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Strategies for bridge maintenance using BIM: an analysis of methodologies and tools

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Ageing bridge stocks and rising traffic loads in Latin America and worldwide demand cost-effective maintenance strategies. Building Information Modelling (BIM) and its convergence with digital-twin, IoT and AI techniques have shown promise, yet their adoption for bridge upkeep remains fragmentary. This review aimed to (i) synthesise current scientific evidence on BIM-based bridge maintenance, (ii) classify methodologies and tools through a domain taxonomy, and (iii) identify research gaps that hinder large-scale implementation. A PRISMA-guided systematic literature review was conducted in Scopus and Web of Science (search cut-off = 1 February 2024). Inclusion criteria targeted peer-reviewed, open-access studies (2020–2024) that applied BIM to the maintenance of existing bridges. Twenty-five articles met the criteria and were appraised with Mixed-Methods Appraisal Tool (MMAT 2018). Seven dominant research themes were identified, with damage visualization (7 studies) and 3-D geometric modelling (6) being the most frequent, followed by information exchange/management (4). Specifically, LiDAR and photogrammetry enabled sub-centimetre models; Convolutional Neural Networks (CNN) and You Only Look Once (YOLO) algorithms reached mean average precision up to 0.91 for crack detection. Digital-twin workflows reduced operating costs while requiring higher upfront investment. A seven-domain taxonomy and a cost–technology comparison table is proposed. Key barriers reported include IFC 4.3 interoperability, high LiDAR costs (> 10% of annual budgets), limited visual-programming skills, and cybersecurity concerns in cloud-IoT integrations. BIM supports preventive, data-driven bridge maintenance and has been linked to lower operating costs in several studies; mainstream adoption requires IFC 4.3 based interoperability, targeted training, and open-standard workflows. Future research should focus on standardised performance metrics, edge-AI monitoring and blockchain-secured data exchange.

KEYWORDS

bridge maintenance, 3D visualization technologies, photogrammetry and LiDAR, real-time structural monitoring, bim

1 Introduction

Today, infrastructure managers and owners, including roads, bridges, and pavements, face multiple challenges such as aging structures and their exposure to increased loads, higher speeds, and extreme weather events (Hagedorn et al., 2023). In response to these challenges, the maintenance of existing structures has been prioritized, which is essential

due to the high cost associated with building new infrastructure (Byun et al., 2021). Specifically, bridges, as critical components of road infrastructure, require specialized treatment throughout their lifecycle (Isailovic et al., 2020). During this cycle, bridges incur annual costs ranging from 0.4% to 2% of construction costs, accounting for between 16% and 80% of the total cost in the phases of operation, inspection, and eventual demolition (Artus and Koch, 2020).

Recent studies have enabled a cost-profile comparison between digital twins and traditional inspections. Digital-twin implementations demanded higher upfront expenditure, covering 3-D modelling, IoT integration and cloud-computing resources (Futai et al., 2022), whereas conventional visual-inspection approaches involved lower initial outlays (Sofia et al., 2020). Nonetheless, digital twins achieved lower operating costs by supporting predictive maintenance and reducing service interruptions (Futai et al., 2022; Ai et al., 2024); traditional practices, being largely reactive, exhibited higher operational spending due to frequent inspections (Sofia et al., 2020; Ai et al., 2024). In the long term, digital-twin adoption generated substantial savings through optimised maintenance schedules and early fault detection (Futai et al., 2022; Schneider et al., 2025; Haslbeck and Braml, 2024), while traditional methods accrued greater costs because of unexpected failures and extensive repairs (Ai et al., 2024; Hossain and Chang, 2024). Deploying a digital twin also required an advanced technological stack—laser scanners, IoT devices and cloud-computing capabilities (Futai et al., 2022; Hosamo and Hosamo, 2022), contrasting with the basic manual tools and periodic inspections typical of traditional schemes (Sofia et al., 2020). As summarised in Table 1, these cost differentials reinforce the economic rationale for adopting digital-twin strategies.

It is estimated that in the next decade, 47% of these structures will exceed 30 years of age, a figure expected to rise to 80% in the following 20 years (Jeon et al., 2023). Such projections raise serious concerns about operational safety, given the significant number of bridges that will remain in service (Li et al., 2023). In this context, the maintenance and operational safety of bridges become critically important for countries reliant on these infrastructures (Isailovic et al., 2020). A promising strategy to address these challenges is the implementation of Building Information Modeling (BIM) (Ciccone et al., 2022).

Building Information Modeling (BIM) is an advanced methodology that has been applied in architecture, engineering, and construction (Van et al., 2022). However, creating BIM models for pre-existing structures presents significant challenges due to the difficulty in accurately representing the existing structure within a model (Artus et al., 2022). To tackle these challenges, various 3D modeling techniques have been developed, such as photogrammetry (Isailovic et al., 2020; Artus and Koch, 2020; Gan et al., 2023; Wójcik and Zarski, 2021), LiDAR scanning (Lee et al., 2021), semi-automatic methods from hand-drawn and computer-assisted plans (Poku-Agyemang and Reiterer, 2023), and direct structural modeling (Poku-Agyemang and Reiterer, 2023; Kaewunru et al., 2021; Zhou, 2022). These techniques provide the necessary geometric and semantic information to facilitate proper bridge maintenance (Artus and Koch, 2020). In this context, these techniques should be understood as data-acquisition and modeling enablers that feed the information model; by themselves they do not constitute BIM.

