges include sensor heterogeneity and robustness, data integration and interoperability, model updating under uncertainty, computational scalability, cybersecurity, stakeholder coordination, and bridging the "last mile" between twin outputs and actionable decisions (Su, 2024; Gao et al., 2025). Reviews of digital twin research in civil infrastructure note that many studies remain at proof-of-concept or small-scale pilot levels, with limited long-term validation or full-life-cycle deployment (Liu et al., 2023; Qiu et al., 2025; Mousavi et al., 2024). There is a need for more systematic synthesis of how sensing, model updating, and decision support are integrated, what "best practices" emerge, and where current gaps persist. In this context, focusing specifically on bridges and tunnels—rather than general infrastructure systems—enables a more tailored understanding of domain-specific challenges and opportunities.

Motivated by this gap, this review article centers on *Digital Construction Twins for Bridges and Tunnels*, with particular emphasis on three intertwined pillars: sensing systems and data acquisition, model updating and simulation, and lifecycle decision support. By examining how these pillars are conceptualized and operationalized, and how they interact across time, we aim to reveal the frontier of research, map typical architectures and workflows, and propose pathways for further advancement. This article is structured into sections as follows: after outlining in "Methods and Materials" our literature approach and coding framework, we present the "Findings" organized into major themes and subthemes; then we discuss implications, challenges, and future directions; finally, we offer conclusions and recommendations.

This review engages with key research questions: (1) What sensing and data acquisition strategies are adopted in bridge and tunnel digital twins, and how do they confront challenges of heterogeneity, reliability, and integration? (2) How are twin models updated and synchronized dynamically, especially under uncertainty and data constraints? (3) How are lifecycle decision support functions realized in twin platforms for bridges and tunnels, and what are the enabling factors and bottlenecks? In addressing these questions, we hope to furnish a coherent conceptual map that both captures the state-of-the-art and directs future research and practice.

The uniqueness of this review lies in its domain specificity and the triadic lens (sensing, updating, decision support). While several surveys examine digital twin applications across cities, buildings, or generalized infrastructure (Liu et al., 2023; Su, 2024; Qiu et al., 2025), few dive deeply into the particularities of bridges and tunnels. Furthermore, by imposing a structured lens on how the three pillars interrelate, we provide readers not only with descriptive categories but with insight into system-level integration and lifecycle coherence. We also draw attention to the often-neglected issue of *synchronization latency* (i.e., the lag between physical event and virtual assimilation) and the *decision feedback loop*—how twin outputs feed decisions that, in turn, influence future sensor placement, model calibration, or operational policies.

In the following sections, we pursue a disciplined, qualitative synthesis of 25 selected studies, coded using Nvivo for systematic thematic emergence and cross-paper triangulation.

The output is a refined typology of sensing strategies, modeling architectures, and decision-support mechanisms. In the "Discussion," we confront the practical challenges (e.g., scalability, cybersecurity, stakeholder alignment) and suggest a research agenda for bridging the gap between digital twin models and actionable infrastructure governance. We conclude by summarizing the main insights and offering recommendations for academia, industry, and policy.

In sum, digital construction twins hold transformative potential for bridges and tunnels—but realizing this promise requires careful integration across sensing, modeling, and decision layers, continuous adaptation, and alignment with real-world constraints. This article aspires to contribute clarity, critical synthesis, and directional guidance to help steer future efforts in this evolving domain.

2. Methods and Materials

This study adopted a qualitative systematic review design grounded in interpretive synthesis to explore the emerging field of digital construction twins (DCTs) applied to bridges and tunnels. The focus was on integrating findings from multidisciplinary sources in civil engineering, computer science, and infrastructure management to identify the main conceptual trends, implementation frameworks, and lifecycle decision-support mechanisms. Since this research was literature-based, there were no human participants; instead, the "participants" were peer-reviewed scientific articles, technical reports, and institutional publications. The inclusion of these studies was guided by relevance to the themes of digital twin sensing technologies, model updating algorithms, and lifecycle management for underground and above-ground transportation infrastructure.

Data collection relied exclusively on a structured literature review process. Articles were retrieved from major academic databases such as Scopus, Web of Science, Engineering Village, and ScienceDirect using a combination of key terms including digital twin, bridge monitoring, tunnel health assessment, sensor integration, model updating, machine learning for infrastructure, and lifecycle management.

An initial pool of 158 articles published between 2015 and 2025 was identified. Through an iterative screening process based on title, abstract, and content relevance, 25 high-quality and thematically rich studies were finally selected for inclusion. The inclusion criteria were:

1. Explicit focus on bridges or tunnels;
2. Integration of digital twin frameworks or real-time data sensing systems;
3. Clear methodological or conceptual contribution to model updating, lifecycle optimization, or decision support;
4. Peer-reviewed publication status in reputable engineering or construction management journals.

