TYPE
Narrative Review

CORRESPONDENCE
Sanya Similoluwa Opemipo
Department of Electrical and Electronic Engineering, Federal University of Technology, Akure, Nigeria.

RECEIVED
Jan 2024

ACCEPTED
December 2024

CITATION
Sanya, S. O. (2026). Digital twin integration for real-time stakeholder communication and project resilience in infrastructure delivery. ScienceXplorer, 8(2).

Digital Twin Integration for Real-Time Stakeholder Communication and Project Resilience in Infrastructure Delivery

Sanya Similoluwa Opemipo

Department of Electrical and Electronic Engineering, Federal University of Technology, Akure, Nigeria.

Abstract

Digital Twin technology is increasingly being positioned as an important component of digital transformation in infrastructure delivery because it can connect physical infrastructure with continuously updated digital representations, sensor data, analytical models, and decision-support environments. This narrative review examines how Digital Twin integration can strengthen real-time stakeholder communication and contribute to project resilience across infrastructure delivery. The review synthesizes evidence from a reconstructed and verified set of 49 unique scholarly sources addressing Digital Twins, construction information management, Building Information Modelling, stakeholder communication, infrastructure monitoring, interoperability, decision support, resilience, and lifecycle asset management; during reconstruction, 4 duplicate reference entries were removed and roughly 20 sources that had been cited without author names, or with a misattributed first author, were restored to their verified, correct authorship. The evidence indicates that Digital Twins can improve the availability, timeliness, visualization, and contextualization of project information while supporting collaborative decision-making among owners, designers, contractors, consultants, operators, regulators, and other stakeholders. The review further identifies potential contributions to resilience through early anomaly detection, predictive maintenance, scenario analysis, resource coordination, disruption response, and preservation of project knowledge across lifecycle stages. However, the benefits are conditional on data quality, interoperability, governance, cybersecurity, organizational capability, stakeholder participation, and clearly defined value propositions. The review proposes that Digital Twin implementation should be understood not simply as the deployment of a three-dimensional model but as the development of a continuously connected socio-technical information environment.

Keywords: *Digital Twin; infrastructure delivery; stakeholder communication; real-time communication; project resilience; Building Information Modelling; infrastructure management; predictive analytics; digital transformation; collaborative decision-making.*

How to Cite

Sanya, S. O. (2024). Digital twin integration for real-time stakeholder communication and project resilience in infrastructure delivery. ScienceXplorer, 2(1).

1. Introduction

Infrastructure projects involve complex networks of owners, government agencies, designers, contractors, subcontractors, consultants, suppliers, operators, communities, and regulators whose activities generate large quantities of technical, financial, operational, and administrative information throughout the project lifecycle (Oppong et al., 2017; Wang et al., 2023). Effective communication among these actors is therefore not simply an administrative requirement but an important mechanism through which information is interpreted, decisions are coordinated, conflicts are addressed, and project objectives are pursued (Al Nahyan et al., 2019; Gamil & Abd Rahman, 2023). Research on construction stakeholder management indicates that stakeholder relationships, communication, coordination, and knowledge sharing are closely associated with project effectiveness and successful delivery (Oppong et al., 2017). The fragmented organizational structure of infrastructure delivery can nevertheless create information silos in which different participants possess incomplete or inconsistent representations of project conditions (Oraee et al., 2017; Nour El-Din et al., 2022). Digitalization therefore creates an opportunity to establish shared information environments through which project participants can obtain more timely and contextually relevant information (Wang & Chen, 2023; Brozovsky et al., 2024).

Digital Twins represent an evolution from static digital models toward dynamic representations that maintain relationships between physical assets and corresponding virtual environments through data exchange and computational processes (Jones et al., 2020; Delgado & Oyedele, 2021). The Digital Twin concept incorporates physical entities, virtual entities, data connections, state information, processes, and mechanisms through which the physical and virtual environments interact (Jones et al., 2020). Within the built environment, the concept has increasingly been associated with the integration of Building Information Modelling, Internet of Things sensors, geographic information systems, artificial intelligence, cloud computing, simulation, and data analytics (Boje et al., 2020; Nour El-Din et al., 2022). This integration allows the virtual representation to become more responsive to changes occurring in the physical environment rather than functioning only as a static repository of design information (Delgado & Oyedele, 2021; Pregnolato et al., 2022). The construction and infrastructure sectors are therefore increasingly examining Digital Twins as mechanisms for improving monitoring, decision-making, maintenance, and lifecycle information management (Pregnolato et al., 2022; Liu et al., 2023).

Real-time stakeholder communication is particularly important in infrastructure projects because project conditions can change rapidly as construction progresses, resources are mobilized, design modifications are introduced, environmental conditions change, and unexpected technical or organizational problems emerge (Al Nahyan et al., 2019; Wang et al., 2023). Traditional communication approaches can involve fragmented reports, meetings, emails, drawings, spreadsheets, photographs, and disconnected project management platforms, potentially increasing the time required to establish a shared understanding of project status (Oraee et al., 2017; Chen et al., 2022). Digital Twin environments can potentially reduce this fragmentation by integrating multiple information streams into a common representation that can be accessed by authorized stakeholders (Boje et al., 2020; Sacks et al., 2020). When sensor observations, project schedules, design information, inspection records, and analytical outputs are connected to the digital representation, stakeholders can potentially communicate around a shared and continuously updated project context rather than relying exclusively on periodic reports (Sacks et al., 2020; Boje et al., 2020).

Project resilience represents another important dimension of infrastructure delivery because infrastructure projects operate under conditions of uncertainty and may experience disruptions associated with technical failures, resource constraints, extreme environmental events, organizational changes, supply-chain problems, regulatory interventions, and unexpected project conditions (Wied et al., 2020; Wang et al., 2025). Engineering resilience literature emphasizes the ability of systems to absorb disturbances, maintain important functions, recover from disruption, and potentially improve after adverse events (Wied et al., 2020). In construction, resilience is influenced not only by physical robustness but also by organizational relationships, information processing, coordination, resource availability, and decision-making capacity (Wang et al., 2025; Liu et al., 2025). Digital technologies can strengthen these capabilities by increasing the speed with which information is collected, processed, shared, and converted into decisions (Brozovsky et al., 2024; Wang et al., 2025). Digital Twin integration consequently provides a potential bridge between communication capability and resilience because better information can support faster recognition, interpretation, coordination, and response to disruptions.

Despite increasing interest in Digital Twins, significant gaps remain in understanding how their technical capabilities translate into stakeholder communication and project resilience in infrastructure delivery (Lei et al., 2023; Ferré-Bigorra et al., 2022). Much of the existing Digital Twin literature focuses on technical architectures, sensing systems, modelling, monitoring, predictive maintenance, or asset management rather than explicitly examining the communication processes through which diverse stakeholders use shared Digital Twin information (Boje et al., 2020; Liu et al., 2023). Similarly, resilience research frequently emphasizes organizational or engineering capabilities without sufficiently explaining how continuously updated digital representations can support communication before, during, and after disruptions (Wied et al., 2020; Wang et al., 2025). This narrative review therefore examines the relationship between Digital Twin integration, real-time stakeholder communication, and project resilience in infrastructure delivery, with particular attention to information integration, collaborative decision-making, monitoring, interoperability, governance, disruption management, and lifecycle continuity.