Within this framework, Building Information Modeling (BIM) is understood as an information management process across the asset life cycle rather than as a stand-alone technology. This perspective is established by the ISO 19650 series, which defines roles, responsibilities, and workflows for information delivery and management (Abanda et al., 2025a; Park, 2024; Abanda et al., 2025b). Within this scheme, key deliverables structure the production and exchange of data, namely OIR, AIR, EIR, BEP, and the PIM and AIM models (Oliveira et al., 2024; Trani et al., 2024). In addition, the Common Data Environment (CDE) provides a central repository that ensures data integrity, accessibility, and traceability throughout the asset life cycle (Park, 2024; Xiang et al., 2025; Jaskula et al., 2024; Preidel et al., 2016; Preidel et al., 2018; Klemm-Albert et al., 2018). The Level of Information Need (LOIN), in turn, specifies the scope and granularity required at each stage, so that information remains sufficient, relevant, and usable for decision-making in bridge operation and maintenance (Trani et al., 2024; Abualdenien and Borrmann, 2022; Wogan et al., 2024). This information-management perspective underpins the assessment of maintenance needs discussed next. Determining the need for bridge maintenance is a complex process that requires detailed and meticulous analysis to conduct a proper assessment (Poku-Agyemang and Reiterer, 2023). Conventional methods, reliant on visual inspections, are subjective and error-prone due to the lack of objective data

TABLE 1 Cost and Technology Comparison—Digital Twins vs. Traditional Methods.

Aspect	Digital twins	Traditional methods
Initial costs	High (3-D modelling, IoT integration, cloud computing) (Futai et al., 2022)	Lower (manual inspections, conventional tools) (Sofia et al., 2020)
Operating costs	Lower (predictive maintenance, reduced downtime) (Futai et al., 2022; Ai et al., 2024)	Higher (reactive maintenance, frequent inspections) (Sofia et al., 2020; Ai et al., 2024)
Long-term outcome	Significant savings through optimised schedules and early-fault detection (Futai et al., 2022; Schneider et al., 2025; Haslbeck and Braml, 2024)	Higher long-term costs owing to unexpected failures and extensive repairs (Ai et al., 2024; Hossain and Chang, 2024)
Technological needs	Advanced stack (laser scanners, IoT, cloud computing) (Futai et al., 2022; Hosamo and Hosamo, 2022)	Basic tools (manual equipment, periodic inspections) (Sofia et al., 2020)

supporting maintenance decisions (Zhou, 2022). In contrast, BIM-based workflows provide a more accurate and efficient alternative for damage detection and structural maintenance (Gan et al., 2023). Despite its benefits, the application of BIM in bridge management and maintenance has been limited due to the complexity associated with these tasks (Zhou, 2022). A feasible solution is to integrate BIM with Structural Health Monitoring (SHM) systems to assess the operational performance of old structures and determine maintenance needs (Fawad et al., 2023; Sakr and Sadhu, 2023). SHM is a non-destructive system that allows real-time monitoring of structural health (Scianna et al., 2022), aiding in the performance evaluation of the bridge during its operational and service phase (Sakr and Sadhu, 2023). Recent studies have shown that SHM can be employed for real-time structural monitoring to assess maintenance needs (Sakr and Sadhu, 2023). Additionally, the integration of the Internet of Things (IoT) with BIM models enables the development of a real-time connection between the physical model and its digital twin (Scianna et al., 2022), providing an advanced technological solution for this purpose (Fawad et al., 2023). This not only delivers detailed monitoring information throughout the bridge's lifecycle (Singh and Sadhu, 2020), but also assists in the implementation of preventative maintenance strategies (Ciccone et al., 2022).

In this context, it is imperative to conduct a comprehensive review of the existing literature on the use of BIM in the maintenance of existing bridges. This review is crucial as periodic BIM-based monitoring accurately identifies structural failures (Zhou, 2022; Yang and Xia, 2023), essential for planning effective maintenance strategies that enhance infrastructure safety. Additionally, such data-driven management promotes efficient lifecycle management of the infrastructure (Hagedorn et al., 2023; Singh and Sadhu, 2020).

Finally, this article systematically examines the recent scientific literature on the use of BIM in bridge maintenance. It aims to identify methodologies, tools, and reported outcomes, enabling the determination of best practices, and addressing the challenges associated with using BIM in this field. The study seeks to answer the following research question: What are the trends, key findings, and knowledge gaps in the scientific literature on the use of BIM in existing bridge maintenance, and how can these contributions inform best practices and future strategies in this area?

2 Methodology

This study was conducted as a descriptive literature review, using scientific articles as primary information sources. The focus was on the maintenance of existing bridges using BIM. A comprehensive review was performed using the Scopus and Web of Science databases, alone were selected because recent bibliometric studies showed that the two databases together covered more than 95% of citations in civil engineering and construction science, provided standardized metadata that facilitated deduplication, and allowed trend comparisons with previous reviews on BIM for infrastructure. This ensured the quality and pertinence of the reviewed articles. In accordance with the PRISMA 2020 guidelines, an ex-post protocol was registered in the Open Science Framework, which publicly documented the objectives, search strategy, and selection criteria applied. This registration aimed to reinforce the transparency of the process without altering the corpus under analysis.

