DIGITAL TWINS FOR BRIDGE MANAGEMENT

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ABSTRACT

Digital twins (DTs) are increasingly seen as a promising tool for bridge management, yet bridge owners hold diverging views on bridge digital twin (BDT) requirements, benefits, and feasibility. The International Association for Bridge Maintenance and Safety (IABMAS) Working Group on Digital Twins conducted an international survey of bridge owners and reviewed current developments in DT and case studies. The survey covered owners' management needs, DT definitions, input/output expectations, and perceived potential. Owners see promise in DTs but want clearer guidance on minimum requirements, practical benefits, and scalable implementation strategies. Case studies illustrate their strengths in lifecycle decision-making and weaknesses tied to data fragmentation. Coherent data standards, platform interoperability, and integration with existing asset management workflows are essential. This work outlines a roadmap toward a harmonized, owner-centered BDT framework grounded in coherent standards, scalable implementation paths, and cross-sectoral collaboration.

KEYWORDS: assessment, existing bridges, survey, owner's perspective, decision-making support, input data

Introduction

According to the County Surveyors Society (CSS), "Asset management is a strategic approach that identifies the optimal allocation of resources for the management, operation, preservation, and enhancement of the highway infrastructure that meets the needs of current and future customers" (County Surveyors Society 2004). In line with this, bridge management can be considered as a systematic process of maintaining, improving, and operating a bridge network through coordinated activities of inspection, evaluation, prioritization, and intervention planning of individual assets within the network (Sousa et al. 2014). The extent of information stored in a bridge management system (BMS) varies widely (Yang and Frangopol 2018; Mirzaei et al. 2014)—from limited overviews of georeferenced assets with brief descriptions to complete systems that include all documentation, inspection reports, assessment calculations, and more. The more information available, the better a BMS can support decision-making on the required actions for assets and networks. The goal of complete BMS approaches is to increasingly incorporate diverse advanced digital technologies to optimize maintenance strategies and enhance infrastructure resilience.

However, despite their widespread adoption, traditional BMS implementations suffer from important limitations that restrict their effectiveness. First, most of them rely heavily on periodic visual inspections and manual data entry, which capture only discrete snapshots of a bridge's condition and provide no continuous insight into its real-time condition or degradation processes (Biondini and Frangopol 2016). Second, information in a BMS is often scattered: inspection reports, design files, load ratings, and maintenance records may be stored in various formats and platforms, making it difficult to achieve a unified, up-to-date view of asset health

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(Gao et al. 2024). Third, many of them lack predictive capabilities. They typically do not integrate automated analytics, real-time sensor data, or physics-based simulations, limiting the ability to forecast deterioration and to plan proactive maintenance (Zonta et al. 2014). These limitations make conventional systems reactive rather than proactive and hinder their capacity to support data-driven, risk-based management. In contrast, digital twins offer these missing capabilities. One of the principal advantages of digital twin (DT) technology lies in its ability to mirror a physical entity—whether an asset, process, system, or service—and synchronize this representation in real time through continuous data streams. This dynamic updating with operational data enables advanced functionalities such as system monitoring, data analysis, forecasting, and optimization, all of which support informed and efficient decision-making (Shim et al. 2019).

The origins of the DT concept can be traced back to aerospace applications at NASA (Shafto et al. 2010), where a DT was defined as "an integrated multi-physics, multi-scale, and probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and other data to mirror the life of its physical counterpart" (Shafto et al. 2010). Building on this foundation, the American Institute of Aeronautics and Astronautics (AIAA) provides a concise, cross-domain definition, describing a DT as "a virtual representation of a connected physical asset" (AIAA 2020). This definition emphasizes the essential characteristics of continuous connectivity, lifecycle relevance, and the twin's role in supporting analysis, prediction, and decision-making, irrespective of the application domain. A National Academies ad hoc committee examined how DTs are defined and applied across domains, identified foundational mathematical, statistical, and computational gaps, and assessed needs for validation, uncertainty quantification, best practices, and cross-domain translation to enable robust and scalable DT systems. Through three public workshops in biomedical, environmental, and engineering contexts, the committee gathered stakeholder input and produced a consensus report outlining key challenges, opportunities, and roles for advancing rigorous DT development across science and society (Willcox et al. 2024). Similarly, the Digital Twin Consortium (2026) hosts working groups that bring together industry and academic members to collaborate on sector-specific and cross-sector applications of DTs, focusing on interoperability, standards, data modeling, security, and emerging technologies such as AI. Through expert-led initiatives, these groups develop frameworks, share use cases and research, and promote best practices to advance scalable, secure, and cross-domain DT adoption. It should be noted that the best practices from these efforts can inform bridge engineering applications, and that these groups have not addressed bridge management to date.

Moreover, Wimmer and Braml (2024) state that in the construction industry, the term "digital twin" cannot be taken separately from the transition to Industry 4.0 (Eastman 2011; Daniotti et al. 2022). The architecture of a DT typically comprises five core environments: physical, virtual, data, analytical, and connection (Grübel et al. 2022). The **physical environment** corresponds to the real-world system and captures raw data, which is subsequently stored in the **data environment**. The **virtual environment** provides an accessible digital representation, often abstracting underlying complexity for user interaction. The **analytical environment** incorporates simulation models, automation processes, and user-facing services that facilitate interpretation and decision-making. Finally, the **connection environment** manages data exchange across all components via sensor networks and communication protocols, ensuring synchronized interaction between physical and digital systems.

In the built environment, physical properties are particularly important, and model-based and service-based approaches are the most applicable for transfer from the manufacturing field (Pregnolato et al. 2022; Boje et al. 2020; Delgado and Oyedele 2021). At the network level, Steyn and Broekman (2022) show how a road network can be twinned, with a focus on twinning the asphalt pavement surfacing using visual simultaneous localization and mapping using uncrewed aerial vehicles (UAVs), light detection and ranging, traffic counting, road surface temperatures, and potential inferences based on these data, showing micro- and macro-twinning potential. Moreover, optimization can be achieved by merging DTs with machine learning algorithms, as evidenced by the case of steel structures, where DTs are combined with random forest algorithms to better assess structural safety (Zhu and Wang 2022). In addition, research on merging information from structural monitoring (Chacón et al. 2023a; Lazoglu et al. 2023; Ai et al. 2024) and bridge load testing (Chacón et al. 2023b; Jasiński et al. 2023; Zandi and Malekloo 2025; Bertola et al. 2025; Lantsoght 2023) into DTs paves the way to richer DT models for bridge management (Hakimi et al. 2023; Jiménez Rios et al. 2023) and underlines the need for appropriate methods of data fusion and integration (Ramonell et al. 2023).

In the context of road and bridge engineering, Yan et al. (2025) observe that research has predominantly focused on data perception and virtual model creation, while comparatively less attention has been devoted to data processing and to the interaction between physical and virtual entities. In practice, fully real-time operation is often neither necessary nor feasible for bridge owners; instead, right-time updates aligned with inspections, monitoring campaigns, load tests, or critical events are typically more relevant. Yan et al. (2025) further note that most DT applications in road engineering currently target the operation and maintenance phases, with limited emphasis on construction, rehabilitation, and end-of-life stages. Consequently, key future needs include the establishment of uniform standards, improved data interaction and assimilation techniques, cost-effective development strategies, and the extension of DT concepts across the full asset lifecycle.

In contrast to building information modeling (BIM) for bridges, the application of DTs within this sector remains largely unstandardized (Nhamage et al. 2025). Efforts to address this issue have included the publication

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of ISO/IEC 30173 in 2023 (International Electrotechnical Commission 2023), which introduces a unified terminology applicable across multiple domains, including buildings and civil infrastructure, and technical reports such as CEN/TR 18077 (CEN/TC 442/WG 9 2024) which collates case studies of DTs applied to the built environment, including infrastructures, in Europe. Researchers have also proposed specific definitions of DT, emphasizing its integration with BIM to create interoperable digital models of existing bridges that conform to BIM schemas adapted for bridge structures. The recent ISO approval and accreditation of the IFC 4.3 schema have significantly advanced interoperability within bridge information modeling (BrIM) (Costin and Muller 2023), with a key focus on developing digital bridge models in open-standard formats (OpenBIM). For existing bridge assets, strategies such as scan-to-BIM (Hajdin et al. 2024)—based on laser scanning and photogrammetry—and parametric reconstruction from 2D sketches are commonly employed. Nevertheless, currently this requires manual processing, which can be tedious, and even though massive openBIM plans are being implemented in several countries and regions, uncertainties persist regarding the most appropriate approach. A particular challenge lies in the fact that BMS are—to put in simple terms—semantically rich but geometrically poor, whereas DTs are exactly the opposite. The deployment of AI (Hajdin et al. 2024) together with machine-readable ontologies can significantly facilitate the semiautomatic to automatic acquisition of BIM/DT from existing data (point clouds or sketches). Bridge digital twins (BDTs) can be interpreted as a natural evolution of BIM-based workflows. BIM models developed for design and construction can form a foundation upon which DTs evolve to support operation, maintenance, and lifecycle decision-making. Importantly, a DT does not inherently require a 3D model; however, when a BIM or BrIM model exists, it provides a valuable geometric and informational backbone. The use of open standards, particularly IFC, is critical to ensure interoperability, scalability, and long-term viability across tools, vendors, and owner organizations.