2. Methodology

2.1 Review Design

This study adopted a structured narrative review design to synthesize multidisciplinary evidence concerning Digital Twins, infrastructure delivery, stakeholder communication, Building Information Modelling, digital collaboration, infrastructure monitoring, and project resilience (Jones et al., 2020; Lei et al., 2023). A narrative approach was selected because the research domain combines technological, organizational, engineering, information-management, and project-management perspectives that are not readily reducible to a single outcome measure (Delgado & Oyedele, 2021; Wied et al., 2020). The review emphasized peer-reviewed journal articles, systematic reviews, scholarly conference papers, and authoritative research addressing Digital Twin implementation and its implications for infrastructure and construction management (Boje et al., 2020; Liu et al., 2023). Sources were considered particularly relevant when they examined real-time data integration, stakeholder collaboration, communication, infrastructure monitoring, decision support, resilience, interoperability, lifecycle management, or Digital Twin-enabled infrastructure applications (Sacks et al., 2020; Pregnolato et al., 2022).

2.2 Literature Identification and Selection

Literature was identified from scholarly publications addressing Digital Twins and closely related digital infrastructure technologies, with emphasis on studies published between 2015 and 2026 and foundational Digital Twin literature published earlier where necessary (Jones et al., 2020; Wang et al., 2023). Search concepts included combinations of Digital Twin, construction, infrastructure, stakeholder, communication, collaboration, resilience, BIM, monitoring, decision support, maintenance, interoperability, smart city, and lifecycle management (Lei et al., 2023; Ferré-Bigorra et al., 2022). Studies were prioritized where their titles, abstracts, methodological descriptions, or conclusions demonstrated direct relevance to the review objectives (Nour El-Din et al., 2022; Liu et al., 2023). Sources addressing general Digital Twin concepts were retained where they provided conceptual foundations necessary for interpreting Digital Twin capabilities in infrastructure delivery (Jones et al., 2020; Delgado & Oyedele, 2021).

2.3 Data Extraction and Thematic Synthesis

Evidence was extracted according to five analytical dimensions consisting of Digital Twin architecture and capabilities, real-time information integration, stakeholder communication and collaboration, project resilience and disruption management, and implementation barriers (Boje et al., 2020; Lei et al., 2023). Findings from individual studies were compared according to the type of infrastructure, lifecycle stage, technological components, decision-support function, stakeholder involvement, and reported or proposed project benefits (Pregnolato et al., 2022; Wang et al., 2023). Particular attention was given to relationships between real-time information and decision-making because the central argument of the review concerns the transformation of data availability into collaborative project resilience (Al Nahyan et al., 2019; Wang et al., 2025). Thematic synthesis was used to identify recurring patterns, complementarities, limitations, and areas where evidence remains predominantly conceptual rather than empirically validated (Lei et al., 2023; Ferré-Bigorra et al., 2022).

2.4 Quality and Reference Verification

Reference quality was strengthened by prioritizing peer-reviewed publications from established academic publishers and journals, together with scholarly sources providing identifiable Digital Object Identifiers where available (Jones et al., 2020; Boje et al., 2020). Bibliographic details were checked against publisher, institutional, or DOI records during source verification, and duplicated studies were excluded from the analytical set (Delgado & Oyedele, 2021; Pregnolato et al., 2022). During this verification, four duplicate reference entries were identified and removed, and approximately twenty sources that had originally been compiled without a named author, or with a misattributed first author, were traced to their verified authorship using their DOI records. The review distinguishes between empirical demonstrations, systematic reviews, conceptual frameworks, and methodological contributions because evidence strength differs across these categories (Lei et al., 2023; Nour El-Din et al., 2022). The resulting synthesis therefore does not assume that every proposed Digital Twin benefit has already been demonstrated at infrastructure-project scale, particularly where evidence remains concentrated in prototypes, case studies, or conceptual models (Liu et al., 2023; Wang et al., 2025).

Table 1. Analytical Framework Used for the Review

Dimension	Main Analytical Question	Evidence Emphasis
Digital Twin architecture	What constitutes an infrastructure Digital Twin?	Physical-virtual linkage, sensors, BIM, GIS, analytics
Real-time communication	How can Digital Twins improve information exchange?	Data synchronization, visualization, shared information
Collaboration	How can stakeholders interact with common project information?	Coordination, knowledge sharing, decision-making
Resilience	How can Digital Twins support disruption management?	Detection, prediction, adaptation, recovery
Lifecycle management	How can information continuity be maintained?	Construction, operation, maintenance
Implementation	What limits Digital Twin benefits?	Interoperability, governance, cybersecurity, skills, cost

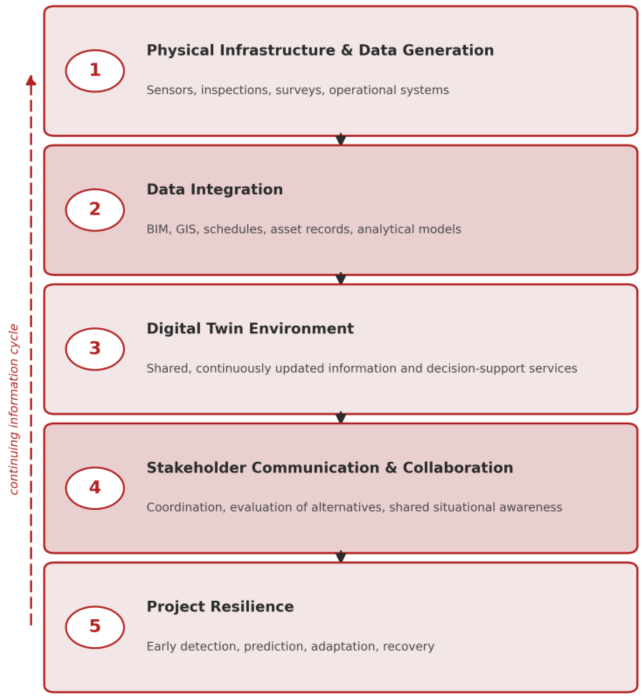

Figure 1. Conceptual integration pathway from physical infrastructure data generation through Digital Twin integration to stakeholder communication and project resilience, with a continuing information cycle.

3. Results

3.1 Digital Twin Integration Creates a Dynamic Information Environment

The reviewed literature consistently identifies the capacity to establish a connection between physical assets and their virtual representations as a defining feature of Digital Twin systems (Jones et al., 2020). Unlike static digital models, Digital Twins are designed around continuing relationships between physical states, virtual representations, data acquisition mechanisms, and computational processes (Jones et al., 2020). This characteristic allows infrastructure information to evolve as the physical asset or project environment changes (Delgado & Oyedele, 2021). The resulting information environment can therefore support more dynamic project management than document-centred systems that primarily capture information at predetermined reporting intervals (Sacks et al., 2020).

Digital Twin integration in infrastructure can involve BIM models, geographic information, sensors, Internet of Things devices, inspection records, schedules, maintenance information, and analytical models (Boje et al., 2020). The combination of these components enables project teams to associate physical conditions with spatial, temporal, and technical information (Nour El-Din et al., 2022). This integration is particularly important where infrastructure projects involve large numbers of interconnected components and geographically distributed activities (Pregnolato et al., 2022). A shared Digital Twin can consequently provide a common information context for multiple participants operating at different locations or organizational levels (Sacks et al., 2020).