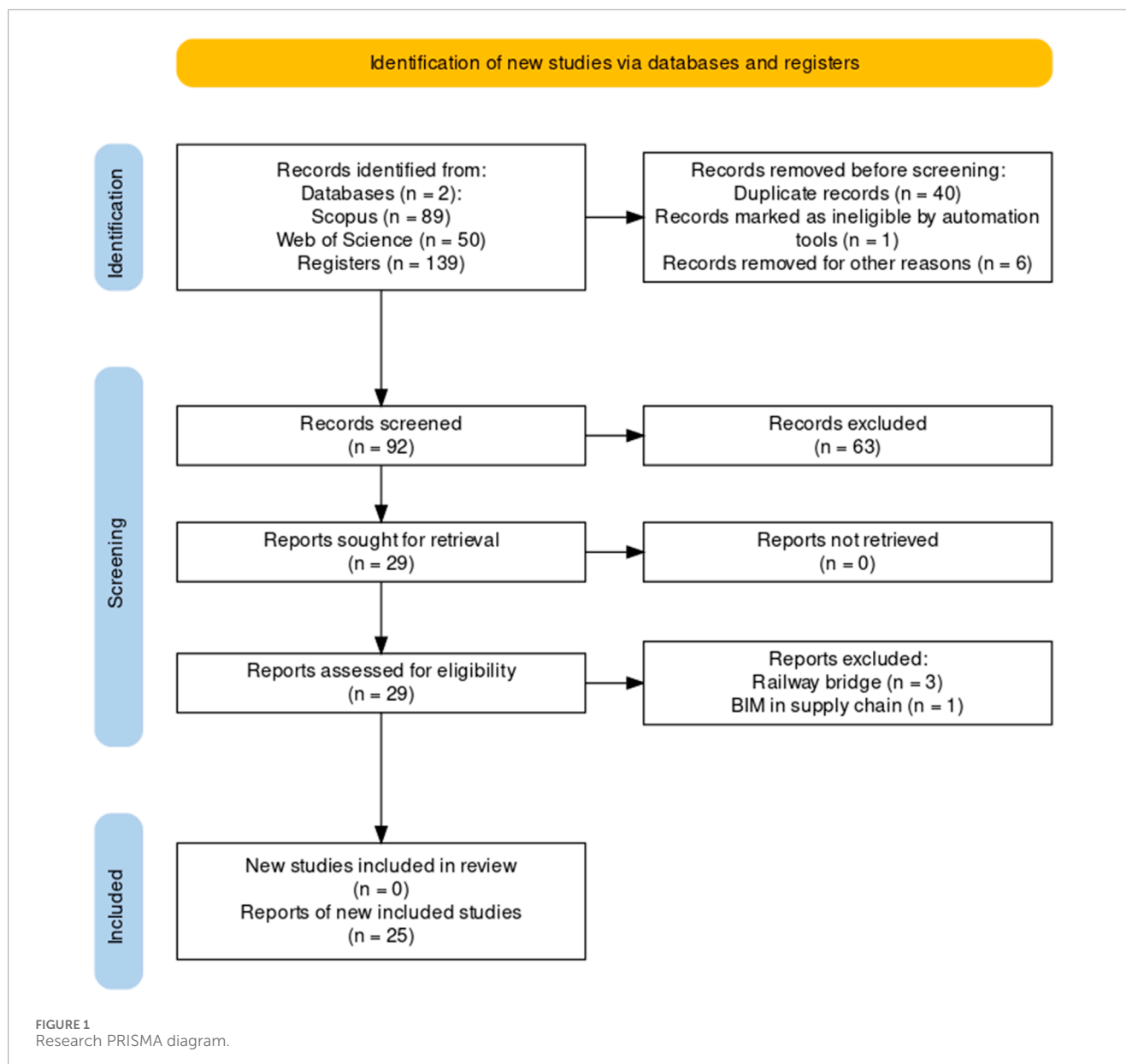
Consequently, deliberately narrow scope criteria were adopted in order to preserve thematic coherence and cross-study comparability; the asset type was limited to bridges and the life-cycle phase was restricted to operation and maintenance, with contributions exclusively focused on design or construction excluded. These decisions prioritise practical applicability for bridge O&M and account for the number of studies ultimately included. Regarding the inclusion criteria, the search was conducted considering: 1) articles that included the keywords “Building Information Modeling” and “Bridge” in the title, abstract, and keywords; 2) articles published between 2020 and 2024; 3) articles addressing the topic of bridge maintenance using BIM. On the other hand, the following exclusion criteria were considered: 1) works that did not correspond to the article format were excluded; 2) articles that were not available as open access were excluded, thus ensuring the accessibility and relevance of the selected material. The 2020–2024 time window was justified because, from 2020 onward, the IFC 4.3 bridge extension, the widespread diffusion of portable LiDAR scanners, and the integration of BIM and IoT in infrastructure maintenance reached maturity. The restriction therefore ensured that the review captured state-of-the-art technologies and avoided duplicating earlier syntheses focused on preceding periods.

This rigorous selection process identified a total of 139 articles, with 89 extracted from Scopus and 50 from Web of Science. These documents can be retrieved using the following search formulas with a cutoff date of February 1, 2024: for Scopus: (TITLE-ABS-KEY (“Building Information Modeling”) AND TITLE-ABS-KEY (bridge)) AND PUBYEAR > 2019 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (OA, “all”)) and for Web of Science: Click here, as evidenced in Figure 1.

Following a meticulous search strategy that initially identified 139 studies, Figure 1 presents the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) Diagram, which outlines the document filtration process. From the identified documents, 40 duplicates were excluded using Power BI. Additionally, the article “A BIM technology-based underwater structure damage identification and management method” was removed due to inaccessibility, and six more were excluded for not being open access, including publications from ASCE (2 articles), Emerald Insight (3 articles), and Taylor and Francis Online (1 article). Consequently, the “Screening” phase commenced with 92 articles, ready for further rigorous evaluation.

During the “Screening” phase, 63 studies were excluded. Of these, 43 were discarded for not featuring the crucial study variables “Building Information Modeling” and “Bridge” in their titles, with 22 from Scopus and 21 from Web of Science. Furthermore, after reviewing the abstracts, 20 more articles were eliminated as their content strayed from the research focus, addressing topics such as bridge design using BIM, BIM in buildings, BIM in cultural heritage contexts, BIM for seismic behavior of bridges, BIM in railway bridges, and BIM related to thermal properties, with 11 from Scopus and 9 from Web of Science. This rigorous selection process led to a subsequent phase with 29 relevant articles.