As the definitions and usage of DTs remain highly inconsistent across the bridge engineering industry and, in general, in the construction industry (Abdelrahman et al. 2025), the International Association for Bridge Maintenance and Safety (IABMAS) community recognized the need for a coordinated effort to clarify expectations and harmonize practices. To this end, a transversal working group was established across the three Technical Committees (TCs) of IABMAS, namely Bridge Health Monitoring, Bridge Management, and Bridge Load Testing. Given that both monitoring and load testing provide key data streams for updating and validating DTs, the combined expertise of these committees is essential for developing a coherent approach. The aim of the working group is to establish a common basis for the definition, use, requirements, and inputs and outputs for DTs for bridge management. To achieve this, the working group is undertaking several coordinated activities: preparation of the present paper, development of an industry-oriented DT white paper, organization of a dedicated workshop at IABMAS 2026, execution of a targeted survey of bridge owners, and ongoing liaison with the parent committees and other international bodies. The working group consists of 33 members, representing the three TCs of IABMAS, as well as liaisons with the international concrete federation *fib*, Eurostruct, the International Association for Bridge and Structural Engineering (IABSE), and the Permanent International Association of Road Congresses (PIARC). Members represent all continents and come from academia or industry or are bridge owners.

Given the diverging views on BDT requirements, benefits, and feasibility, this paper provides baseline evidence on the needs of bridge owners. These needs have been mapped using a targeted survey, a review of DT developments, and case studies to highlight the applicability. These activities offer a novel insight into how DTs can meaningfully support bridge owners and refine the agenda for the forthcoming IABMAS 2026 workshop, which aims to advance a more unified and practice-oriented DT framework.

Baseline Data: Needs of Bridge Owners

To implement DTs into bridge management solutions, it is important to carefully listen to bridge owners' needs. This section presents the baseline data from an international survey of bridge owners on current bridge management practices, digitalization, and the perceived potential of DTs. The results provide insight into the current adoption levels of BIM/BrIM, structural health monitoring, and DT technologies, as well as the main operational challenges faced by bridge owners and their expectations for future digital tools in bridge management.

Description of the Survey

The IABMAS Working Group on Digital Twins, composed of members from the IABMAS TCs on Bridge Load Testing, Bridge Health Monitoring and Bridge Management, identified DTs as an important common topic of study for enhancing bridge safety and management. The working group designed a survey to identify topics for a planned future workshop. The survey had as its objective to identify the needs of bridge owners for bridge management and their perception regarding DTs. The survey design was done in the working group and underwent various iterations and discussions before launching. The main identified topics to include in the survey were: baseline data (current BMS use, current BIM/BrIM use, current DT use at asset and network level), perceptions of DTs (in terms of definitions, potential value at asset and network level, and concerns), current bridge management challenges and potential of DTs to address these challenges, necessary DT inputs, and information to prepare the IABMAS 2026 workshop. The survey was hosted on the Qualtrics platform, facilitating data analysis and reporting. Survey respondents were recruited through the professional network of the working group members, through the committees of IABMAS and

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the Transportation Research Board (TRB), and by providing a QR code at various presentations and events to get further responses.

Respondents Overview

In total, 164 responses were received, of which 145 provided informed consent. Filtering out the empty and incomplete responses, a dataset of 88 responses is obtained, representing 20 countries of all six inhabited continents. In total, 63 respondents represent bridge owners, 13 industry, and 12 academia. This paper reports only the results of the 63 respondents that are bridge owners. Figure 1 gives an overview of the countries represented by the survey respondents. The countries with the largest number of respondents are the United States (19 respondents), Germany (12 respondents), Chile (9 respondents) and Sweden (4 respondents).

Among the 52 respondents who answered the question on the use of BIM/BrIM tools in bridge management, only 10 (19%) reported using such tools, while 42 (81%) indicated they do not. Adoption of DT technology is similarly limited (see Table 1): of 52 respondents, 17 (33%) reported currently using DTs for bridges, and 35 (67%) reported not using them. Use of digital methods for monitoring bridge or network-level status also remains modest, with 20 of 52 respondents (38%) indicating yes and 32 (62%) no. Despite this relatively low level of current implementation, interest in DT technologies is significantly higher. Of 46 respondents, 41 (89%) expressed interest in exploring DTs for individual bridge assets, and 29 (63%) indicated interest at the network level. These results point to a substantial gap between current practice and desired future capabilities, suggesting strong momentum toward more advanced digital workflows despite limited present adoption.

The challenges identified by bridge owners are presented in Figure 2, with "maintenance and preservation planning" and "decision support and risk management" as the two main challenges identified. Other written-in responses were funding and finance, prioritizing innovations, storage of data, recommendations for clients, incorporating climate change, and developing R&D.

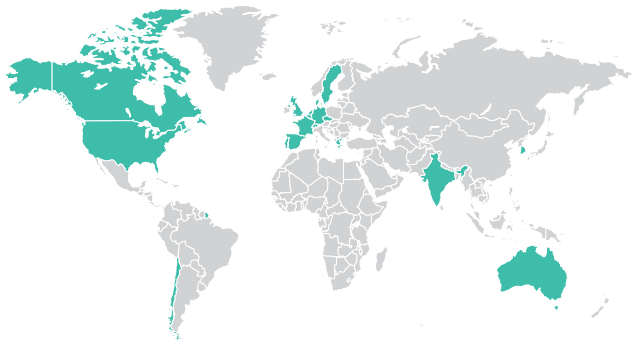


Figure 1. World map showing the countries represented by survey respondents.

TABLE 1

Summary of survey responses related to the use of digital twins

Survey responses	Yes	No
Using BIM/BrIM tools in bridge management (n = 52)	10 (19%)	42 (81%)
Using digital twin technology for bridges (n = 52)	17 (33%)	35 (67%)
Using digital methods to monitor bridge or network status (n = 52)	20 (38%)	32 (62%)
Interested in digital twins at the individual asset level (n = 46)	41 (89%)	5 (11%)
Interested in digital twins at network level (n = 46)	29 (63%)	17 (37%)

Bridge Owner Needs for Digital Twins

A critical challenge concerns the implementation of global BIM methodologies tailored to bridge projects, fostering collaboration among project managers, asset owners, structural engineers, contractors, and maintenance teams. Unlike general BIM, which has achieved widespread adoption across industry and government sectors and is even mandated in certain jurisdictions, full adoption of BrIM has not yet been achieved. However, with the formal integration of BrIM into the broader BIM framework, bridge projects are expected to adopt procedures analogous to those applied in building projects. Furthermore, the incorporation of advanced technologies—including the Internet of Things (IoT), artificial intelligence and machine learning (AI/ML), cloud computing, extended reality (VR/AR/MR), and 5G wireless connectivity—offers significant potential to enhance the monitoring (including the long-term

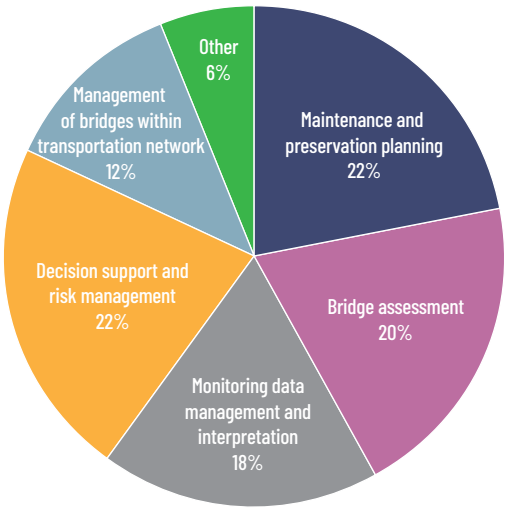


Figure 2. Bridge management challenges as identified by respondents.

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structural health monitoring [SHM] of bridges under scrutiny due to potential malfunctioning) and management of bridge infrastructure. A gap persists in the availability of unified platforms capable of consolidating these diverse technologies to deliver a fully functional BDT (Honghong et al. 2023).

Analysis of the survey responses reinforces these observations. Although respondents represent a broad international cross-section of bridge owners, only a small fraction currently uses BIM or BrIM tools in their management workflows, and an equally limited number employ any form of DT technology. At the same time, an overwhelming majority express interest in exploring DT solutions at both the asset and network levels, revealing a clear gap between perceived value and actual deployment. Responses further highlight fragmented digital practices: many owners rely on conventional inspection reports and isolated monitoring efforts, while only a minority use systematic SHM, nondestructive testing (NDT), or network-level digital monitoring platforms. This fragmentation echoes long-standing national concerns identified by the American Association of State Highway and Transportation Officials (AASHTO), which in 2019 formally recognized that the lack of a unified, interoperable data schema impedes lifecycle asset management and seamless data exchange (AASHTO 2019). Several owners note that data are dispersed across incompatible formats and legacy systems, hindering integration and long-term traceability. The AASHTO Board of Directors' 2019 resolution adopting the Industry Foundation Classes (IFC) schema as the national standard underscores this same challenge and highlights the need for coordinated cross-disciplinary efforts to ensure interoperability across tools, vendors, and platforms. The replies therefore point to an urgent need for unified data environments, clearer implementation pathways, and guidance on how BrIM, SHM, and other digital technologies can be coherently combined to form sustainable DT ecosystems.