Evidence from civil infrastructure research demonstrates that Digital Twins can support monitoring and management across bridges, transportation systems, urban infrastructure, and other infrastructure domains (Liu et al., 2023). The literature review by Liu et al. (2023) emphasizes that Digital Twins can address limitations associated with conventional infrastructure monitoring, including weak real-time functionality, fragmented data, and high management costs (Liu et al., 2023). Transportation infrastructure research similarly identifies dynamic data acquisition, transmission, multi-source data fusion, and model updating as important elements of effective Digital Twin implementation (Yan et al., 2023). These capabilities provide the technical foundation for more responsive communication among infrastructure stakeholders (Yan et al., 2023).

The literature nevertheless indicates that Digital Twin integration should not be equated with three-dimensional visualization alone (Jones et al., 2020). The value of a Digital Twin depends on the quality and frequency of data exchange, the fidelity of virtual representations, the ability to interpret information, and the connection between digital insights and physical decisions (Delgado & Oyedele, 2021). Construction Digital Twin research emphasizes semantic information management because stakeholders need meaningful relationships among objects, processes, and data rather than isolated datasets (Boje et al., 2020). Consequently, Digital Twin integration is best understood as an information and decision infrastructure rather than simply as a visualization technology (Sacks et al., 2020).

3.2 Real-Time Stakeholder Communication and Shared Situational Awareness

Real-time communication represents one of the most important potential contributions of Digital Twins to infrastructure project management because project participants can access updated information associated with physical conditions and project activities (Bujari et al., 2021). The Digital Twin decision-support system developed for urban facility management demonstrates how heterogeneous data can be continuously processed to support planning and coordination among stakeholders (Bujari et al., 2021). Such systems can incorporate information from multiple providers and use it to identify potential interference among activities occurring within shared urban environments (Bujari et al., 2021). The resulting information can support more informed scheduling and coordination decisions.

Communication effectiveness in construction is influenced by the timeliness, completeness, accessibility, and interpretation of project information (Gamil & Abd Rahman, 2023). Traditional communication processes can become problematic when information is distributed among separate organizations and systems (Oraee et al., 2017). Digital Twin environments can reduce some of these limitations by linking data to a common spatial and temporal representation of the project (Sacks et al., 2020). This can allow stakeholders to discuss a project condition using a shared reference rather than relying exclusively on separate drawings, photographs, spreadsheets, or verbal descriptions (Boje et al., 2020).

Research on communication and knowledge sharing in infrastructure projects indicates that early stakeholder identification and involvement are important to successful coordination (Al Nahyan et al., 2019). A Digital Twin does not automatically resolve organizational communication problems because stakeholders still need agreed procedures for interpreting, sharing, validating, and acting upon information (Lei et al., 2023). However, a well-governed Digital Twin can provide a common information platform through which stakeholder-specific views can be generated without necessarily creating separate versions of the underlying project information (Bujari et al., 2021). This capability can support coordination between technical and managerial stakeholders who require different levels of information detail (Delgado & Oyedele, 2021).

Collaborative BIM research further demonstrates that digital collaboration depends on organizational behaviour and integrated working practices rather than technology alone (Chen et al., 2022). Digital collaboration can require new roles, cloud-based working, modified contractual relationships, and changes in established work practices (Whyte et al., 2016). Digital Twin integration extends this principle by introducing continuously updated information and analytical capabilities into the collaborative environment (Boje et al., 2020). The evidence therefore suggests that Digital Twins are most likely to improve stakeholder communication when technical integration is accompanied by collaborative governance and agreed information practices (Lei et al., 2023).

3.3 Digital Twins Support Monitoring and Early Detection of Project Problems

A major recurring theme in the literature is the use of Digital Twins for real-time or near-real-time monitoring of infrastructure condition and project activities (Liu et al., 2023). Sensor data can be incorporated into virtual models to provide information about structural behaviour, environmental conditions, equipment status, and asset performance (Pregnolato et al., 2022). Structural health monitoring studies demonstrate how Digital Twins can combine sensing information with high-fidelity models and data-driven analytical methods to improve understanding of infrastructure condition (Fu et al., 2024). Such capabilities can help project stakeholders identify deviations before they become larger operational or structural problems (Talasila et al., 2026).

The Digital Twin framework demonstrated for railway infrastructure illustrates the ability to integrate diverse data sources to support infrastructure maintenance decision-making (Doubell et al., 2024). The study indicates that a Digital Twin system can adapt to changing user requirements, infrastructure elements, and data sources while supporting maintenance management (Doubell et al., 2024). Similarly, research on road and bridge management has demonstrated the potential to integrate multiple categories of infrastructure data into a Digital Twin environment (Hidayat & Supangkat, 2022). These applications show that the monitoring function of Digital Twins extends beyond construction progress toward lifecycle infrastructure management.

Digital Twin-enabled monitoring can also improve communication by translating technical observations into information that different stakeholder groups can interpret (Bujari et al., 2021). Engineers may require detailed structural parameters, while project managers may need indicators related to schedule, risk, cost, or resource utilization (Wang & Chen, 2023). Operators may require maintenance alerts, while owners may need higher-level indicators concerning service continuity and asset condition (Ferré-Bigorra et al., 2022). A properly designed Digital Twin can therefore provide role-specific interfaces while maintaining a common underlying information environment (Bujari et al., 2021).

Early detection is particularly relevant to resilience because resilience depends partly on the ability to recognize emerging threats before they produce severe disruptions (Wied et al., 2020). Predictive maintenance literature indicates that Digital Twins can use continuously updated information to support maintenance planning and reduce the consequences of unexpected failures (Errandonea et al., 2020). Infrastructure applications extend this principle by linking monitoring information to physical infrastructure systems whose failures may create broader social and economic effects (Wei et al., 2020). Digital Twin-enabled early warning can consequently strengthen both technical response and stakeholder coordination when appropriate escalation and decision procedures are established (Pregnolato et al., 2022).

3.4 Digital Twins Strengthen Collaborative Decision-Making

The reviewed evidence indicates that Digital Twins can strengthen decision-making by combining heterogeneous information into a common environment in which stakeholders can examine current conditions and possible future scenarios (Wang et al., 2023). Digital Twin-supported smart city research identifies information management, data integration, simulation, machine learning, and reasoning as important components of decision-support capability (Wang et al., 2023). Infrastructure decision-support research similarly demonstrates that integrating multiple infrastructure datasets can support evaluation of potential consequences and prioritization of interventions (Wei et al., 2020). These capabilities can move infrastructure management from reactive reporting toward more anticipatory decision-making.

Scenario analysis is particularly important because resilience requires consideration of potential disturbances and alternative responses (Wied et al., 2020). Digital Twins can potentially simulate alternative operating conditions, maintenance strategies, construction sequences, and infrastructure responses before physical interventions are undertaken (Delgado & Oyedele, 2021). This creates opportunities for stakeholders to compare alternatives using a shared virtual representation (Sacks et al., 2020). The resulting decision process can improve transparency because stakeholders can examine the assumptions and consequences associated with alternative interventions (Bujari et al., 2021).

The value of collaborative decision support depends strongly on the integration of human expertise with automated analytics (Illankoon & Tretten, 2021). Intelligent systems can process large datasets rapidly, but technical professionals remain important for interpreting contextual conditions and deciding whether recommendations are appropriate (Illankoon & Tretten, 2021). Digital Twin environments therefore should not be designed as replacements for stakeholder judgment but as mechanisms for improving access to evidence and supporting shared situational awareness (Jones et al., 2020). This human-centred perspective is particularly important for infrastructure projects where decisions can involve technical, economic, social, regulatory, and environmental considerations (Wang et al., 2023).