Continuing with the selection process, a detailed reading and analysis of the full text of the remaining 29 studies were conducted. In this scrutiny, four articles were excluded for addressing themes unrelated to the objectives of this research: three focused on railway



bridges and one on the implementation of BIM in the supply chain. This review refined the set to 25 articles strictly aligned with bridge maintenance using BIM, thus completing the “Screening” phase with precision and coherence with the proposed methodology.

The selected 25 articles exhibited the following geographical distribution: six from China, five from Germany, four from South Korea, two from Poland, two from Australia, one from Serbia, one from India, two from Italy, and two from Canada. In the temporally moment, 36% of these studies were from 2023, while 20% covered the years from 2020 to 2022, and 4% were from 2024. Regarding the study sample, 96% of the research focused on only one bridge, while 4% analyzed three bridges.

In the analyzed articles, various instruments were used, categorized into five main groups: The first, design and modeling tools, includes software such as Revit, Dynamo, Navisworks, and CSI Bridge, Midas CIM, RM Bridge, OpenSfM, CloudCompare,

Xbim, ReviAPI, JFCOpenShel, ifcElement, Staad, Ifc Bridge, and RolAling, accounting for 46.3% of usage. The second category covers data capture tools like RGB-D cameras, Unmanned Aerial Vehicle (UAV), MPU6050, GPR, laser scanners, drones, OpenSfM, WebGL, GIS, and LiDAR, making up 19.4%. The third includes development and programming tools like Java, Arduino ACC, Excel, Matlab, WebG, SQL, C++, and Python, representing 16.4%. Finally, data management and analysis tools such as SQL and MySQL account for 13.4%, with an additional 4.5% dedicated to advanced data analysis technologies.

To effectively organize the vast amount of data collected, a specially designed matrix was used to classify the 25 selected articles into four key categories: authorship and date of study, research topic, main proposals and contributions, and the methodology used. Following this initial organization, a detailed classification of the articles by their research topics and specific

contributions was carried out, allowing for precise segmentation for future analysis.

The research topics were organized using the Excel tool, where they were appropriately categorized and grouped. For instance, the topic “Semi-automatic method to construct 3D bridge models from hand-drawn and computer-generated plans to efficiently plan bridge supervision and evaluation activities” (Poku-Agyemang and Reiterer, 2023) was classified under the category “3D geometric model of the existing structure.” This classification approach ensured that all related topics were coherently grouped under this category. In total, seven distinct categories were identified, encompassing 25 specific topics. Similarly, the proposals and contributions were categorized and grouped, totaling 75. These were organized based on the frequency of their appearance in the reviewed studies. When selecting proposals and contributions, priority was given to those premises and statements that enhance both theoretical and practical knowledge, essential for advancing maintenance practices of bridges using BIM.

To conclude the methodological section in an organized and accessible manner, the results were structured in two significant ways. First, a bar graph was created to clearly illustrate the distribution of the researched topics. Second, a summary table was generated detailing the frequencies of the proposals and contributions identified in the various studies analyzed. These visual tools enable a quick and effective understanding of the key data gathered during the research, which will be explained in the results section.

Finally, the methodological quality of the twenty-five studies was appraised with the Mixed-Methods Appraisal Tool (MMAT 2018); all obtained scores equal to or higher than 3 out of 5. It was nevertheless acknowledged that limiting the search to two databases and to open-access publications might have excluded relevant work published behind paywalls; Additionally, the exclusive focus on open-access articles retrieved from Scopus and Web of Science may have left out publications from publishers such as ASCE, Emerald, or Taylor and Francis, not due to deliberate exclusion but because they were not retrieved under the applied criteria. This limitation was accepted as a potential coverage bias, partly mitigated by the protocol's transparency and the availability of the extracted dataset for future replications. However, this restriction responded to the need to privilege comparability and methodological consistency over the mere expansion of document counts, so that the resulting synthesis emphasizes the robustness of the evidence rather than the absolute number of studies.

3 Results

In this chapter, the results from the previously detailed methodological application, which focused on bridge maintenance using BIM, are presented. Twenty five studies implementing various techniques and tools under this approach were exhaustively analyzed to identify emerging patterns and current trends in this research area. Two fundamental aspects are presented: first, a synthesis of the researched topics illustrated through a bar graph, and second, a compilation of the most significant proposals and contributions summarized in a detailed table. These elements form the basis for discussing the main findings, which are detailed in the following

sections: the first focuses on specific research topics and the second on major contributions to bridge maintenance using BIM-based workflows.