This need for sustainable ecosystems is particularly acute when addressing the network-level ambitions of bridge owners. The survey results indicate that 63% of respondents are interested in DTs at the network level. However, achieving this scale via traditional SHM is economically unfeasible, since installing fixed instrumentation on every bridge in a vast network is cost-prohibitive and logistically complex. To address this specific network-level scaling challenge and bridge the gap between high interest and current low adoption (only 38% use digital monitoring), emerging research points to crowdsensing as a highly scalable alternative. For example, indirect "drive-by" monitoring leverages the data recorded on passing vehicles, allowing bridge owners to treat the vehicle itself as a moving sensor actuator. This enables the collection of dynamic data from a plethora of bridges without requiring on-site hardware (Malekjafarian et al. 2015). Recent research (Shirzad-Ghaleroudkhani and Gül 2024) has validated that standard smartphones can accurately identify bridge modal properties under real-life conditions, effectively turning traffic into a continuous monitoring stream in a crowdsensed framework. For this data to be actionable within a DT context, it must be robust against environmental noise. Recently, Zeng et al. (2025) proposed the Multibridge Inference SHM framework, which leverages drive-by monitoring and crowdsensing to observe multiple bridges simultaneously, paving the path toward a network-level, real-time data source that complements rigorous SHM techniques and is essential for robust, environment-aware DT ecosystems.

From the survey data it can be seen that DT technology is considered by bridge owners as a promising, still-evolving tool with the potential to ease many of the challenges in bridge management. Several respondents point out its ability to strengthen decision-making by providing richer, real-time structural information, allowing managers to prioritize conservation efforts and evaluate bridge condition with greater accuracy. Others highlight its value for structural assessment (both before and after rehabilitation), especially for complex structures where conventional methods are insufficient. Many emphasize that DTs can integrate diverse data sources, from monitoring systems to hazard information, creating a link between condition data, maintenance strategies, and long-term asset management. Visualization is another advantage: DTs make behavior easier to understand than traditional photographs or inspection notes, which results in better communication, supports inspection quality control, and results in more informed decisions. A few respondents remain unsure or skeptical, but most respondents anticipate that DTs will become a mainstream component of asset management, enhancing existing workflows rather than replacing them. It is important to note that, given the survey's focus on DTs, the sample may be biased toward respondents who are already inclined to engage with or explore this technology. Figure 3 shows the main concerns of bridge owners regarding DTs, with complexity of the system and high cost identified as the largest hurdles. Other concerns that were provided are the human factor (errors related to human operation and interpretation of the

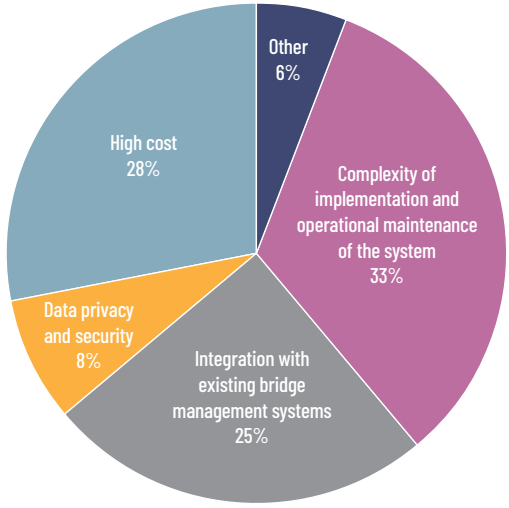


Figure 3. Concerns of bridge owners regarding digital twins.

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system, potentially related to limited digital skills, staff member changes, resistance to changing established workflows, etc.), needed resources, data requirements and storage, owner and client acceptance, applicability across different bridge types, and skepticism regarding the holistic benefits that may not materialize in application.

Digital Twin Definitions

This section combines the input from the survey with concepts from the literature survey discussed in the introduction to develop the necessary input for a first draft definition of a bridge digital twin (BDT). The survey responses reveal a substantial lack of consensus among bridge owners regarding the definition of a digital twin (DT). Most commonly, a DT is referred to as a virtual projection of the real (physical) world. However, there is a very broad range of definitions within this concept, varying from very basic to very advanced models, assigning different features and purposes to the DT. One axis of variation concerns scale. While most bridge owners envision a DT representing an entire bridge asset, others restrict the concept to specific components, subsystems, or performance aspects. A second axis relates to the nature of the digital representation itself. For some bridge owners, a schematic representation of the bridge is sufficient, visualizing data on graphical displays, possibly related to points on a structural plan. In other definitions, a DT should always be a 3D representation of the bridge, either a 3D scan, 3D images, a BIM model, or a finite element model (FEM), the latter also enabling structural analysis. Whereas for some bridge owners, the definition of a DT does not go beyond this 3D model of the bridge, most relate DTs to collected data. Data-related interpretations, however, also vary significantly. Sometimes, only data on the loading side is considered, monitoring traffic on the bridges, allowing for the detection of overweight vehicles. However, most often data on the resistance side is also incorporated into the DT, including information from sensors (Zarate Garnica and Yang 2022), inspections, and other monitoring systems. The level of data processing expected within the DT further distinguishes definitions. For some, it is sufficient that advanced analytics or machine learning methods detect anomalies and generate alerts directly from data streams. Others expect a deeper coupling between data and models, whereby measurements are used to update and calibrate physics-based representations of the structure. In bridge applications, such coupling often relies on systematically identified modal properties. Beyond damage detection, many owners emphasize the importance of service-life prediction and lifecycle decision support, which necessarily requires model-based or hybrid approaches capable of simulating structural performance and degradation over time. Finally, expectations regarding data assimilation range from near-real-time updating to periodic, event-driven updates aligned with inspection or assessment cycles.

The broad range of definitions provided by the bridge owners emphasizes the need for a common and accepted definition of DT technologies for bridges. Based on the most common definitions provided by the bridge owners, an ideal DT should enable asset managers to visualize the bridge, check its status, perform analysis, and generate insights to ensure that the right intervention is done at the right time. It should be a technology supporting better decision-making, relying on a (data) model that reflects the structure, with all its properties. As such, DTs will improve the financial management of the bridge, which is currently handled via resource allocation supported by the BMS, by using integrated data for service-life predictions and optimized maintenance scheduling. To put in simple terms: most owners would like to use their current BMS and enhance it with a more sophisticated geometric representation, i.e., BIM, but also with integrated data streams from sensors and monitoring systems that can support timely damage detection, predictive behavior assessment, and proactive maintenance planning.

To avoid conceptual ambiguity, it is important to distinguish DTs from related but distinct constructs. As emphasized by Yan et al. (2025), BIM models provide data-rich yet primarily static representations of assets, typically developed for design and construction, whereas DTs are characterized by an ongoing, bidirectional connection between the physical asset and its digital counterpart. In this context, bidirectionality does not necessarily imply automated physical control; rather, it denotes a closed information loop. In bridge management, this bidirectionality most commonly manifests through updated assessments, forecasts, and decision-support outputs rather than direct control actions. In other words, data from the physical asset (e.g., monitoring measurements, inspection results, operational records) continuously update and calibrate the digital model, while the digital model generates analyses, forecasts, and decision-support outputs that inform inspection planning, maintenance strategies, and operational interventions on the physical asset. Digital shadows represent an intermediate case, in which information flows unidirectionally from the physical asset to the digital representation, enabling monitoring and visualization but lacking feedback, calibration, or predictive interaction. Although cyber–physical systems share conceptual similarities with DTs, they pursue different objectives and architectures and should therefore not be conflated with DT implementations.

Digital Twins in the Context of Assessment of Existing Bridges

This section discusses the role of DTs in the assessment and management of existing bridges, with a focus on integrating geometric models, monitoring data, semantic frameworks, and data-driven methodologies. It presents current developments in BIM/BrIM integration, sensor fusion, interoperability standards, cybersecurity, model updating techniques, and lifecycle-based implementations, illustrating how DTs can support more informed, resilient, and data-centric bridge management practices.

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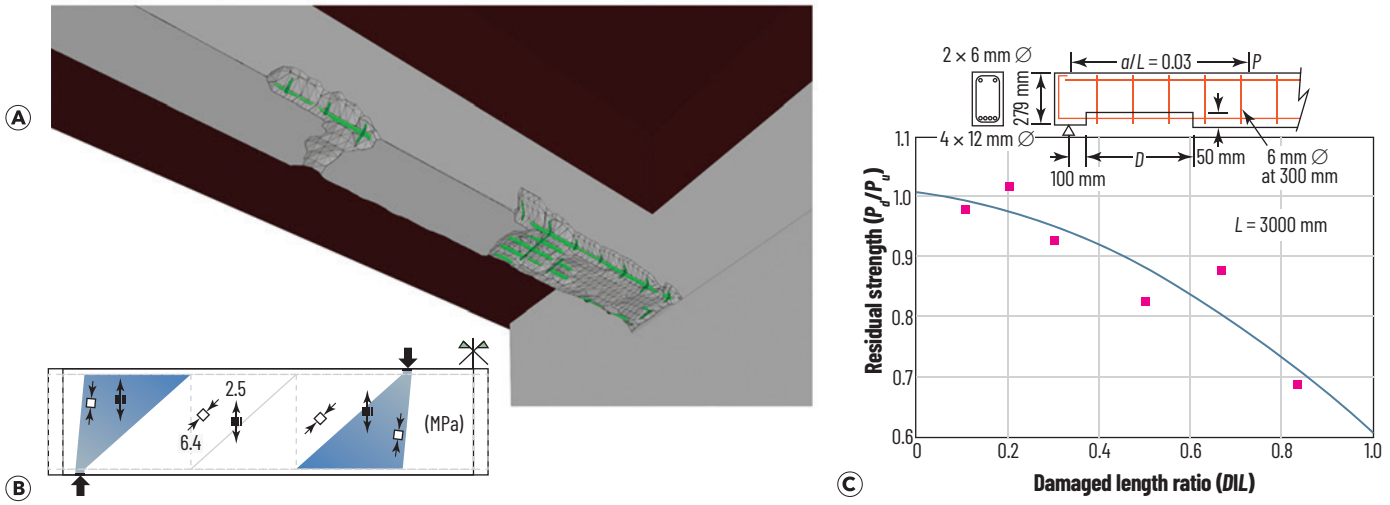


Figure 4. Spalling damage and its structural consequences: (a) photogrammetric recording subtracted from the bridge 3D model; (b) disrupted load path from loss of reinforcement bond, shown as a stress field; (c) resulting reduction in structural resistance (Raoof and Lin 1997).