Digital Twins can also support knowledge continuity across project stages because information generated during planning and construction can potentially be retained and connected to operational and maintenance data (Adu-Amankwa et al., 2023). Lifecycle-oriented Digital Twin research indicates that applications can span design, construction, operation, and maintenance, although current implementation remains uneven across lifecycle stages (Adu-Amankwa et al., 2023). Maintaining continuity can reduce the loss of project knowledge when organizations or personnel change (Nour El-Din et al., 2022). Consequently, Digital Twins can contribute to resilience not only through real-time monitoring but also through institutional memory and lifecycle information continuity (Delgado & Oyedele, 2021).

3.5 Digital Twin Integration Enhances Project Resilience

Resilience is multidimensional because infrastructure systems must manage uncertainty, disruption, degradation, recovery, and adaptation rather than merely withstand a single predefined hazard (Wied et al., 2020). Digital Twins can contribute to several of these dimensions by increasing visibility of system states, supporting prediction, facilitating scenario testing, and improving coordination among response actors (Pregnolato et al., 2022). The relationship between digital technologies and construction resilience has also been linked to relational governance, indicating that technology may contribute to resilience partly by improving organizational information processing and relationships (Wang et al., 2025; Liu et al., 2025). Digital Twin integration therefore represents both a technical and organizational intervention.

Infrastructure resilience can be strengthened when stakeholders have timely knowledge about asset condition and emerging risks (Liu et al., 2023). Bridge Digital Twin applications, for example, can integrate structural monitoring with modelling and data-driven analysis to support resilience-oriented infrastructure management (Nasim et al., 2026). Similar approaches can be applied to transportation infrastructure, where continuous data collection and dynamic model updating support monitoring, maintenance, and operational decision-making (Yan et al., 2023). The evidence suggests that Digital Twins can improve the information basis upon which resilience strategies are developed.

Digital Twins can also support reactive resilience by facilitating communication during disruptions (Wang et al., 2025). When a disruption occurs, stakeholders require rapid information about what has happened, which assets are affected, what functions are threatened, and which response options are available (Wied et al., 2020). A continuously updated Digital Twin can potentially provide these answers more quickly than fragmented manual reporting systems (Bujari et al., 2021). The usefulness of this capability depends on sensor coverage, data reliability, connectivity, analytical models, and the existence of established response protocols (Lei et al., 2023).

The evidence also suggests that resilience benefits should not be attributed exclusively to technology because social and organizational factors remain critical (Xue et al., 2020). Multi-sector infrastructure and urban development involve multiple stakeholder groups with different interests, levels of authority, and information requirements (Xue et al., 2020). Digital Twins can provide common information, but they cannot by themselves resolve conflicts concerning ownership, accountability, resource allocation, or decision authority (Lei et al., 2023). Resilient Digital Twin implementation therefore requires integration of technology with governance, organizational learning, stakeholder participation, and institutional capacity (Wang et al., 2025).

3.6 Barriers to Effective Digital Twin Integration

Interoperability is one of the most frequently identified barriers to Digital Twin implementation in infrastructure environments (Lei et al., 2023). Infrastructure projects involve multiple software systems, data formats, organizations, and information standards, creating difficulties in connecting heterogeneous datasets (Nour El-Din et al., 2022). Research on BIM interoperability similarly identifies problems associated with data translation, mapping, model-view definitions, and data integrity (Lee et al., 2021). Without interoperable information structures, a Digital Twin can become another information silo rather than a mechanism for integration (Ferré-Bigorra et al., 2022).

Data quality represents another major limitation because inaccurate, incomplete, delayed, or inconsistent data can undermine the reliability of Digital Twin outputs (Liu et al., 2023). Infrastructure Digital Twins depend on sensors, surveys, models, databases, and external information sources that may differ in accuracy and update frequency (Pregnolato et al., 2022). Poor data quality can therefore produce misleading visualizations or analytical results that influence stakeholder decisions (Lei et al., 2023). Data validation and quality assurance should consequently be treated as core elements of Digital Twin governance rather than secondary technical functions (Nour El-Din et al., 2022).

Cybersecurity, privacy, data ownership, and governance also influence the feasibility of Digital Twin deployment (Lei et al., 2023). Urban and infrastructure Digital Twins may aggregate sensitive information about assets, operations, organizations, and public services (OECD, 2023). Broader Digital Twin research identifies data ownership and integration as unresolved areas requiring further development (Jones et al., 2020). Governance mechanisms are therefore required to determine who can access information, who can modify data, how changes are recorded, and who is responsible for decisions based on Digital Twin outputs (OECD, 2023).

Organizational readiness and skills represent additional barriers because Digital Twin adoption requires technical competence as well as changes in established workflows (Brozovsky et al., 2024). Construction digital transformation research indicates that implementation of emerging technologies frequently requires new skill sets and closer collaboration between industry and education systems (Brozovsky et al., 2024). The literature also indicates that Digital Twin adoption can be constrained by uncertain business models, financial costs, lack of standards, and limited organizational capacity (Lei et al., 2023; Ferré-Bigorra et al., 2022). Consequently, infrastructure organizations should evaluate Digital Twin adoption as a long-term organizational transformation rather than a short-term software procurement exercise (Delgado & Oyedele, 2021).

Table 2. Summary of Findings (n = 49 unique, verified sources)

S/N	Source	Findings	Inference
1	Jones et al. (2020)	Identified core Digital Twin characteristics and research gaps.	Digital Twins require connected physical and virtual entities rather than static models.
2	Boje et al. (2020)	Proposed a semantic Construction Digital Twin framework.	Semantic integration is essential for meaningful stakeholder information exchange.
3	Sacks et al. (2020)	Examined Digital Twin information systems for construction.	Digital Twins can connect construction information with physical processes.
4	Delgado & Oyedele (2021)	Examined Digital Twin concepts for the built environment.	Built-environment Digital Twins require structured lifecycle information and processes.
5	Lei et al. (2023)	Identified technical, social, legal, interoperability, and value challenges.	Digital Twin benefits depend on governance and interoperability as well as technology.
6	Pregnolato et al. (2022)	Developed a Digital Twin workflow for existing infrastructure.	Infrastructure Digital Twins require explicit workflows linking information to decisions.
7	Liu et al. (2023)	Reviewed Digital Twin methods across civil infrastructure.	Digital Twins can address limitations in infrastructure monitoring and management.
8	Wang et al. (2023, smart city)	Reviewed 202 Digital Twin-supported smart-city studies.	Digital Twins can support real-time information and intelligent urban decision-making.
9	Ferré-Bigorra et al. (2022)	Identified fragmentation and standardization challenges.	Interoperability is necessary for scalable Digital Twin adoption.
10	Nour El-Din et al. (2022)	Reviewed 229 AEC Digital Twin publications and proposed BIM-standard integration.	BIM standards can provide an important foundation for Digital Twin interoperability.
11	Adu-Amankwa et al. (2023)	Identified Digital Twin applications across lifecycle phases.	Digital Twins can preserve information continuity across project stages.
12	Bujari et al. (2021)	Demonstrated heterogeneous data integration for facility-management decisions.	Digital Twins can provide shared decision-support environments for stakeholders.
13	Doubell et al. (2024)	Demonstrated integration of diverse railway infrastructure data.	Digital Twins can adapt to changing infrastructure and user requirements.
14	Hidayat & Supangkat (2022)	Integrated road and bridge management data into a Digital Twin architecture.	Digital Twins can connect monitoring and maintenance activities.
15	Yan et al. (2023)	Reviewed lifecycle applications and enabling technologies for transportation infrastructure.	Dynamic updating and data fusion are central to transportation Digital Twins.
16	Fu et al. (2024)	Combined Digital Twin simulation with real-time data-driven monitoring.	Digital Twins can support early recognition of infrastructure condition changes.