3.1 Main research themes on bridge maintenance using BIM

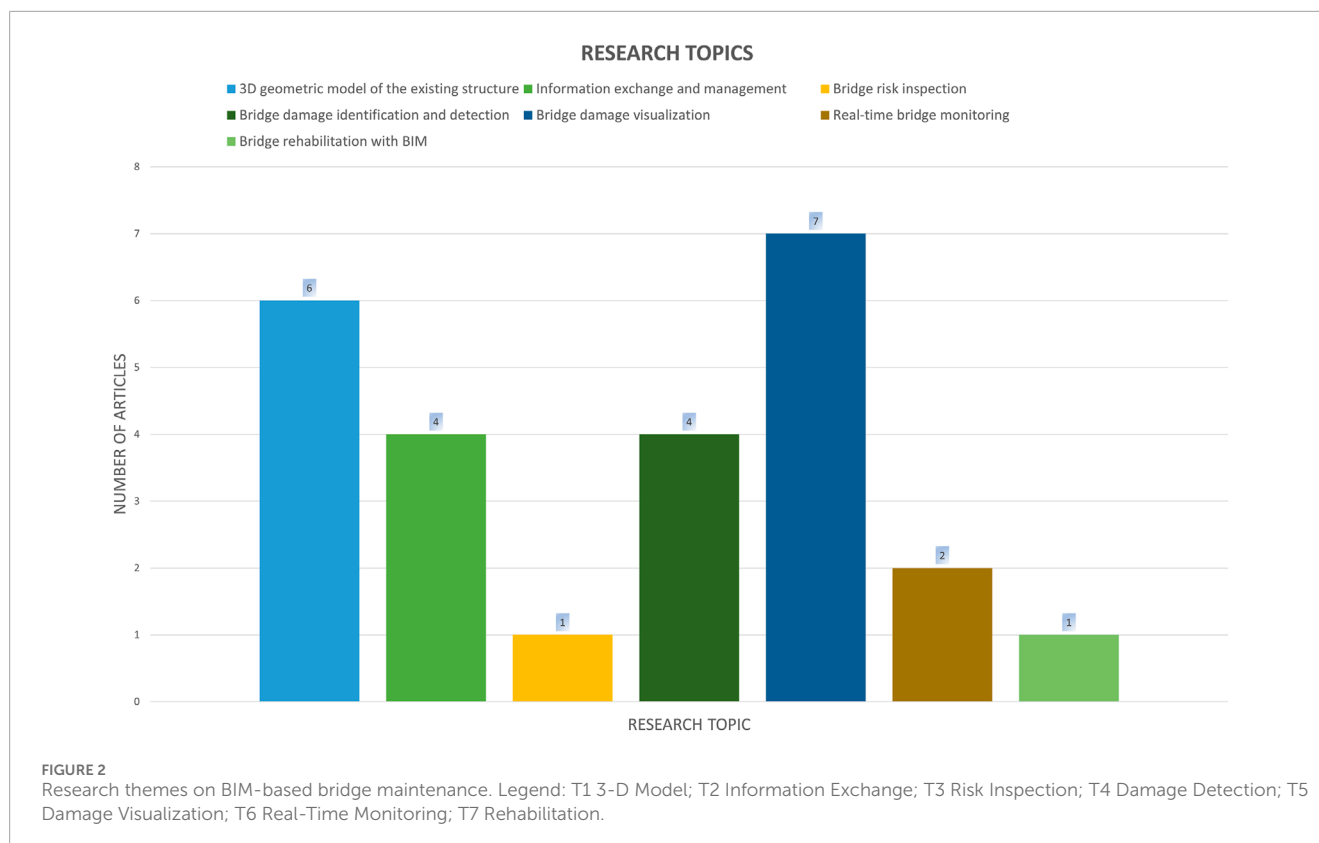
The detailed analysis of the selected articles identified seven predominant research themes in the application of BIM for bridge maintenance. These themes are represented by the Figure 2, which categorizes the articles according to their thematic focus. The sequential arrangement of the topics in the figure has been carefully considered to reflect the progressive flow of maintenance processes, thus enhancing clarity, and understanding of the stages involved.

The data presentation in Figure 2 follows a logical order from left to right, which simplifies the understanding of the collected data. This arrangement is intended to facilitate an objective interpretation of the research results, without making value judgments about them. To enhance readability, a coded legend was added to identify every thematic category: T1 “3-D Geometric Model of the Existing Structure,” T2 “Information Exchange and Management,” T3 “Risk Inspection,” T4 “Damage Identification and Detection,” T5 “Damage Visualization,” T6 “Real-Time Monitoring,” and T7 “Bridge Rehabilitation.” The x-axis also displayed the article count for each category, providing a clear quantitative reference.

The Figure 2, in its left column, features the theme “3D Geometric Model of the Existing Structure,” addressed by six articles. The first of these discusses building a semi-automatic 3D model for bridges from manually drawn and computer-aided design (CAD) plans (Poku-Agyemang and Reiterer, 2023). The second study develops a 3D model in Revit from existing 2D plans using three-dimensional modeling (Kaewunru et al., 2021). These two studies demonstrate different strategies for generating 3D models: one through semi-automatic scanning of plans, and the other through modeling in Revit.

The analysis of the third article describes the creation of a master 3D digital model from existing data on suspension bridges (Dang et al., 2020). The fourth article employs Light Detection and Ranging (LiDAR) technology to model the bridge's existing structure in 3D, automatically extracting critical parameters such as height, length, and width (Lee et al., 2020). The fifth study uses a camera and artificial neural networks to capture images and segment the point cloud, refining the 3D model and removing outliers (Martens et al., 2023). Each of these contributions underscores the use of specific tools and technologies for creating accurate 3D models. Finally, the sixth article offers a panoramic view of 3D modeling methods for identifying damages in bridges, providing a comprehensive overview of the existing techniques for detecting and documenting structural deteriorations (Artus and Koch, 2020).

Continuing with the analysis in the second column of Figure 2, four studies are presented under the theme of “Information Exchange and Management.” The first article proposes an integrated BIM modeling and information management platform aimed at structural monitoring and decision-making (Ciccone et al., 2022). This study explores the potential of BIM modeling to streamline data management and facilitate bridge structural monitoring. The second study uses a web platform to manage information from various



bridges, optimizing damage detection and the communication of necessary repairs (Hagedorn et al., 2023). The third article describes the implementation of a Web Data Management Program (WDMP), combined with Midas CIM, to enhance efficiency in maintenance, repair, and lifespan management of the structure (Byun et al., 2021). This research establishes a management system designed to reduce maintenance costs and information loss. Lastly, the fourth study discusses the application of various BIM and Geographic Information System (GIS) technologies in managing information throughout the planning, design, construction, operation, and maintenance phases (Wei et al., 2021). This study emphasizes the need to deepen data management to optimize decision-making related to the detection of structural irregularities.