Geometric Integration and Sensor Fusion

The assessment of existing bridges involves evaluation of the main performance indicators, which are safety and serviceability. The evaluation of performance indicators can, in principle, be carried out without graphical representation of the structure, its structural system, and load configuration. However, it is foreseeable that the introduction of BIM will significantly facilitate and enhance this process. For example, the spalling shown in Figure 4a has been recorded photogrammetrically and subtracted from the bridge 3D model. This localized damage results in the loss of bond between the reinforcement and surrounding concrete, disrupting the load path illustrated by a stress field in Figure 4b. This disruption leads to reduction of structural resistance, which can be quantified either through analytical model or experimental results as shown in Figure 4c.

In the example above, no structural model (e.g., FEM) is embedded within the BIM. However, such models can be also stored in the BMS. The inclusion of structural models would enable the on-the-fly evaluation of different load combinations including but not limited to exceptional transports. This capability would greatly enhance the responsiveness and accuracy of structural assessments in operational scenarios.

There is a growing trend toward monitoring bridges using a variety of technologies, enabling a deeper understanding of structural behavior under loading. The data collected by these technologies need to be accessible from the BMS. When sensors are installed on a structure, their type and exact location should be recorded, either directly within the BMS or, in the case of a BIM-based BMS, embedded in the 3D model. If sensor data is used to calibrate an embedded FEM, the BIM effectively becomes a DT of the bridge, providing a dynamic, data-informed representation of the structure (see also AMSFree 2022).

Semantic Architecture and Data Frameworks

Designing a functional DT for a BMS requires a semantic foundation able to formalize geometry, materials, processes, and temporal evolution in machine-interpretable form. Beyond representing the physical artifact, a semantic DT must encode how the bridge behaves, how it is inspected, and how its condition changes over time. To achieve this, several semantic requirements must be met. First, geometric semantics must define a fully decomposed representation of the bridge into meaningful components (arches, beams, decks, spandrels, piers, abutments, parapets). While IFC provides core classes such as IfcBridge, IfcElement, and IfcSpatialStructureElement, bridges typically demand complementary ontologies to describe their particular parts or construction phases. This hierarchical decomposition ensures each component can be referenced, inspected, and updated individually. Depending on the bridge type, construction phases may or may not be relevant to the bridge owner. For most bridges, an understanding of how the asset was changed as a result of interventions needs to be available, such as widening, adding sensors, or removing parts. For particular bridges, such as post-tensioned balanced cantilever concrete bridges, the construction sequence is of importance to forecast the long-term deflections and compare these to measured deflections (Lantsoght et al. 2018).

Second, material semantics must capture the constitution of elements through machine-readable descriptions. Here, IfcMaterial, IfcMaterialConstituent, and IfcMaterialLayerSet become essential, allowing explicit definition of material types and properties, deterioration parameters, and uncertainties. These IFC entities can then be linked to laboratory tests, minor destructive testing (MDT), or in situ measurements and stored in an ontology-driven structure that supports traceability and temporal comparison (buildingSMART International

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2025). Third, process semantics require the explicit modeling of inspection routines, diagnostic activities, and maintenance actions. IFC provides relevant classes such as IfcTask, IfcProcedure, IfcWorkSchedule, and IfcCalendar, which allow representing inspection calendars, maintenance cycles, and programmed interventions. Measurement processes—ranging from dynamic identification to surface characterization—can be semantically encoded through entities such as IfcSensor, IfcSensorType, or custom object models representing NDT equipment. Linking these processes to results via ontology for property management (OPM) and the provenance ontology PROV-O enables time-aware updates of the twin (Rasmussen and Lefrançois 2018). Fourth, spatial and network semantics situate the bridge within its territorial context. Ontologies like GeoSPARQL and Simple Features allow embedding the bridge in its railway or hydraulic corridor, enabling multiscale analyses (Battle and Kolas 2011). Finally, interoperability semantics ensure that IFC, IoT, GIS (geographic information system), and inspection-derived data can be integrated within a unified knowledge graph. Satisfying these requirements allows DTs to act as robust assistants for bridge managers, transforming fragmented datasets into actionable, network-level intelligence (Ramonell Cazador 2025).

IT Architecture and Cybersecurity

The effective deployment of BDTs depends not only on structural modeling and data analytics, but also on the IT infrastructure that enables data exchange, connectivity, and security. At the communication layer, BDT architectures rely on bidirectional data pipelines between physical sensors, edge computing nodes, and cloud platforms, where communication complexity, latency, and fault tolerance directly affect the reliability of operation and maintenance services (Gao et al. 2023). Railway bridge implementations have demonstrated this in practice, integrating wireless IoT accelerometers with MQTT connectivity, hybrid on-premises and cloud machine-learning pipelines, and real-time edge processing for automated SHM (Armijo and Zamora-Sánchez 2024).

As BDT platforms connect owner agencies, inspection consultants, and analytical tools through cloud-based and industrial IoT-enabled environments, they face cybersecurity challenges similar to those in other critical infrastructure systems, including risks to data confidentiality, integrity, authentication, and secure communication (Lampropoulos et al. 2024; Itäpelto et al. 2025). Security-enhancing DT applications in cyber–physical systems use AI/ML–based anomaly detection, intrusion detection, simulation, and blockchain-supported data integrity mechanisms to improve monitoring and threat detection (Itäpelto et al. 2025; Qureshi et al. 2025). A reference architecture for cybersecurity DTs in critical infrastructure proposes layered on-site, edge, cloud, and remote tiers with bidirectional twinning communication. The framework enables what-if attack simulation, decision support, and security configuration optimization without disrupting live operations, while also recognizing that the DT itself expands the attack surface and must be secured (Itäpelto et al. 2025). NIST recommends planning DT cybersecurity using a zero-trust model and implementing comprehensive controls, including data integrity protections, strong authentication, access governance, encryption, and physical security of instrumentation and supporting IT systems to ensure trustworthiness (Voas et al. 2025).

Data-Driven and Model-Based Updating Methods

With a robust basic semantic representation of individual assets adequately geo-located, one can foresee a wide variety of methods that can be added to those systems gradually and most crucially, specifically to each asset. That is to say, some bridges may have assessment methods based on data, some others based on models, and some others with hybrid approaches. Information from SHM and other inspections and measurements can be incorporated into BDTs in various ways. For instance, there are the data-based approaches (Fan and Qiao 2011), where monitoring data is analyzed as a function of time. Machine learning and other statistical (pattern recognition) methods are used to detect anomalies in the data, possibly indicating damage in the structure. In these data-based methods, a distinction should be made between supervised and unsupervised learning (Farrar and Worden 2012). Unsupervised learning methods only rely on data collected from the undamaged structure, enabling damage detection and possibly damage localization, but no quantification or prognosis of future damage. Supervised learning methods, on the other hand, also use experimental data from damaged structural states, as such enabling damage quantification (Farrar and Worden 2012). The main issue here is that often only one dataset is available, i.e., either for the damaged or the undamaged state.

To overcome this issue and to also allow for future damage prognosis, model-based methods can be applied (Fan and Qiao 2011; Magalhães et al. 2012), where a detailed numerical model of the structure is updated based on information from measurements, inspections, and monitoring. Various approaches exist within these model-based methods. In many applications, modal data from vibration measurements, such as natural frequencies and displacement mode shapes, is used to update the stiffness and mass of the bridge (Behmanesh and Moaveni 2015; Simoen et al. 2013). In van de Velde et al. (2025), natural frequencies and strain mode shapes are used to update the Young's modulus and shear modulus of reinforced concrete beams. This updating of model parameters can be done both in a deterministic and in a probabilistic way. In deterministic model updating, model parameters are adjusted until the model output corresponds with the monitoring data. In probabilistic approaches, Bayesian inference methods are applied to update prior distributions of model parameters to posterior distributions, incorporating the measurement information (Caspeele et al. 2025; He et al. 2025). The advantage of the latter approach is that it enables taking into account

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relevant measurement and model uncertainties in an appropriate way (He et al. 2025; Vereecken et al. 2024). Various types of measurement information can be incorporated to update relevant parameters, as long as changes in the variable of interest influence the measured parameter.