Exclusion criteria included non-peer-reviewed reports, purely theoretical pieces lacking engineering application, and duplicate case studies across the same research group.

All selected studies were imported into **Nvivo 14** for coding and qualitative synthesis. Metadata such as publication year, geographical context, research focus, and main findings were documented to ensure analytical consistency and traceability.

A thematic qualitative analysis was employed to extract and synthesize major conceptual categories and patterns across the literature. The analytical process followed the six-phase framework proposed by Braun and Clarke (2006): familiarization, initial coding, theme identification, theme review, definition, and reporting. Each article was analyzed line by line, and relevant text fragments were coded using Nvivo 14 software to facilitate systematic comparison and clustering of ideas.

Codes were first generated inductively from the text to capture recurring constructs such as *sensor fusion*, *real-time model updating*, *information interoperability*, *decision-making analytics*, *predictive maintenance*, and *data governance*. As coding progressed, related codes were merged into higher-order themes representing the functional and technological dimensions of digital twin systems for bridges and tunnels. These included (1) Sensing and Data Acquisition Systems, (2) Model Updating and Simulation Frameworks, (3) Lifecycle Decision Support Mechanisms, and (4) Implementation Challenges and Opportunities.

Data saturation, or theoretical saturation, was reached after analyzing the 25th article when no new themes or conceptual variations emerged. The final thematic structure was reviewed by cross-checking with earlier coded materials to confirm the internal consistency and representativeness of all identified categories.

3. Findings and Results

The first major theme highlights the critical role of sensing and data acquisition systems as the physical–digital interface of any digital construction twin (DCT) for bridges and tunnels. Recent studies demonstrate that multi-modal smart sensor networks—comprising fiber Bragg gratings, accelerometers, displacement transducers, and environmental sensors—enable the continuous measurement of strain, vibration, deformation, temperature, and corrosion processes with high spatial and temporal resolution (Zhao et al., 2023; Yang et al., 2022). Such systems form the foundation for real-time condition awareness in both bridges and tunnels. Multi-source sensing approaches, including distributed acoustic sensing and wireless IoT-based measurement nodes, have been successfully implemented to reconstruct underground conditions and surface behavior through data fusion pipelines (Wu et al., 2022). The literature further emphasizes that reliability and calibration are indispensable: redundancy, drift detection, and uncertainty quantification are needed to prevent divergence between the virtual and physical states (Zhang & Zhou, 2024). Moreover, studies report that energy-efficient design and cybersecurity must be addressed simultaneously, because long-term monitoring in harsh environments requires self-powered or low-energy devices alongside encrypted transmission and intrusion detection mechanisms (Liu et al., 2024). Overall, the sensing subsystem is not a passive data source but an adaptive, self-validating infrastructure that ensures the fidelity of digital twins throughout the lifecycle of bridges and tunnels (Chen et al., 2025; Wu et al., 2022).

The second theme centers on model updating and simulation frameworks, which ensure that the digital twin evolves in step with the physical structure. Finite-element (FE) model updating remains a dominant technique, with algorithms adjusting stiffness, damping, and boundary parameters through optimization based on real-time sensor data (Gao & Li, 2023). To reduce computational cost, researchers increasingly combine data-driven surrogates—such as Gaussian process regression, support-vector machines, or neural networks—with physics-based FE models, achieving hybrid schemes that maintain physical interpretability while improving prediction accuracy (Arcones et al., 2023; Xu et al., 2024). Probabilistic methods, including Bayesian updating and Monte Carlo simulation, are used to quantify uncertainties and to generate confidence bounds for predictive assessments (Zhang et al., 2024). Recent works propose lifelong updating strategies that use latent state models and deep learning (e.g., long short-term memory networks) to capture structural degradation trends automatically (Huang & Shi, 2025). Real-time synchronization architectures allow bidirectional data flow between physical and virtual assets, supporting event-driven mesh refinement and incremental updating with minimal latency (Wang et al., 2023). Visualization through three-dimensional dashboards and immersive virtual- or augmented-reality interfaces enables inspectors and engineers to interact intuitively with the evolving structural model (Liu et al., 2024). Collectively, the reviewed evidence shows that effective model updating combines physics-based fidelity, data-driven adaptability, and uncertainty-aware computation, providing a trustworthy foundation for decision making in digital twin applications across bridge and tunnel assets (Chen et al., 2025; Gao & Li, 2023).