The third column of Figure 2 addresses the topic “Risk Inspection in Bridges,” researched in a single study. This article explores the use of digital twins to integrate models, collect, and exchange information relevant to structural risk inspection. Through the BIM model, visualization of cracks and other signs of deterioration is facilitated, allowing for a more precise and efficient evaluation of the bridge’s structural integrity (Kaewunru et al., 2021). According to the authors, the use of digital twins proves to be a powerful tool for data processing and detailed inspection, leveraging the advanced capabilities of BIM.

The fourth column of Figure 2 showcases advancements in “Identification and Damage Detection in Bridges,” a central theme of four articles. The first study combines BIM and neural networks to develop a structural damage identification system (Yang and Xia, 2023). The second paper applies deep learning algorithms alongside BIM, presenting an alternative methodology to using

neural networks (Gan et al., 2023). Both articles identify bridge damages, differing only in their use of BIM with neural networks or deep learning algorithms. The third article uses images and the You Only Look Once (YOLO) model to detect existing structural damage (Jeon et al., 2023), integrating computer vision technologies in infrastructure inspection. The fourth study describes how detected damages are incorporated into the BIM model in the Industry Foundation Classes (IFC) format (Isailovic et al., 2020), facilitating the update and management of the existing model.

In the fifth column of Figure 2, dedicated to “Visualizing Bridge Damage,” seven articles are analyzed. The first study proposes an intelligent system for monitoring damage and cracks using three-dimensional visualization, demonstrating how BIM facilitates structural analysis (Zhou, 2022). The second article develops a maintenance system using a neural network to predict and visualize the detected structural state, highlighting the utility of predictive tools in maintenance (Shen et al., 2023). Both studies showcase the potential of modern technology to enhance the precision in identifying and visualizing structural damage.

The third article explores the integration of 3D crack models within the BIM system, enhancing their visualization and significantly improving the accuracy of infrastructure inspections (Wójcik and Zarski, 2021). Complementing this approach, the fourth study develops a three-dimensional BIM library that catalogs structural defects in bridges, allowing their incorporation into the existing BIM model for detailed visualization of defect conditions (Li et al., 2023). These investigations emphasize the effectiveness of using predefined defect models stored in a BIM library to enrich structural data visualization and management. The fifth article

focuses on visualizing and simulating bridge damage using an existing model in IFC format and processed photographs of the damaged structure, enabling detailed representation within the BIM environment (Artus et al., 2022). This approach facilitates an accurate assessment of structural integrity from images and processed data.

The sixth article focuses on representing and visualizing data obtained from real-time SHM, highlighting the importance of this technology for continuous structural integrity assessment (Singh and Sadhu, 2020). Meanwhile, the seventh article explores the integration of BIM with the IoT using an Arduino microprocessor unit, enabling the real-time tracking and visualization of bridge defects, demonstrating the benefits of combining these technologies for proactive maintenance management (Sakr and Sadhu, 2023). Both studies illustrate the capability to visualize structural defects in real time. However, a key distinction lies in the fact that while the sixth utilizes traditional SHM technologies, the seventh combines BIM with IoT through Arduino, enhancing interaction and precision in detecting structural anomalies.

In the sixth column of Figure 2, two studies under the theme “Real-time Bridge Monitoring” are discussed. The first article implements a SHM system for a bridge, using BIM-based workflows and a Common Data Environment (CDE) to automate the monitoring and analysis of the structure (Fawad et al., 2023). This research demonstrates the effectiveness of a BIM model in managing and monitoring the structural health of bridges. In contrast, the second study sets up a real-time monitoring system for a bridge beam using IoT sensors and a BIM model, allowing sensor data to be transmitted to the BIM model for continuous structural assessment (Scianna et al., 2022).

In the seventh column of Figure 2, the theme “Bridge Rehabilitation with BIM” is introduced, covered by one significant study. This article develops a BIM model specifically designed for bridge rehabilitation, demonstrating the applicability and effectiveness of these tools in structural restoration processes (Van et al., 2022). The research highlights how Staad Pro software was essential in creating BIM models that facilitate bridge rehabilitation, offering detailed and adaptive solutions to enhance existing infrastructure.

The analysis of Figure 2 showcases a variety of themes centered on the use of BIM for bridge maintenance. Damage visualization is a prominent area covered in seven articles, emphasizing the importance of precise damage detection. The 3D geometric modeling of existing structures is also extensively explored in six articles, reflecting the need to accurately represent non-digitized bridges. Additionally, topics such as information exchange and management, along with the identification of existing damages, have been addressed in four articles each. These studies lay a solid foundation for future research in monitoring, inspection, and rehabilitation of bridges using BIM, supported by advancements in 3D modeling and collaborative platforms for information management.

It is important to note that some research areas have received less attention. For instance, real-time bridge monitoring has been the subject of only two articles. Additionally, the risk inspection and rehabilitation of bridges using BIM have each been explored in only one article. These findings reveal a significant knowledge gap in the monitoring, inspection, and rehabilitation of existing

bridges using BIM, highlighting the need for further research in these critical areas to enhance bridge maintenance practices. To complement the thematic analysis, Figure 3 depicts a keyword co-occurrence network generated with VOSviewer. The map revealed five main clusters: (i) a yellow cluster centred on *building information modelling* and *architectural design*, which dominated the literature and acted as the articulating hub; (ii) a blue cluster linking *point cloud*, *structural analysis* and *information management*, indicating the prominence of data capture and processing; (iii) a red cluster where *maintenance* connected with *sustainability*, *life-cycle analysis* and *information system*, reflecting the focus on maintenance strategies and lifecycle management; (iv) a green cluster associated with *engineering*, *decision making* and *bridge*, highlighting BIM-supported decision making for infrastructure; and (v) a cyan cluster grouping terms related to *bridge* and *generative design*, suggesting emerging lines in parametric optimisation. Link-density metrics confirmed the central role of BIM as an intermediary node between geometric modelling, structural analysis and maintenance, whereas the relative dispersion of the term *maintenance* underscored the need for greater convergence between conceptual research and practical applications.