These methods could also be further extended by including time-dependent degradation models. As such, based on the measurement data, distributions of variables in these degradation models can be inferred, providing more accurate predictions of the remaining service life of the bridge. In such approaches, chloride profile measurements can be useful additions to the DT, providing information about the time to initiation of corrosion, but also indications of appropriate repair techniques (Van Den Hende 2025). Also, information from visual observations and crack width measurements proves useful Van Den Hende 2025; Vereecken et al. (2024). To account for the spatial character of degradation, or the heterogeneous character of concrete in general, spatial variation can be incorporated in the model, for example, by the use of random fields. For example, in Vereecken et al. (2022), it has been illustrated how a spatially varying distribution of the corrosion degree can be updated based on data from ambient vibration tests and strain measurements obtained under proof-loading. However, one main concern when applying these model-based methods is the required accuracy of the model. Every deviation between the DT model and reality might lead to incorrect inferences based on the monitoring (Van Den Hende 2025; Vereecken et al. 2024). Moreover, whereas the combination of various amounts of heterogeneous measurement data has been shown promising when updating the corrosion process of reinforced concrete (RC) or prestressed concrete (PC) bridges (Vereecken et al. 2022), quantification of corrosion based on vibration-based methods only still remains challenging, even more for PC than for RC structures (Van Den Hende 2025).

Regional Progress and Lifecycle Implementations

In Chile, the application of BDTs has focused primarily on the development of models representing existing bridges. Such initiatives have enabled the collection of detailed structural information through technologies such as lidar, combined with traditional and technology-enhanced inspection methods. These enhanced inspection techniques currently include visual surveys supported by technologies such as UAVs, in addition to conventional inspections conducted in accordance with protocols established by the Ministry of Public Works (MOP) and the State Railways (EFE) (Requesens and Valenzuela 2025). The analytical capabilities of DTs are not limited solely to assessing condition and damage, nor to documenting geometric or structural characteristics. Emerging research is also exploring their use for training future inspectors and for improving the visualization of structural condition for office-based engineering teams. This is being enabled by digitalization at different levels. The first level relates to general structural characteristics, including bridge access points and the main components, such as the superstructure and substructure. A second level corresponds to DT integration with geospatial and contextual information, incorporating GIS to connect structural data with broader parameters such as climate-change scenarios or environmental conditions—an approach aligned with methodologies observed internationally, for instance in recent European initiatives on climate-resilient infrastructure (e.g., CEN/TC 442/WG 9 on BIM interoperability (CEN/TC 442/WG 9 2024) and PIARC technical reports on asset management (World Road Association [PIARC] 2023). Finally, digitalization efforts are also targeting highly specific or singular components, such as support-bearing systems in railway structures, particularly those involving metallic bearings, where sensor-based monitoring and FEM updating techniques have been widely reported in the international literature (Jiménez Rios et al. 2023).

Comparable developments can be found elsewhere in Latin America. Countries such as Brazil, Colombia, and Mexico have initiated research programs applying lidar-based surveys, UAV inspections, and early-stage DT models for bridges and road corridors—for instance, pilot implementations for monitoring PC bridges in Colombia and geospatial-integrated DT frameworks in Brazil for highway infrastructure management (Machado et al. 2025; Futai et al. 2022). Current BMS typically contain information on construction materials, which is essential for accurate condition forecasting. However, during maintenance interventions, entire elements or partial sections may be replaced with different materials (e.g., ultra-high performance concrete). Such changes can be adequately represented only through BIM, which can serve as a repository for detailed asset history. Moreover, historic records of materials used are valuable for assessing the global warming potential, as they allow precise evaluation of the quantities of demolished and newly installed materials (as addressed in the GreeInfraTwins project [GreenInfraTwins 2025]).

The technical capabilities outlined above—from semantic bridge decomposition and material tracking to sensor integration and model-based condition assessment—are being systematically operationalized in the United States through coordinated federal and multistate initiatives. Following AASHTO's 2019 adoption of IFC as the national standard, the Transportation Pooled Fund TPF-5(372) project has mobilized 24 participating states with over US$2.5 million in commitments to develop the foundational infrastructure for BDTs focused specifically on existing asset management (AASHTO 2024). The project's 2023 Information Delivery Manual for design-to-construction data exchange establishes standardized semantic structures for bridge decomposition, material constituent definitions, and inspection process formalization—directly addressing the geometric, material, and process semantics requirements discussed (AASHTO 2023). Complementing this bridge-specific work, the US FHWA's (Federal Highway Administration) BIM for Infrastructure roadmap provides a systematic framework for

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extending these capabilities across the asset lifecycle, with particular emphasis on digital as-builts (DABs) that capture the as-constructed condition essential for model-based assessment methods (Mallela and Bhargava 2021). The roadmap's phased approach—from initial information delivery manuals through modular information delivery specifications to pilot implementations and software vendor certification—reflects recognition that sustainable DT deployment for existing bridges requires not only technical standards but also validation protocols, interoperability testing, and stakeholder engagement mechanisms (Mallela and Bhargava 2021). Ongoing development of a comprehensive US national bridge and infrastructure data dictionary (Costin and Muller 2023) further addresses the semantic consistency necessary to integrate heterogeneous measurement data from visual inspections, SHM systems, NDT methods, and material testing into unified knowledge graphs capable of supporting the probabilistic model updating and degradation forecasting approaches described in recent European research (He et al. 2025; Vereecken et al. 2024; van de Velde et al. 2025). This combination of standards development, pooled state funding, and phased implementation guidance is helping US bridge owners move DT capabilities from concept to practice—from detailed material tracking to network-wide management—across their diverse agencies and aging bridge inventories, though this work remains in progress.

Case Studies

This section presents representative international case studies demonstrating the practical implementation of DTs across different stages of the bridge lifecycle. The examples illustrate how DTs can integrate inspection data, structural health monitoring, numerical modeling, geospatial information, and risk-based assessment methods to support condition evaluation, maintenance planning, and lifecycle-oriented decision-making for existing bridge assets.

Case Studies in Spain

As an example of demonstration of practical deployment of DTs in bridge management, three representative case studies were developed at the Universitat Politècnica de Catalunya (UPC) in close collaboration with Spanish infrastructure authorities, including ADIF (https://www.adif.es), the Ministry of Transport and Sustainable Mobility (MITMA; https://www.transportes.gob.es), and Infraestructures de Catalunya (https://infraestructures.cat). Collectively, these cases illustrate a coherent temporal storyline across the lifecycle of bridges—from load testing at the beginning of service life, throughout routine inspection during service life, up to evaluation at the end of the service life—showing how DTs can accompany assets from their "digital birth" to their long-term surveillance and assessment. Figure 5 shows the geographical location and lifecycle stage of each of the three bridges in these case studies.

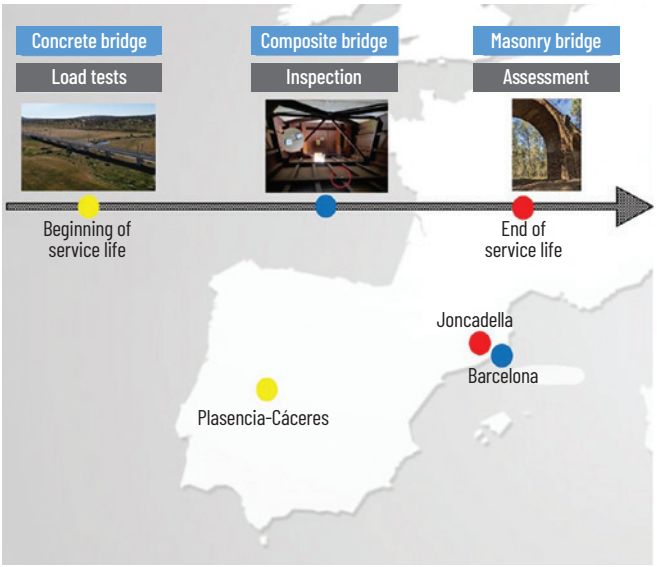
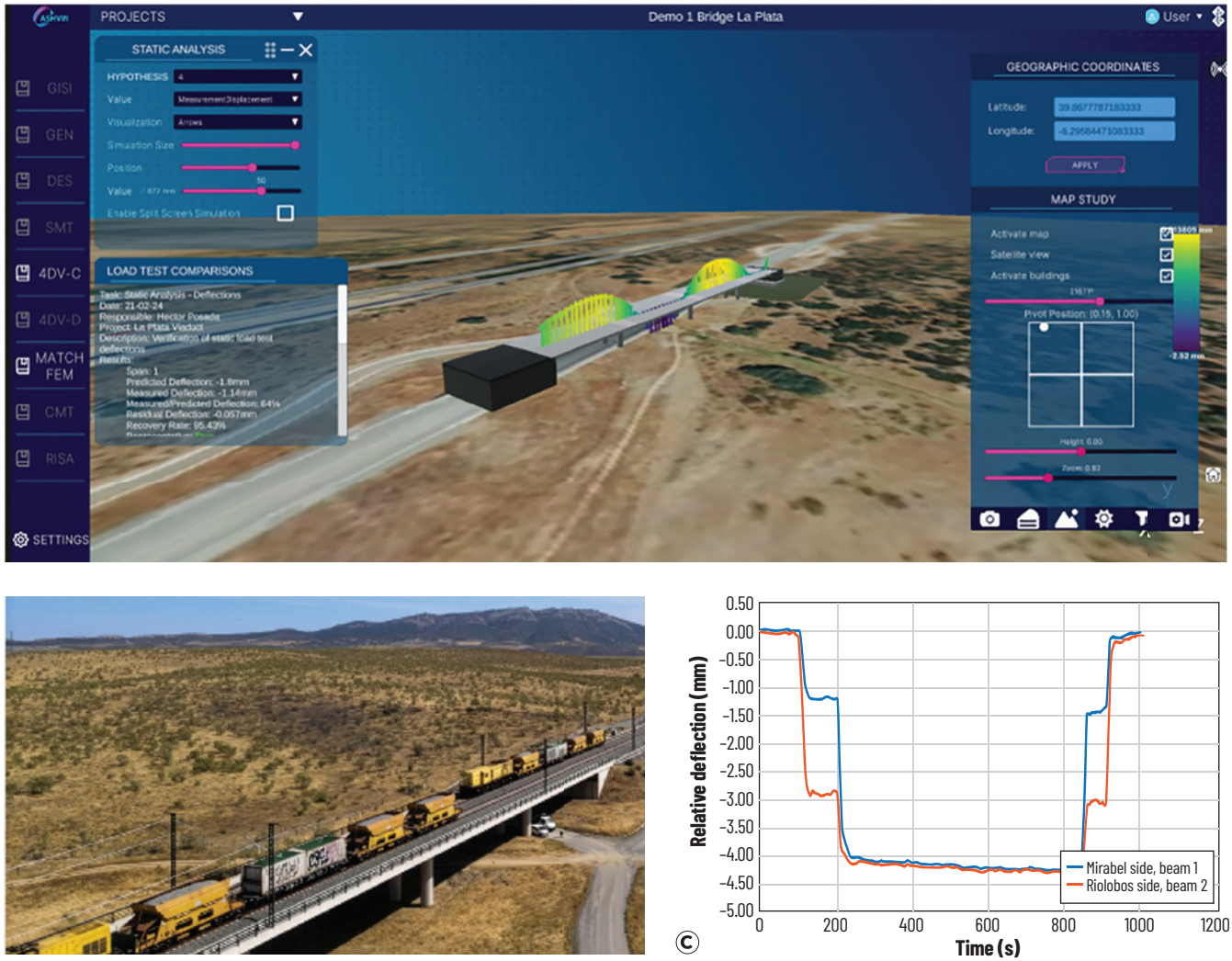