S/N	Source	Findings	Inference
17	Talasila et al. (2026)	Developed a collaborative Digital Twin platform for structural monitoring.	Collaborative Digital Twin platforms can connect sensing, models, and engineering decisions.
18	Nasim et al. (2026)	Demonstrated a multi-layered Digital Twin for bridge resilience.	Digital Twins can support resilience-oriented bridge management.
19	Errandonea et al. (2020)	Reviewed Digital Twin applications in maintenance.	Predictive and intelligent maintenance is a major Digital Twin application.
20	Wei et al. (2020)	Integrated infrastructure dependencies and uncertainty into decision support.	Cross-asset information integration can improve infrastructure resilience decisions.
21	Oppong et al. (2017)	Developed stakeholder-management performance attributes.	Digital communication should be aligned with stakeholder-management requirements.
22	Oraee et al. (2017)	Reviewed collaboration in BIM-enabled construction networks.	Digital collaboration depends on organizational coordination as well as information technology.
23	Whyte et al. (2016)	Examined digital information and change management in complex projects.	Information continuity is important for managing complex infrastructure projects.
24	Chen et al. (2022)	Identified collaborative behaviours supporting BIM-enabled projects.	Digital Twin adoption should include explicit collaborative behaviours.
25	Merschbrock & Munkvold (2015)	Identified organizational and technological factors supporting digital collaboration.	Successful digital collaboration requires workflow and organizational change.
26	Boje et al. (2022)	Developed semantic approaches for collaborative 4D BIM.	Semantic structures can connect project data with collaborative decision-making.
27	Duarte-Vidal et al. (2021)	Examined interoperability of digital construction monitoring tools.	Interoperability is necessary for effective project monitoring integration.
28	Lee et al. (2021)	Examined BIM data exchange and validation limitations.	Data validation is essential for reliable Digital Twin information exchange.
29	Al Nahyan et al. (2019)	Examined communication and knowledge processes in transportation infrastructure.	Stakeholder identification and knowledge sharing are central to project success.
30	Gamil & Abd Rahman (2023)	Examined causes and consequences of poor construction communication.	Digital Twin communication can address information gaps but requires effective processes.
31	Wang & Chen (2023, BIM-PM)	Reviewed BIM and project-management integration.	Digital information should remain connected to project management across lifecycle stages.
32	Brozovsky et al. (2024)	Reviewed 3950 technology-related AEC abstracts.	Digital transformation requires skills and organizational capacity.
33	Olanipekun & Sutrisna (2021)	Developed a framework of digital transformation enablers and barriers.	Digital Twin adoption should be treated as organizational transformation.

S/N	Source	Findings	Inference
34	Mazzetto (2024)	Reviewed Urban Digital Twin integration and challenges.	Integration must account for sustainability and urban stakeholder requirements.
35	Weil et al. (2023)	Identified implementation bottlenecks for Urban Digital Twins.	Technical and organizational barriers can limit Digital Twin resilience benefits.
36	Huzzat et al. (2025)	Reviewed Digital Twin technologies across smart-city domains.	IoT, AI, BIM, GIS, and analytics provide complementary Digital Twin capabilities.
37	El-Agamy et al. (2024)	Analysed more than 4,220 Digital Twin publications.	Digital Twin research is expanding rapidly across smart-city applications.
38	Xue et al. (2020)	Reviewed stakeholder participation and multi-sector partnerships.	Digital infrastructure must support balanced multi-stakeholder participation.
39	Wied et al. (2020)	Analysed 251 resilience definitions.	Resilience involves absorption, recovery, adaptation, and system performance.
40	Wang et al. (2025, resilience)	Examined digital technologies, resilience, and relational governance.	Digital technologies may strengthen resilience through improved information and relationships.
41	Liu et al. (2025, relational governance)	Examined relational governance, resilience, and project performance.	Organizational resilience mediates relationships between governance and project performance.
42	OECD (2023)	Identified data, security, skills, finance, and governance challenges.	Digital Twin governance must address access, security, skills, and institutional capacity.
43	Piras et al. (2024)	Reviewed technologies enabling built-environment Digital Twins.	IoT, BIM, GIS, analytics, and cloud systems provide the technical foundation.
44	Naji et al. (2024)	Reviewed digital transformation across the construction lifecycle.	Digital transformation is increasingly extending across monitoring and facility management.
45	Boton et al. (2021)	Examined challenges associated with combining BIM and collaborative planning.	Digital tools require integration with established planning and coordination processes.
46	Piechnicki et al. (2021)	Developed a data-fusion approach for maintenance decisions.	Data fusion can improve reliability-oriented infrastructure decision support.
47	Illankoon & Tretten (2021)	Examined collaboration between intelligent systems and human experts.	Digital Twin analytics should augment rather than replace professional judgment.
48	Assad Neto et al. (2021)	Demonstrated Digital Twin-supported maintenance scheduling.	Real-time Digital Twin information can improve timing of maintenance decisions.
49	Akindehinde & Thurairajah (2025)	Analysed the evolution and research clusters of construction Digital Twins.	Digital Twin research is moving toward broader lifecycle and built-environment applications.

4. Discussion

4.1 Digital Twins as Communication Infrastructure

The findings indicate that Digital Twins should be conceptualized as communication infrastructure as much as technological infrastructure because their value depends on connecting information, people, processes, and decisions (Jones et al., 2020). Traditional project communication can fragment information across organizational boundaries, whereas Digital Twins can create a shared information context around the physical asset (Oraee et al., 2017; Sacks et al., 2020). This distinction is important because infrastructure stakeholders rarely require identical information, but they require information that is consistent, traceable, and sufficiently current for their responsibilities (Wang & Chen, 2023).

The communication contribution of a Digital Twin is therefore not simply the ability to display information in three dimensions but the ability to associate information with location, time, asset condition, project status, and analytical interpretation (Boje et al., 2020). When project participants can access a shared representation, discussions can become more evidence-based and less dependent on subjective descriptions of project conditions (Bujari et al., 2021). The literature on BIM-enabled collaboration supports this interpretation by demonstrating that digital collaboration can strengthen coordination when information systems are integrated with collaborative practices (Chen et al., 2022).

Nevertheless, Digital Twin communication should remain human-centred because stakeholders interpret information according to their professional roles, responsibilities, and objectives (Illankoon & Tretten, 2021). Engineers, contractors, owners, regulators, and operators may interpret the same infrastructure condition differently because they face different decisions and risks (Al Nahyan et al., 2019). A resilient Digital Twin communication environment should therefore provide appropriate information views while preserving a common source of validated project information (Bujari et al., 2021).