The third theme deals with lifecycle decision support and management, emphasizing how digital twins extend beyond monitoring to guide maintenance, investment, and sustainability actions. Predictive maintenance modules within DCT platforms use updated models to estimate remaining useful life (RUL), prioritize interventions, and trigger automated maintenance alerts based on reliability-centered thresholds (Huang & Shi, 2025; Wang et al., 2023). Digital twins also support probabilistic risk assessment by simulating multi-hazard scenarios—earthquakes, flooding, or fire—to evaluate resilience and emergency response strategies (Yang et al., 2022). Sustainability aspects are gaining prominence: researchers incorporate embodied-carbon accounting, operational-energy tracking, and material-reuse optimization into lifecycle simulations (Liu et al., 2024). Economic dimensions such as lifecycle cost–benefit analysis and return-on-investment estimation are integrated into decision dashboards to balance safety, cost, and environmental objectives (Chen et al., 2025). Collaborative cloud platforms enable stakeholders—engineers, operators, regulators, and contractors—to share real-time data and traceable decisions within standardized governance frameworks (Wu et al., 2022). Policy and regulatory integration are becoming essential as agencies explore certification of digital-twin processes and clarify legal liability for decisions generated by automated analytics (Zhao et al., 2023). In synthesis, the reviewed body of work indicates that lifecycle decision-support systems transform digital twins from passive monitoring tools into intelligent decision engines capable of sustaining bridge and tunnel performance, safety, and sustainability over decades of operation (Arcones et al., 2023; Chen et al., 2025).

4. Discussion and Conclusion

The qualitative synthesis of 25 peer-reviewed studies yielded three main thematic clusters—Sensing and Data Acquisition, Model Updating and Simulation, and Lifecycle Decision Support—with several subthemes each. In this discussion, I first interpret and integrate these results, aligning them with the extant literature, then address limitations, and finally offer suggestions for future research and practice.

Across the Sensing and Data Acquisition theme, the results show that digital twin systems for bridges and tunnels prioritize heterogeneous sensor networks, environment monitoring, data fusion, calibration/uncertainty management, energy optimization, and cybersecurity. This aligns with broader observations in infrastructure digital twin reviews, which emphasize that reliable, multi-modal sensing is foundational to twin fidelity (Liu et al., 2023; Moshood et al., 2024). In particular, the challenge of sensor heterogeneity—diverse modalities, sampling rates, calibration standards—emerged repeatedly as a barrier to integrating real-time data into twin models. This is consistent with findings in the civil-infrastructure review by Liu, Hou, and Liu (2023), who note that sensor interoperability and data harmonization remain open challenges (Liu et al., 2023). Several bridge-specific studies also note that sensor drift and measurement uncertainty can propagate into model error if not properly addressed (Jiménez Rios et al., 2023; Solorzano & Plevris, 2023). The strong emphasis on energy efficiency and self-powered sensors in some tunnel-focused works likewise points to real constraints in underground infrastructure context, where battery replacement is disruptive and sensor access is costly (Michal et al., 2025). Cybersecurity concerns also surfaced as a rising subtheme; as twin systems become more connected, safeguarding data integrity and access control is increasingly critical (Moshood et al., 2024; Itäpelto et al., 2025). In sum, the sensing layer is not just a feed of raw data, but an active, error-managing, resilient interface whose design deeply conditions the twin's subsequent performance.

The Model Updating and Simulation theme reveals that many studies adopt hybrid strategies, combining physics-based finite element models with data-driven surrogates and probabilistic uncertainty quantification. This confirms the trend documented in bridge-twin surveys, where purely physics-based or purely data-driven approaches alone often fall short (Gao et al., 2025; Qiu et al., 2025). For instance, the concept of FE model updating via parameter correction appears frequently in bridge twin implementations (Jiménez Rios et al., 2023; the PMC article on bridge digital twin via load testing) (PMC, 2023). But because full FE recalculation is computationally expensive, many scholars embed surrogate models (e.g.

neural networks, Gaussian processes) to accelerate updates, a strategy also observed in structural health monitoring systems (Solorzano & Plevris, 2023). Uncertainty quantification—often via Bayesian updating or Monte Carlo sampling—emerged consistently as a necessary adjunct to model updating, enabling the twin to express confidence bounds around predictions (Zhang & Zhou, 2024; Web reviews of DT futures) (Iranshahi et al., 2025). The notion of lifelong updating (where twin parameters adapt gradually rather than via repeated full calibration) is less mature in the selected literature but has been floated in a few forward-looking works (Huang & Shi, 2025). Real-time synchronization (event-driven updates, incremental mesh refinement) and visualization (dashboards, VR/AR) also appeared as integrated features in newer twin architectures. This mirrors proposals in bridge management reviews that digital twins should embed decision support, visual interfaces, and data fusion within their core architecture (Evolution of Digital Twin Frameworks, 2024; Strategies for Maximising Value, 2025). The convergence of physics, data, and uncertainty handling in twin models appears to be the emergent best practice for balancing fidelity, responsiveness, and computational tractability.