Figure 5. The geographical location and lifecycle stage of the three bridges studied in Spain.

The first case concerns a series of load tests performed on several high-speed railway bridges in Extremadura, Spain (Chacón et al. 2023b). This episode involved the coordinated acquisition of measurements (static and dynamic data), structural simulations, comparisons between both, and geometric–geospatial data. The resulting dataset enabled the creation of a DT that captures the digital birth of these assets, synthesizing their structural response, reference geometry, and operational context. As illustrated in Figure 6, the twin encapsulates the earliest and most fundamental layer of a bridge's lifecycle information related to its structural behavior. In Spain, load tests are mandatory for the vast majority of bridges (Bertola et al. 2025). Load tests represent an ideal episode for a comprehensive digital twinning of assets, since all efforts related to logistics, measurements, comparisons, and approval can be synthetized in digital applications of great use in subsequent episodes of the bridge during its lifecycle.

The second case focuses on the digital twinning of multilevel inspection processes for a composite road bridge in the metropolitan area of Barcelona. Routine image-based inspections, principal inspections with sensors, and special inspections involving laser-scanning and FEM-based diagnosis were all integrated into a single DT (Chacón et al. 2026a). This case highlights both the necessity and feasibility of integrating heterogeneous agents and inspection modalities, acknowledging that such processes may occur at different times and through different specialized teams. Figure 7 shows the combined outputs from the three inspection levels, demonstrating how images, sensor data, and geometry-based analyses converge within one coherent digital environment. Image data collection results in color maps of the state of the steel plates; sensor data collection results in modal analysis visualizations of the bridge. Geometry data collection results in the storage,

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Figure 6. Connection between load test and digital twin: (a) dynamic analysis results visualized in the bridge digital twin; (b) static load test with comparison of measured and predicted structural response; (c) measured deflections during load test.

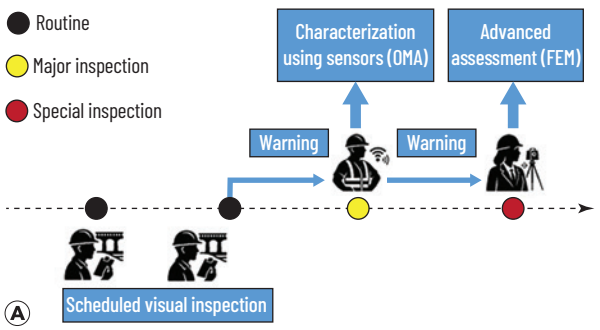
management, and further use of realistic geometries from the bridge. In this case, the geometries of the steel plates were laser-scanned, transformed into IFC elements, time-stamped, and stored. Managers can select these geometries from the twin and send them for finite element analysis (FEA) if needed during the lifecycle. It is worth pointing out that in this case, no FEA is performed in this application. Geometries are retrieved and sent to those stakeholders dealing with appropriate FEA software.

The third case examines an aging masonry railway bridge in Catalonia that has already exceeded its nominal service life. Here, the DT supports the documentation of valuable information related to its material (NDT and MDT tests, respectively) as well as the evaluation of the structure through standardized indicators such as the Masonry Quality Index (MQI) (Chacón et al. 2026b). The geometric twin was generated through a scan-to-BIM workflow based on laser-scanner point clouds that were subsequently transformed in IFC objects using MatchFEM, a UPC-developed plugin for managing IFC-based DTs (Posada et al. 2025). This case opens the role of DTs for managing network levels. For an individual asset, information is organized systematically and presented in web applications for inspectors and engineers orchestrating material testing, diagnostics, and performance evaluation (see Figure 8). Each individual asset together with its geometrical, material, and assessment information can be aggregated in GIS-based applications as shown in Figure 9.

Case Study in Sweden

The Kalix Bridge in northern Sweden provides a representative example of the development and application of a structural digital twin (SDT) for bridge management (Figure 10). The bridge, constructed in 1956, was a five-span post-tensioned concrete box-girder structure with a maximum span of

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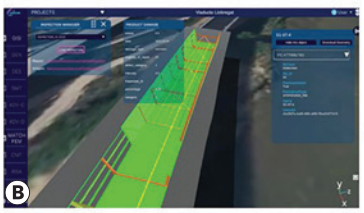




Image data collection, annotation, and visualization





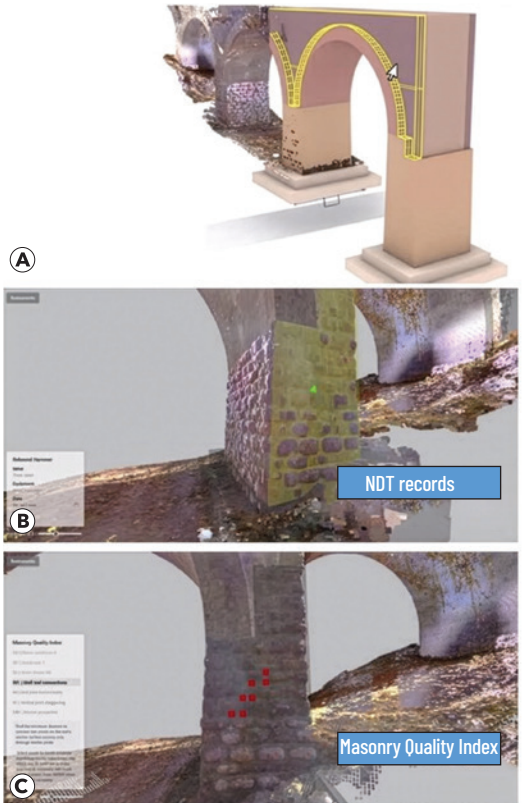
Sensor data collection (accelerations), processing, and visualization





Geometry data collection, storage, and management of geometrical objects for FE-based analysis

Figure 7. Different twin inspection applications for existing bridges during their lifecycle: (a) multilevel inspection workflow, progressing from routine visual inspection through sensor-based characterization to advanced FEM assessment when triggered by warnings; (b–d) data collection at the three inspection levels.

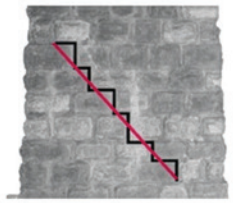




Major inspection



Material data



Evaluation according to MQ Index

Figure 8. Systematic twinning of geometrical, material, and assessment data for a set of similar existing masonry bridges that exceeded their nominal service life: (a) scan-to-BIM geometric twin generated from laser-scanner point clouds and transformed into IFC objects using MatchFEM; (b) NDT and MDT material data linked to the 3D model via georeferenced records; (c) structural evaluation using the Masonry Quality Index (MQI), with results mapped onto the twin and assessed through standardized indicators.