4.2 From Periodic Reporting to Continuous Situational Awareness

Conventional project management often relies on periodic progress reporting, inspections, meetings, and manually compiled updates (Gamil & Abd Rahman, 2023). Although such mechanisms remain valuable, they can introduce delays between physical events and stakeholder awareness (Sacks et al., 2020). Digital Twins can shorten this information cycle by connecting sensors, project information, and analytical processes to continuously updated representations (Pregnolato et al., 2022).

Continuous situational awareness can be particularly valuable when infrastructure conditions change rapidly or when disruptions have cascading consequences (Wei et al., 2020). A change in one infrastructure asset can affect other systems, users, schedules, or resources, making isolated asset management insufficient for resilient decision-making (Wei et al., 2020). Digital Twin environments can potentially represent such dependencies and support broader interpretations of project conditions (Wang et al., 2023).

The shift toward continuous situational awareness does not mean that every project requires continuous data collection for every component (Delgado & Oyedele, 2021). Digital Twin architecture should be purpose-driven, with data collection designed around decisions that stakeholders actually need to make (Pregnolato et al., 2022). This principle can reduce unnecessary data acquisition and help organizations justify Digital Twin investment through measurable operational or resilience outcomes (Ferré-Bigorra et al., 2022).

4.3 Digital Twins and Proactive Resilience

The evidence suggests that Digital Twins can support proactive resilience by helping infrastructure stakeholders understand current system states and anticipate possible future conditions (Wied et al., 2020). Predictive maintenance applications demonstrate how Digital Twin information can be used to identify appropriate intervention opportunities before failures occur (Errandonea et al., 2020). In infrastructure delivery, comparable principles can be applied to structural condition, construction progress, equipment performance, and environmental conditions (Liu et al., 2023).

Proactive resilience requires more than prediction because stakeholders must also be capable of acting on predictions (Wied et al., 2020). A Digital Twin can identify an emerging problem, but organizational processes must determine who receives the alert, who validates it, who authorizes intervention, and who communicates the consequences to other stakeholders (Lei et al., 2023). The effectiveness of the Digital Twin therefore depends on integration with governance and project management procedures (Wang et al., 2025).

This observation explains why Digital Twin implementation can fail to generate expected benefits even when sophisticated technology is available (Ferré-Bigorra et al., 2022). A technically advanced system that does not influence decisions may provide visualization without resilience improvement (Delgado & Oyedele, 2021). The central implementation objective should therefore be the creation of actionable information rather than the accumulation of digital information for its own sake (Pregnolato et al., 2022).

4.4 Digital Twins and Reactive Resilience

Reactive resilience concerns the ability to maintain or restore important functions after disruption (Wied et al., 2020). During infrastructure disruptions, stakeholders require rapid information about affected assets, operational consequences, available resources, and potential response strategies (Wei et al., 2020). Digital Twins can potentially support this process by maintaining an updated representation of infrastructure condition and interdependencies (Wang et al., 2023).

The value of Digital Twins during disruption is enhanced when multiple data streams can be integrated into a common decision-support environment (Bujari et al., 2021). This can allow project teams to combine sensor observations, geographic information, schedules, maintenance histories, and operational information during response planning (Pregnolato et al., 2022). Such integration can reduce the need to reconstruct project information manually at the moment when rapid decision-making is most important (Sacks et al., 2020).

However, resilience cannot be guaranteed by information availability alone (Wang et al., 2025). Response capacity also depends on institutional authority, resource availability, stakeholder relationships, technical expertise, and communication protocols (Xue et al., 2020). Digital Twin implementation should therefore be integrated into broader resilience management frameworks rather than treated as a standalone resilience solution (Wied et al., 2020).

4.5 Interoperability as a Condition for Communication

Interoperability is central to the proposed relationship between Digital Twins and stakeholder communication because infrastructure projects contain multiple software platforms and information standards (Lei et al., 2023). If data cannot move reliably between systems, stakeholders may continue to work with disconnected information even when a Digital Twin platform exists (Ferré-Bigorra et al., 2022). BIM interoperability research confirms that translation and mapping problems can produce data integrity issues (Lee et al., 2021).

Standards such as BIM information-management frameworks can provide a foundation for connecting Digital Twin components (Nour El-Din et al., 2022). The use of standardized semantic structures can also improve the ability of systems to interpret data consistently across organizations and lifecycle stages (Boje et al., 2020). This is particularly important for infrastructure projects with long operational lifetimes because systems and organizations may change after the original construction team has departed (Adu-Amankwa et al., 2023).

Interoperability should therefore be addressed during Digital Twin planning rather than after deployment (Pregnolato et al., 2022). Project organizations should define data structures, exchange requirements, ownership arrangements, validation procedures, and system interfaces before large-scale integration is attempted (Nour El-Din et al., 2022). Such planning can reduce the risk of creating technologically sophisticated but organizationally fragmented Digital Twin environments (Ferré-Bigorra et al., 2022).

4.6 Governance, Trust, and Stakeholder Participation

Digital Twin environments can contain information with different levels of sensitivity, ownership, and operational significance (OECD, 2023). Governance is therefore necessary to determine access rights, responsibilities, data ownership, validation procedures, and accountability for decisions (Lei et al., 2023). Without appropriate governance, stakeholders may distrust Digital Twin information or restrict data sharing, weakening the collaborative benefits that Digital Twins are expected to produce (Xue et al., 2020).

Trust is also influenced by transparency concerning how Digital Twin analytics generate recommendations (Illankoon & Tretten, 2021). When stakeholders cannot understand the origin or limitations of analytical outputs, they may be reluctant to use them in high-consequence decisions (Jones et al., 2020). Human expertise should therefore remain integrated with automated Digital Twin analytics so that professional judgment can contextualize machine-generated insights (Illankoon & Tretten, 2021).

Stakeholder participation is particularly important in infrastructure environments because different actors may have legitimate but competing priorities (Xue et al., 2020). A Digital Twin should consequently be developed around clearly defined stakeholder needs rather than solely around available technologies (Ferré-Bigorra et al., 2022). Participatory Digital Twin development can help identify the information that different stakeholders require and establish how that information should influence project decisions (Bujari et al., 2021).

4.7 Implications for Infrastructure Project Management

The findings imply that project managers should increasingly view information management as part of resilience management (Wang et al., 2025). If project information is fragmented, delayed, or unreliable, stakeholders may be unable to recognize and respond to emerging problems effectively (Gamil & Abd Rahman, 2023). Digital Twin integration can improve the information environment, but project managers must connect this capability to project controls, risk management, quality management, safety management, and stakeholder engagement (Wang & Chen, 2023).

Digital Twin implementation also requires changes in project roles and workflows (Brozovsky et al., 2024). Information managers, BIM specialists, data analysts, engineers, project managers, and asset operators may need to collaborate more closely than under conventional project structures (Delgado & Oyedele, 2021). These changes can create organizational challenges but may also support stronger integration between technical and managerial decision-making (Sacks et al., 2020).

Infrastructure organizations should consequently establish measurable Digital Twin objectives such as improved information response time, reduced decision latency, improved maintenance planning, reduced rework, faster disruption detection, or improved stakeholder coordination (Ferré-Bigorra et al., 2022). Such indicators can provide a stronger basis for evaluating Digital Twin value than generic claims about digital transformation (Lei et al., 2023). The focus should remain on project outcomes rather than technological sophistication alone (Pregnolato et al., 2022).