As a complement to the thematic structure shown in Figure 3, and before presenting the domain synthesis, the CiteScore quartile of the journal in which each included article was published was retrieved from Scopus/SciVal. This established that the reviewed articles drew primarily on high-impact venues. Table 2 reports the distribution of the 25 articles by the quartile of their publishing journals.

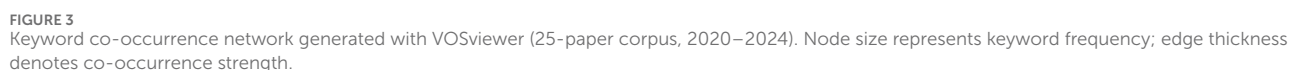
The distribution confirmed a predominance of Q1 with 16 of 25 articles and Q2 with 7 of 25, so 92% of the set came from top tiers. Q3 and Q4 contained one article each. On this basis, the subsequent thematic and methodological analysis was conducted, which strengthened the credibility of the identified trends and the practical relevance of the conclusions for maintenance management.

3.2 Domain taxonomy and key contributions

The examination of the 25 selected articles revealed seven thematic domains that encompassed the key contributions to BIM-based bridge maintenance. Consistent with the research themes identified in Table 3, these domains were: 3-D Modelling and Data Capture, Monitoring and Diagnosis, Information Management, Damage Detection, Advanced Visualisation, Parameter Quality, and Lifecycle Collaboration. Table 2 presents the resulting taxonomy and summarises each domain with a representative contribution and its frequency.

As observed in Table 3, the frequencies of the proposals and/or contributions varied between 19 and 3, reflecting the diversity of approaches present in the academic literature that was analyzed.

A particularly highlighted category was “3D Model Construction from photogrammetry, 2D plans, modeling, or laser scanning” which had a frequency of 18. This category described methods for converting an existing bridge’s model into a 3D representation. Techniques included photogrammetry using Unmanned Aerial Vehicles (UAVs), LiDAR scanning, and 2D plan digitization, which generated a point cloud for creating



Quartile	Overall n	Overall %	2020	2021	2022	2023	2024
Q1 (top 25%)	16	64%	4	2	3	7	0
Q2 (26%–50%)	7	28%	2	2	0	1	2
Q3 (51%–75%)	1	4%	0	0	0	1	0
Q4 (76%–100%)	1	4%	0	0	1	0	0
Total	25	100%	6	4	4	9	2

In another highlighted category, “Data Exchange According to Requirements, Processing Time, and Details,” which reached a frequency of 11, a collaborative platform compatible with Ethernet and Wi-Fi was developed. This platform was designed to ensure a continuous data workflow and integrate BIM models for storage, processing, and information management. It facilitated standardized information management among project participants,

Among the categories with lower frequency is “Quality of the Parameters Extracted from the Model” with a frequency of three. These studies focused on evaluating the quality of parameters derived from BIM. To address this challenge, the use of LiDAR scanning, model validation through Finite Element Modeling (FEM) of bridges, and more comprehensive studies on BIM/GIS integration were recommended. These measures aim to increase the

TABLE 3 Domain taxonomy and key contributions for BIM-based bridge maintenance.

Thematic domain	Representative contribution	Frequency
3-D Modelling and Data Capture	3-D model construction via photogrammetry, LiDAR and plan digitisation	18
Monitoring and Diagnosis	Defect monitoring in 3-D models using sensors and AI (LSTM, neural networks)	19
Information Management	Data-exchange platforms compliant with IFC and BIM-GIS/ERP links	11
Damage Detection	CNN/YOLO algorithms for crack localisation and sizing	7 (+4)
Advanced Visualisation	Interactive defect visualisation in 3-D structures	4
Parameter Quality	Parameter validation through LiDAR and FEM	3
Lifecycle Collaboration	Collaborative BIM models during operation and maintenance	9

accuracy and reliability of 3D models, allowing for more precise extraction of structural parameters from bridges.

In another noteworthy category, “Increased data volume used to train the model’s accuracy in crack detection” which reached a frequency of four, the use of extensive databases to train convolutional neural network (CNN) models is highlighted. This approach significantly enhances the accuracy of damage detection in bridges. Additionally, the use of the DIM extension to enrich models with additional data, such as chloride migration in bridge structures, is discussed.

Another highlighted category is “Damage Detection in Bridges Using Algorithms” with a frequency of seven. Research in this area focuses on the development of smart systems that integrate BIM and GIS technology and utilize sensors and high-resolution photography as data sources. These systems feed neural networks and the YOLO model, significantly improving the accuracy of identifying the location and extent of damage in bridges.

Within the category “Visualization of Defects in 3D Structures” which has a frequency of four, efforts to visually represent damage and cracks in three dimensions in critical areas of bridges are highlighted. This method not only enhances the understanding of structural defects but also integrates vital information for making strategic decisions about bridge rehabilitation.

The most prominent category according to Table 3 is “Monitoring of Defects in Structures through 3D Models” which has a frequency of 19. It focuses on using sensors installed on bridges to collect data periodically. This data is processed using advanced techniques such as neural networks, deep learning, and Long Short-Term Memory (LSTM). Identified defects are integrated into 3D BIM models to simulate structural behavior using tools like Stadd Pro software. This system aims to provide real-time analytical capabilities and is augmented by augmented reality to optimize decision-making in bridge maintenance, thus minimizing potential damage and deterioration.