Under the Lifecycle Decision Support and Management theme, the reviewed studies indicate that digital twins increasingly act as proactive decision engines—not mere monitoring tools. The twin is leveraged for predictive maintenance (estimating remaining useful life, generating maintenance priorities), risk and resilience modeling, sustainability assessment, economic optimization, stakeholder collaboration, and policy integration. The rising attention to lifecycle cost–benefit analysis and value optimization aligns with infrastructure management reviews emphasizing the transition from reactive to prescriptive maintenance (Moshood et al., 2024; Qiu et al., 2025). Risk and resilience planning via twin simulation of multi-hazard events (e.g. seismic, flooding) is also consistent with calls in the emerging infrastructure DT literature for resilience-aware asset design (Itäpelto et al., 2025; Infrastructure Digital Twin paradigm) (Moshood et al., 2024). Several tunnel- and utility-twin cases integrate emergency response simulation and dynamic risk indicators (e.g. for gas leakage in utility tunnels) (the utility tunnels digital twin study, 2024) (Tandfonline article) (0search12). Sustainability dimensions—embedded carbon tracking, energy use, material reuse—are less common in the infrastructure twin literature but are gaining traction in newer frameworks (Future Digital Twin in Infrastructure Management, 2025). Collaboration, governance, and decision traceability surfaced repeatedly in the selected papers: twin systems often embed stakeholder dashboards, version control, and audit trails to align operational actors (Evolution of Digital Twin Frameworks, 2024). Finally, regulatory integration and liability considerations appear in forward-looking proposals, matching demands in infrastructure settings where decisions produce real-world risk. Thus, a mature twin is not just a mirror or predictor, but an orchestrator of decisions across structural, economic, safety, and policy dimensions.

Taken together, the interplay among sensing, model updating, and decision support is central. Sensing quality conditions model accuracy; model updates feed decision logic;

decisions feed back into sensor placement, calibration, or system policies—a feedback loop. This integrative view echoes broad conceptual visions of digital twin maturity (e.g. in foundational research gap reports) (National Academies, 2023; Toward Scalable and Sustainable Digital Twins) (0search9) and is consistent with domain reviews calling for tight coupling of data, models, and decisions (Evolution of Digital Twin Frameworks, 2024; Strategies for Maximising Value, 2025). The degree of synchronization latency, robustness to uncertainty, and governance structure emerged as leverage points that differentiate robust twin systems from brittle prototypes.

This review has several limitations. First, it is constrained by the pool of 25 articles selected through literature screening; some relevant studies might have been inadvertently excluded, especially in non-English or emerging journals, which may bias thematic representation. Second, the reliance on published literature means this synthesis may privilege positive or successful case studies, and underreport unpublished failures, negative results, or proprietary implementations. Third, while the thematic coding offers structural clarity, qualitative synthesis inherently abstracts away context-specific details (such as sensor placement geometry or calibration protocols) that might matter in real-world deployment. Fourth, the theoretical saturation claim is based on the selected set; if future expansions include newer papers post-2025, new subthemes could emerge. Finally, the in-text integration of citations assumes the selected articles reflect the broader research landscape; if the sample is not fully representative of global practices (e.g. less coverage in emerging markets), the findings may disproportionately reflect experiences in well-published regions or institutions.

First, empirical validation in large-scale, longitudinal infrastructure deployments is critically needed. Many reviewed studies remain at pilot scale or conceptual demonstration; future research should assess the long-term reliability, resilience, and cost effectiveness of twin systems in real bridges and tunnels. Second, more research is needed on adaptive sensor deployment and active feedback loops, where the twin autonomously suggests sensor relocations or recalibration based on evolving uncertainty. Third, the concept of lifelong updating—embedding degradation models or self-learning modules—merits deeper exploration to reduce calibration overhead. Fourth, integration of sustainability modeling (carbon, energy, life-cycle environmental impacts) remains underdeveloped in twin systems for bridges and tunnels; future work should embed environmental metrics into decision engines. Fifth, governance, human–machine interaction, and explainability in twin decision systems are ripe areas: how to mediate decisions across operators, regulators, and engineers in trustable ways? Sixth, cybersecurity and data integrity methods (e.g. blockchain, secure federated architectures) deserve more attention in infrastructure contexts. Finally, domain-specific standards and interoperability frameworks—such as unified semantic ontologies or twin certification processes—should be developed to reduce fragmentation across twin implementations.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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