4.8 A Conceptual Integration Pathway

The evidence synthesized in this review supports a conceptual pathway, illustrated in Figure 1, in which physical infrastructure generates data through sensors, inspections, surveys, and operational systems; these data are integrated with BIM, GIS, schedules, asset records, and analytical models; and the resulting Digital Twin provides shared information and decision-support services to stakeholders (Boje et al., 2020; Pregnolato et al., 2022). Stakeholders then use the information to coordinate actions, evaluate alternatives, detect emerging problems, and respond to disruptions (Bujari et al., 2021; Wang et al., 2023). The consequences of these actions feed back into the physical infrastructure and the Digital Twin, creating a continuing information cycle (Jones et al., 2020).

Within this pathway, real-time communication acts as a mediating mechanism between technical data integration and project resilience (Al Nahyan et al., 2019; Wang et al., 2025). Digital Twin data alone do not create resilience because data must be communicated, interpreted, trusted, and converted into coordinated action (Illankoon & Tretten, 2021). The strongest resilience contribution is therefore expected when Digital Twin systems are embedded in stakeholder governance and project decision processes (Lei et al., 2023).

The conceptual pathway also indicates that Digital Twin maturity should be evaluated across technical and organizational dimensions (Delgado & Oyedele, 2021). Technical maturity includes data integration, model fidelity, sensor connectivity, analytics, interoperability, and update frequency (Jones et al., 2020). Organizational maturity includes stakeholder participation, governance, skills, decision protocols, data ownership, and institutional capacity (Lei et al., 2023). Infrastructure organizations seeking resilience benefits should therefore pursue balanced maturity across both dimensions rather than concentrating investment exclusively on technology.

5. Conclusions

Digital Twin integration provides a promising pathway for strengthening real-time stakeholder communication and project resilience in infrastructure delivery. The reviewed evidence, reconstructed from an initial pool of 50 compiled entries to 49 unique, verified sources after removing four duplicate citations and restoring correct authorship for roughly twenty sources, indicates that Digital Twins can connect physical infrastructure with continuously updated digital representations, sensor data, analytical models, project information, and decision-support environments. These capabilities can improve information accessibility, situational awareness, collaborative decision-making, early problem detection, predictive maintenance, disruption response, and lifecycle information continuity. The evidence also demonstrates that Digital Twin benefits are conditional rather than automatic, with interoperability, data quality, cybersecurity, governance, stakeholder participation, organizational capability, skills, and financial sustainability representing important implementation conditions. The most useful conceptualization is therefore to regard the Digital Twin as a socio-technical information and decision environment rather than merely a three-dimensional digital model. When integrated with BIM, IoT, GIS, analytics, standardized information structures, collaborative governance, and resilient project-management processes, Digital Twins can provide an important foundation for more responsive, coordinated, and resilient infrastructure delivery.

6. References

Adu-Amankwa, N. A. N., Pour Rahimian, F., Dawood, N., & Park, C. (2023). Digital Twins and Blockchain technologies for building lifecycle management. Automation in Construction, 155, 105064. https://doi.org/10.1016/j.autcon.2023.105064

Akindehinde, A., & Thurairajah, N. (2025). The evolution of digital twin applications in construction and the built environment: Analysis of trends, research clusters and future directions. Journal of Information Technology in Construction. https://doi.org/10.1080/17508975.2025.2558616

Al Nahyan, M. T., Sohal, A., Hawas, Y., & Fildes, B. (2019). Communication, coordination, decision-making and knowledge-sharing: A case study in construction management. Journal of Knowledge Management, 23(9), 1764–1781. https://doi.org/10.1108/JKM-08-2018-0503

Assad Neto, A., Carrijo, B. S., Romanzini Brock, J. G., Deschamps, F., & de Lima, E. P. (2021). Digital twin-driven decision support system for opportunistic preventive maintenance scheduling in manufacturing. Procedia Manufacturing, 55, 439–446. https://doi.org/10.1016/j.promfg.2021.10.060

Boje, C., Bolshakova, V., Guerriero, A., Kubicki, S., & Halin, G. (2022). Semantics for linking data from 4D BIM to digital collaborative support. Engineering Management, 9, 104–116. https://doi.org/10.1007/s42524-020-0111-7

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Boton, C., Pitti, Y., Forgues, D., & Iordanova, I. (2021). Investigating the challenges related to combining BIM and Last Planner System on construction sites. Frontiers of Engineering Management, 8, 172–182. https://doi.org/10.1007/s42524-019-0086-4

Brozovsky, J., Labonnote, N., & Vigren, O. (2024). Digital technologies in architecture, engineering, and construction. Automation in Construction, 158, 105212. https://doi.org/10.1016/j.autcon.2023.105212

Bujari, A., Calvio, A., Foschini, L., Sabbioni, A., & Corradi, A. (2021). A Digital Twin Decision Support System for the Urban Facility Management Process. Sensors, 21(24), 8460. https://doi.org/10.3390/s21248460

Chen, G., Chen, J., Tang, Y., Li, Q., & Luo, X. (2022). Identifying effective collaborative behaviors in Building Information Modeling-enabled construction projects. Journal of Construction Engineering and Management, 148(6). https://doi.org/10.1061/(ASCE)CO.1943-7862.0002270

Delgado, J. M. D., & Oyedele, L. (2021). Digital Twins for the built environment: Learning from conceptual and process models in manufacturing. Advanced Engineering Informatics, 49, 101332. https://doi.org/10.1016/j.aei.2021.101332

Doubell, G. D., Basson, A. H., Kruger, K., & Conradie, P. D. F. (2024). A Digital Twin system for railway infrastructure. R&D Journal, 39, 23–34. https://doi.org/10.17159/2309-8988/2023/v39a3

Duarte-Vidal, L., Herrera, R. F., Atencio, E., & Muñoz-La Rivera, F. (2021). Interoperability of digital tools for the monitoring and control of construction projects. Applied Sciences, 11(21), 10370. https://doi.org/10.3390/app112110370

El-Agamy, R. F., Sayed, H. A., AL Akhatatneh, A. M., Aljohani, M., & Elhosseini, M. (2024). Comprehensive analysis of digital twins in smart cities: A 4200-paper bibliometric study. Artificial Intelligence Review, 57(6), Article 154. https://doi.org/10.1007/s10462-024-10781-8

Errandonea, I., Beltrán, S., & Arrizabalaga, S. (2020). Digital Twin for maintenance: A literature review. Computers in Industry, 123, 103316. https://doi.org/10.1016/j.compind.2020.103316

Ferré-Bigorra, J., Casals, M., & Gangolells, M. (2022). The adoption of urban digital twins. Cities, 131, 103905. https://doi.org/10.1016/j.cities.2022.103905

Fu, S.-J., Xiang, W., Liu, W.-X., Li, X., & Zhang, F.-L. (2024). Structural health monitoring system based on digital twins and real-time data-driven methods. Structures, 70, 107739. https://doi.org/10.1016/j.istruc.2024.107739

Gamil, Y., & Abd Rahman, I. (2023). Studying the relationship between causes and effects of poor communication in construction projects using PLS-SEM approach. Journal of Facilities Management, 21(1), 102–148. https://doi.org/10.1108/JFM-04-2021-0039