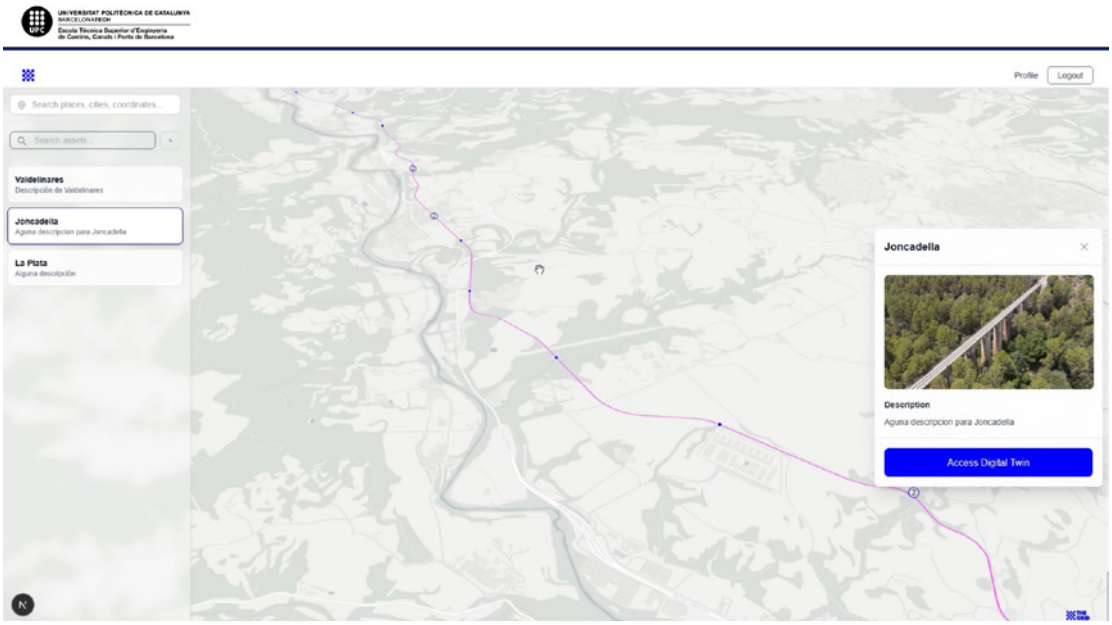


Figure 9. Aggregation of bridge data in GIS-based applications for network analysis.

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Figure 10. The Kalix Bridge in 2021 (photo courtesy Sas et al. 2024).

approximately 94 m and a total length of 283.6 m (Sas et al. 2024), with geometry as indicated in Figure 11. Following a structural assessment in 2014, the bridge was found not to fully comply with current code requirements, particularly regarding durability-related aspects. As a replacement bridge was constructed in 2019–2021, the existing bridge served as a full-scale testbed prior to demolition, enabling integrated monitoring, modeling, and validation activities that form the backbone of an SDT framework.

EXPERIMENTAL ASSESSMENT AND DATA INTEGRATION

An extensive experimental campaign was carried out before demolition (Sas et al. 2024). The program included proof load testing under realistic convoy loads at the serviceability limit state, comprehensive instrumentation (strain gauges, LVDTs [linear variable differential transformers], accelerometers, inclinometers, and temperature sensors), and multiple NDT methods. In addition, residual prestressing forces were evaluated, and material properties were characterized through core sampling.

The collected data enabled calibration of linear and nonlinear FEMs, including representation of prestressing, staged construction, and preexisting cracking (Sas et al. 2024). Model updating based on measured strain and displacement responses reduced epistemic uncertainties and allowed assessment of reserve capacity. This integration of measurement data and physics-based modeling reflects a core principle of DTs for bridge management.

In parallel, a reliability-based management framework was developed to link structural performance indicators with decision-support metrics (Sas et al. 2024). The case demonstrates how DTs can extend beyond structural simulation to support risk-informed asset management.

SATELLITE-ENHANCED MONITORING

Satellite-based interferometric synthetic aperture radar (InSAR) data were incorporated to complement contact-based monitoring (Zandi and Malekloo 2025). Sentinel-1 data from the European Ground Motion Service (2019–2023) were processed, identifying 146 persistent scatter points in the bridge area. After coherence-based filtering, longitudinal displacement trends were evaluated by dividing the bridge into span-based segments (Zandi and Malekloo 2025).

The analysis indicated consistent vertical displacement trends over the observation period, demonstrating the feasibility of integrating spaceborne measurements into a bridge DT workflow (Figure 12). While satellite data do not replace local instrumentation, they provide wide-area coverage, historical back-analysis, and independent validation of displacement patterns.

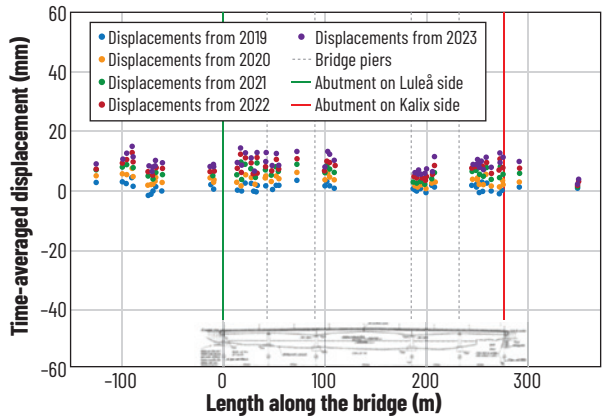


Figure 12. Vertical displacement trends of the Kalix Bridge over the observation period (2019–2023), obtained from satellite-based Interferometric Synthetic Aperture Radar (InSAR). Displacements are shown as a function of position along the bridge; data are filtered to include only points with coherence > 0.65 (Zandi and Malekloo 2025).

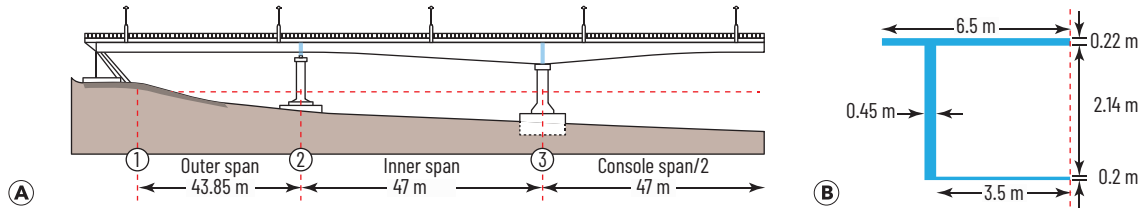


Figure 11. The Kalix Bridge: (a) overall structural geometry and span lengths; (b) representative cross-section of the prestressed concrete girder (reproduced from Sas et al. 2024).

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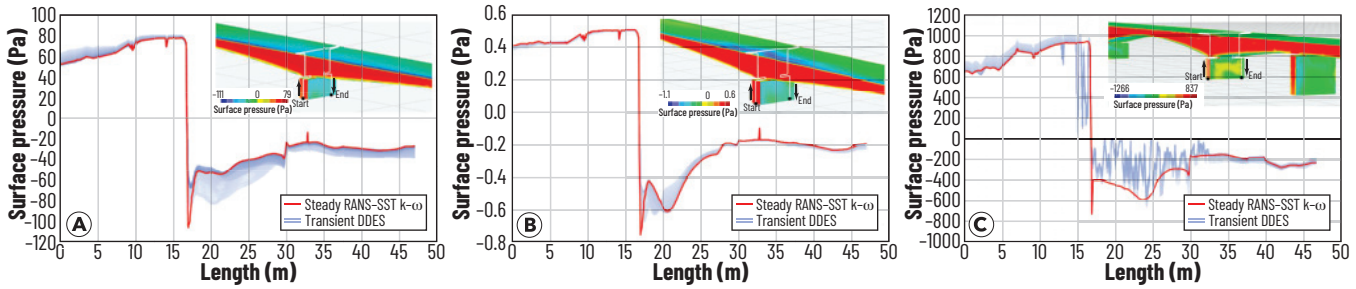


Figure 13. Surface pressure distribution along the probe line for three loading scenarios, based on 60-time steps (Δt = 0.5 s). Results compare steady RANS (SST k-ω) and transient DDES simulations (Kazemian et al. 2023): (a) extreme wind condition; (b) extreme cold condition; (c) wind design values corresponding to a 3000-year return period.

EXTREME CLIMATE LOAD SIMULATION

The Kalix Bridge DT was further extended to quantify structural loads induced by extreme climate events (Kazemian et al. 2021). Transient computational fluid dynamics simulations were performed to estimate wind and hydrodynamic pressures under extreme wind and extreme cold conditions, and under a 3000-year return period scenario. Wind loads were derived using a hybrid RANS–LES turbulence approach, and river flow effects were modeled using a Volume of Fluid method (Kazemian et al. 2023) (Figure 13). The resulting pressure distributions were proposed as critical load inputs for structural analysis, illustrating how DTs can incorporate future climate scenarios and multiphysics modeling into resilience assessment.

IMPLICATIONS FOR BRIDGE MANAGEMENT

The Kalix Bridge case study demonstrates that a bridge-oriented DT can integrate:

- inspection and NDT data,
- SHM,
- calibrated FEMs,
- satellite-based displacement measurements, and
- scenario-based climate load simulations.

The project highlights the importance of coherent data integration, model calibration, and lifecycle-oriented thinking. It also illustrates that, for bridge management applications, right-time updates aligned with inspections and monitoring campaigns may be more practical than strict real-time synchronization.

Overall, the Kalix Bridge provides a validated example of how DTs can support condition assessment, uncertainty reduction, and risk-informed decision-making within existing bridge management frameworks.

Case Studies in North America

These lifecycle-oriented implementations find operational parallels in North American practice, where state transportation agencies are similarly leveraging DT capabilities to address workforce constraints and aging infrastructure challenges.