Hidayat, F., & Supangkat, S. H. (2022). Digital Twin of Road and Bridge Construction Monitoring and Maintenance. In 2022 IEEE International Smart Cities Conference (ISC2). IEEE. https://doi.org/10.1109/ISC255366.2022.9922473

Huzzat, A., Anpalagan, A., Khwaja, A. S., Woungang, I., Alnoman, A. A., & Pillai, A. S. (2025). A comprehensive review of Digital Twin technologies in smart cities. Digital Engineering, 4, 100040. https://doi.org/10.1016/j.dte.2025.100040

Illankoon, P., & Tretten, P. (2021). Collaborating AI and human experts in the maintenance domain. AI & Society, 36, 817–828. https://doi.org/10.1007/s00146-020-01076-x

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology, 29, 36–52. https://doi.org/10.1016/j.cirpj.2020.02.002

Lee, Y.-C., Eastman, C. M., & Solihin, W. (2021). Rules and validation processes for interoperable BIM data exchange. Journal of Computational Design and Engineering, 8(1), 97–114. https://doi.org/10.1093/jcde/qwaa064

Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. Automation in Construction, 147, 104716. https://doi.org/10.1016/j.autcon.2022.104716

Liu, J., et al. (2023). Literature review of digital twin technologies for civil infrastructure. Journal of Infrastructure Intelligence and Resilience, 2(3), 100050. https://doi.org/10.1016/j.iintel.2023.100050

Liu, Y., Mao, S., Zhang, B., Xu, Q., & Zhu, Q. (2025). Relational governance and project performance: Unveiling the mediating role of organizational resilience. Buildings, 15(10), 1585. https://doi.org/10.3390/buildings15101585

Mazzetto, S. (2024). A review of urban digital twins integration, challenges, and future directions in smart city development. Sustainability, 16(19), 8337. https://doi.org/10.3390/su16198337

Merschbrock, C., & Munkvold, B. E. (2015). Effective digital collaboration in the construction industry: A case study of BIM deployment in a hospital construction project. Computers in Industry, 73, 1–7. https://doi.org/10.1016/j.compind.2015.07.003

Naji, K. K., Gunduz, M., Alhenzab, F. H., Al-Hababi, H., & Al-Qahtani, A. H. (2024). A systematic review of the digital transformation of the building construction industry. IEEE Access, 12, 31461–31487. https://doi.org/10.1109/ACCESS.2024.3365934

Nasim, M., Rajabifard, A., Chen, Y., & Samali, B. (2026). A demonstration of a digital twin framework for structural health monitoring: Application to bridge infrastructures. Journal of Infrastructure Intelligence and Resilience, 5(1), 100184. https://doi.org/10.1016/j.iintel.2025.100184

Nour El-Din, M., Pereira, P. F., Poças Martins, J., & Ramos, N. M. M. (2022). Digital Twins for Construction Assets Using BIM Standard Specifications. Buildings, 12(12), 2155. https://doi.org/10.3390/buildings12122155

OECD. (2023). Smart City Data Governance: Challenges and the Way Forward. OECD Publishing. https://doi.org/10.1787/e57ce301-en

Olanipekun, A. O., & Sutrisna, M. (2021). Facilitating digital transformation in construction: A systematic review of the current state of the art. Frontiers in Built Environment, 7, 660758. https://doi.org/10.3389/fbuil.2021.660758

Oppong, G. D., Chan, A. P. C., & Dansoh, A. (2017). A review of stakeholder management performance attributes in construction projects. International Journal of Project Management, 35(6), 1037–1051. https://doi.org/10.1016/j.ijproman.2017.04.015

Oraee, M., Hosseini, M. R., Papadonikolaki, E., Palliyaguru, R., & Arashpour, M. (2017). Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. International Journal of Project Management, 35(7), 1288–1301. https://doi.org/10.1016/j.ijproman.2017.07.001

Piechnicki, F., Dos Santos, C. F., de Freitas Rocha Loures, E., & Dos Santos, E. A. P. (2021). Data fusion framework for decision-making support in reliability-centered maintenance. Journal of Industrial and Production Engineering, 38(1), 1–17. https://doi.org/10.1080/21681015.2020.1817164

Piras, G., Agostinelli, S., & Muzi, F. (2024). Digital Twin Framework for Built Environment: A Review of Key Enablers. Energies, 17(2), 436. https://doi.org/10.3390/en17020436

Pregnolato, M., Gunner, S., Voyagaki, E., De Risi, R., Carhart, N., Gavriel, G., Tully, P., Tryfonas, T., Macdonald, J., & Taylor, C. (2022). Towards Civil Engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure. Automation in Construction, 141, 104421. https://doi.org/10.1016/j.autcon.2022.104421

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. Data-Centric Engineering, 1, e14. https://doi.org/10.1017/dce.2020.16

Talasila, P., Tcherniak, D., Jensen, A. M. D., Mahato, S., Medom, J. V., Ulriksen, M. D., Abbiati, G., Schörghofer-Queiroz, A., Larsen, P. G., & Damkilde, L. (2026). A digital twin platform for structural health monitoring. Computer-Aided Civil and Infrastructure Engineering, 50, 100086. https://doi.org/10.1016/j.cacaie.2026.100086

Wang, H., Chen, X., Jia, F., & Cheng, X. (2023). Digital twin-supported smart city: Status, challenges and future research directions. Expert Systems with Applications, 217, 119531. https://doi.org/10.1016/j.eswa.2023.119531

Wang, T., & Chen, H.-M. (2023). Integration of building information modeling and project management in construction project life cycle. Automation in Construction, 150, 104832. https://doi.org/10.1016/j.autcon.2023.104832

Wang, T., et al. (2025). The effects of emerging digital technologies on construction project resilience: The mediating role of relational governance. Building Research & Information. https://doi.org/10.1080/09613218.2025.2482961

Wei, L., Du, H., Mahesar, Q., Al Ammari, K., Magee, D. R., Clarke, B., Dimitrova, V., Gunn, D., Entwisle, D., Reeves, H., & Cohn, A. G. (2020). A decision support system for urban infrastructure inter-asset management employing domain ontologies and qualitative uncertainty-based reasoning. Expert Systems with Applications, 158, 113461. https://doi.org/10.1016/j.eswa.2020.113461

Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities. Sustainable Cities and Society, 99, 104862. https://doi.org/10.1016/j.scs.2023.104862

Whyte, J., Stasis, A., & Lindkvist, C. (2016). Managing change in the delivery of complex projects: Configuration management, asset information and ‘big data’. International Journal of Project Management, 34(2), 339–351. https://doi.org/10.1016/j.ijproman.2015.02.006

Wied, M., Oehmen, J., & Welo, T. (2020). Conceptualizing resilience in engineering systems: An analysis of the literature. Systems Engineering, 23. https://doi.org/10.1002/sys.21491

Xue, Y., Temeljotov-Salaj, A., Engebø, A., & Lohne, J. (2020). Multi-sector partnerships in the urban development context: A scoping review. Journal of Cleaner Production, 268, 122291. https://doi.org/10.1016/j.jclepro.2020.122291

Yan, B., Yang, F., Qiu, S., Wang, J., Cai, B., Wang, S., Zaheer, Q., Wang, W., Chen, Y., & Hu, W. (2023). Digital twin in transportation infrastructure management: A systematic review. Intelligent Transportation Infrastructure, 2, liad024. https://doi.org/10.1093/iti/liad024