The Minnesota Department of Transportation's (MnDOT) rehabilitation planning for the historic Robert Street Bridge demonstrates how UAS-based reality capture combined with AI-assisted defect detection can transform inspection workflows for existing structures (Becher and Lovelace 2024; Taurand et al. 2024). Collins Engineers' approach—creating georeferenced DTs to enable office-based pre-inspection, followed by field verification using tablet-based custom forms—achieved a 30% reduction in inspection hours while substantially increasing data quality and completeness. The project's integration of AI/ML crack and spall detection algorithms with the 3D reality model allowed engineers to shift from manual discontinuity documentation to validation and decision-making, directly addressing the workforce shortage challenges articulated by bridge owners in the survey responses. The DT served as a centralized, cloud-based platform shared across the entire project team, including MnDOT and consultant partners, enabling real-time collaborative access to inspection data, testing results, and 3D reality models—a practical demonstration of how data integration supports management decisions. Quantitative outcomes included a 1000-fold increase in the amount of quantifiable data available to decision-makers, a projected 20% reduction in future construction costs, and reduced lane closure time, benefiting both inspector safety and the traveling public. The project also identified potential for IoT sensor integration within the same DT environment, enabling continuous SHM data to be visualized alongside the existing reality model. Like the Spanish cases, the Minnesota project illustrates how DTs can synthesize heterogeneous data sources (photogrammetry, visual inspection, material testing) into unified decision-support environments, while demonstrating that such implementations yield measurable benefits in inspection efficiency, construction cost reduction, and team collaboration—outcomes that resonate with bridge owners' expressed needs for practical demonstrations of DT value propositions.

Case Studies Around the World

Other noteworthy case studies from the literature can be mentioned here as well. In Australia, a BIM-based DT of a railway bridge (Kaewunruen et al. 2022) showed how BIM integration

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can be used through a lifecycle analysis, resulting in enhanced operation, maintenance, and asset management for the railway bridge. In addition, the authors report on the ability of the DT to generate a virtual collaboration platform for co-simulations and co-creation of values across stakeholders participating in the various steps of the asset's lifecycle and enhancing a reduction in costs and greenhouse gas emissions. Similarly, an SHM-based DT of an existing steel railway bridge in Belgium (Maes and Lombaert 2023) shows the applicability of a limited number of sensors and extrapolation methods to derive the structural responses at other locations in the structure. In Germany, the openLAB PC bridge is equipped with sensors during its construction and coupled to a DT, which will serve to monitor baseline performance for the first years. Then, damage states will be studied by carrying out load tests to high load levels, so that the link between monitoring data and physical damage can be improved (Herbers et al. 2024).

Discussion and Working Definition of Bridge Digital Twin

Based on the survey, the insights from literature, and the reported case studies, it can be identified that a dialogue with bridge owners to identify the needs, opportunities, and potential challenges for using DTs for bridge management is necessary. The planned workshop at IABMAS 2026 aims to address this. In the survey, owners voiced opinions on how DTs can address their main bridge management challenges in the following way: making best use of technology, tools for prioritization and decision-making, better condition assessment, and integration with rehabilitation strategies. Other bridge owners indicated they are unsure how, and whether, DTs can support them with their bridge management challenges. In addition, the topics bridge owners considered most relevant for the workshop are: the value of DTs in improving bridge performance understanding (33 respondents), standardization and data formats for DTs (32 respondents), defining inputs and outputs of DT models (31 respondents), and real-world case studies from other industries (31 respondents). Technology transfer, best practices, return-on-investment data, and the ability to integrate with existing platforms were added in the comments as topics to address. Bringing these ideas together, it is important to develop DT methods that meet the needs of bridge owners and address current bridge management challenges in a practice-oriented way. From this point of view, a workshop seems to be the appropriate format to bring together technology developers, researchers developing methodologies, and bridge owners who can provide practical input.

The novelty of the presented work lies in the breadth of the approach, mapping the current status of DT applications in bridge management, and tracing the next steps to develop methods and tools that truly serve the bridge owners and align with their needs for bridge management, while listening well to their concerns when it comes to new technology and adoption. From this perspective, the tailored survey presented in this paper provides new insights into the needs of bridge owners and the specific understanding and expectations they have regarding DTs. As such, the results of this survey can be reviewed by researchers working on the topic, in such a way that they can consider the needs of end users when developing new approaches. At the same time, the literature review, the reported case studies, and the existing experience and knowledge in the IABMAS working group, represented here by the international authorship of this work, provide an overview of the current state of the art from which to depart and further develop. In addition, the reader can refer to reported case studies in the literature, such as Wenner et al. (2021) and Wimmer and Braml (2024) within the construction industry and Braik and Koliou (2023) for energy infrastructure.

Building on the AIAA definition of a DT as a virtual representation of a connected physical asset and incorporating insights from Yan et al. (2025), a bridge digital twin (BDT) can be defined as ***a continuously or periodically connected digital representation of a physical bridge asset that integrates geometry, materials, structural behavior, condition state, and lifecycle information through coherent data–model interactions, with the explicit purpose of supporting assessment, prediction, and decision-making throughout the bridge lifecycle.***

This definition emphasizes several characteristics that are particularly relevant for bridge management. First, connectivity does not necessarily imply real-time operation. While continuous data streaming may be beneficial for certain monitored structures, many bridge management decisions rely on right-time updates triggered by inspections, monitoring campaigns, load tests, or significant events. Second, a BDT is not defined solely by the presence of a 3D model. Although BIM or BrIM models often provide a valuable geometric and informational backbone, the defining feature of a BDT lies in the coupling between digital models and observational data, enabling the twin to evolve with the physical asset over time. This interpretation is consistent with cross-domain findings by Dalibor et al. (2022), which show that DTs fundamentally function as evolving digital–physical systems supporting understanding, management, and design across the system lifecycle.

In the context of bridge and infrastructure management, semantically rich DTs are therefore understood as digital replicas of physical assets whose geometry, materials, temporal evolution, and management processes are represented through machine-interpretable, semantically structured data, typically within a BIM-based BMS environment (Shafto et al. 2010; Yan et al. 2025; Dalibor et al. 2022). As many countries increasingly rely on BIM-driven digitalization strategies and open standards such as IFC, these models offer a familiar and robust foundation for asset managers. Beyond BIM, bridges generate large volumes of heterogeneous data through IoT platforms, sensor networks, inspections, and GIS-based asset management systems. The integration of these diverse data streams naturally motivates a semantic web architecture, where ontologies, RDF (resource description framework) graphs, and linked-data principles enable information from BIM, IoT, and GIS to coexist, interoperate, and evolve coherently. In

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this sense, a semantic DT extends well beyond a geometric model, constituting a web-native, ontology-driven information construct capable of contextualizing multiscale data across the bridge lifecycle and supporting advanced querying, reasoning, and decision-making for managers, inspectors, and engineers alike (Boje et al. 2020; Heise et al. 2025; Ramonell et al. 2023; Hagedorn et al. 2023). On the other hand, another crucial point is data sensitivity in digital infrastructure systems. As highlighted by Yembergenova (2025) and Yembergenova and Chacón (n.d.), they propose a human-twin framework for managing sensitive data in DT systems, particularly in bridge digitalization contexts.

Summary and Conclusions

This work summarizes the work of the IABMAS Working Group on Digital Twins, combining a targeted international survey of bridge owners, a literature review of DT developments, and an overview of representative case studies. The results show that bridge owners recognize the potential of DTs to improve bridge assessment and management, but are challenged by different data definitions, limitations of existing platforms, confusing and diverging definitions of what a DT entails, and uncertainty regarding practical implementation and long-term platform operability. This paper therefore has as its main thesis that DTs should not be isolated technological tools, but should be considered as improvements of bridge management systems that must be interoperable, semantically robust, and clearly aligned with owner needs (Hajdin 2025).

The main conclusions of this work are as follows:

- **DTs are perceived as promising tools, but there is confusion about what they are and what they are not.** Bridge owners see value for condition assessment, prioritization, and lifecycle decision-making, yet call for clearer, shared definitions and minimum functional requirements.
- **Data fragmentation and interoperability issues are primary obstacles.** Effective DTs require coherent standards and semantic architectures that integrate BIM/BrIM, SHM, NDT/MDT, GIS, and analytical models into a unified, queryable environment.
- **The owners' expectations span a broad spectrum of complexity.** Definitions range from simple 2D/3D visualizations to fully coupled, real-time, model-updating systems, some of which include forecasting capabilities and economic plug-ins to support decision-making. These differences show the need for guidance on scalable implementation paths that consider existing solutions and the owners' particular needs and constraints, rather than one-size-fits-all solutions.
- **The case studies confirm lifecycle value when DTs are embedded in workflows.** Practical examples from Spain addressing different material and bridge types, all using IFC, show how DTs can support digital birth using load testing information, multilevel inspection integration, and late-life evaluation, improving traceability and structured decision-making support.
- **To fully leverage technological capabilities, the needs and realities of bridge owners need to be put front and center in technical conversations.** A roadmap based on workshops (starting with the one planned for IABMAS 2026), a white paper, and cross-sectoral collaboration are essential to align research and industry solutions with owners' operational constraints, risk perceptions, and investment priorities.

In summary, DTs can become a useful tool for modern bridge management, but only if their development starts from the needs of the owners, applies robust data and semantic standards so that the solutions are sustainable, and is based on collaborative frameworks that translate technical potential into practical, scalable tools.

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