Another category, with a frequency of nine, focuses on “Collaborative BIM Model Throughout the Project Lifecycle.” These studies emphasize the importance of BIM models throughout the entire construction project lifecycle, especially during the operation and maintenance phases of bridges. BIM tools facilitate collaboration and interconnection among various

project stakeholders, thereby improving decision-making in maintenance.

In conclusion, Table 3 highlights key areas in bridge maintenance using BIM. The construction of 3D models and the monitoring of defects are the most researched topics, reflecting the critical need for detailed models and defect analysis for effective management. Other important areas include data exchange and the collaborative use of BIM, which are essential for optimizing decision-making and maintenance. Less frequent studies, such as improving the accuracy of crack detection and evaluating the quality of parameters, are also crucial for advancing BIM practices.

4 Discussion

In this study, the following stages are outlined for discussing the results: 1) 3D Geometric Modeling of the existing structure, 2) Identification and management of defects in bridges using BIM, 3) Visualization and monitoring of bridge damages through BIM, and 4) Bridge rehabilitation via BIM. Subsequently, the findings from the research related to each of these stages are explored in detail.

4.1 3D geometric model of the existing structure

The 3D BIM model of the existing structure is crucial for efficient data exchange, incorporating appropriate geometric and semantic information (Artus and Koch, 2020; Martens et al., 2023). To achieve this, a detailed Scan-to-BIM process is essential, which involves collecting the necessary data to develop the BIM model (Lee et al., 2020). This process is organized into four fundamental stages: data capture, semantic segmentation, 3D modeling, and BIM model generation, each critical for the project’s success (Martens et al., 2023).

In the data capture stage for 3D modeling of existing structures within a BIM environment, various techniques such as photogrammetry (Isailovic et al., 2020; Artus and Koch, 2020; Gan et al., 2023; Wójcik and Zarski, 2021) and LiDAR scanning (Lee et al., 2020). This approach demanded a balance between

resolution and field efficiency: point densities above 50 pts/m² increased sub-centimetre accuracy, yet doubled acquisition time and raised over-noise in heavily vegetated areas, thereby requiring additional filtering stages. Although effective, these methods can be costly and limited in access (Poku-Agyemang and Reiterer, 2023). To overcome these barriers, a semi-automatic method using hand-drawn or computer-generated plans has been developed to construct the 3D model (Poku-Agyemang and Reiterer, 2023). Alternatively, modeling in Revit from 2D drawings provides precise geometric parameters such as height, length, and width (Poku-Agyemang and Reiterer, 2023; Kaewunru et al., 2021; Zhou, 2022). This phase results in a point cloud that provides detailed information on the structural shape, making it crucial to assign semantic information to each point for subsequent use in the BIM model (Lee et al., 2021; Lee et al., 2020).

In the semantic segmentation stage, neural networks and deep learning techniques are used to assign semantic information to each point in the point cloud, simplifying the process without extensive training and with minimal data (Martens et al., 2023; Shen et al., 2023). Although deep learning is effective (Lee et al., 2021), semantic information alone is insufficient to create a complete BIM model; accurate structural parameters such as height, length, and width are required during the BIM scanning stage (Artus and Koch, 2020; Lee et al., 2021; Lee et al., 2020). To streamline this process, automatic methods have been developed to reduce noise, perform 3D transformations, and extract parameters, thereby reducing the time and resources needed to achieve a detailed BIM model (Isailovic et al., 2020; Lee et al., 2020).

4.2 Bridge defect identification and management with BIM

Bridge defects can be classified as structural, functional, and durability related (Artus and Koch, 2020). Traditionally, inspectors manually collected defect data, a method that is subjective and error-prone, complicating accurate measurement of damage characteristics like length, depth, and width (Ciccone et al., 2022; Gan et al., 2023). In response, photogrammetry produces point clouds, orthomosaics, and measurements that, when integrated into the information model within BIM-based workflows, enable objective and traceable damage detection and quantification for maintenance management (Isailovic et al., 2020; Jeon et al., 2023; Artus et al., 2022; Gan et al., 2023; Yang and Xia, 2023). Absolute accuracy hinged on proper georeferencing with ground-control points; a root-mean-square error of ± 14 mm was recorded when fewer than five linearly distributed points were used, compared with ± 6 mm when at least eight concentric points were deployed.

To precisely locate damage on bridge sections, intelligent algorithms based on neural networks are employed (Kaewunru et al., 2021; Yang and Xia, 2023). Beyond locating damage, it's crucial to determine its magnitude, a task efficiently performed by the R-CNN method (Artus et al., 2022; Gan et al., 2023). Alternatively, the YOLO algorithm is noted for its damage detection capabilities (Jeon et al., 2023). Model performance was constrained by the scarcity of bridge-specific training datasets; a 9-percentage-point drop in mAP was observed when the model was applied to carbonation-degraded concrete, highlighting the need for domain-adaptation strategies

prior to transfer across pathologies. The data on the location and extent of cracks is integrated into the BIM model of the bridge for accurate structural assessment. Additionally, predictive crack models are generated using the LSTM method, enhancing the anticipation of structural issues (Shen et al., 2023). To manage this extensive information, collaborative platforms are essential to facilitate storage, organization, and access to data by all project stakeholders (Ciccone et al., 2022).

A digital platform optimizes the management of defects and the BIM model of the existing structure, facilitating comprehensive information handling that allows access for all project participants (Hagedorn et al., 2023; Jeon et al., 2023). These platforms support management and maintenance, enhance bridge condition assessments, and foster collaboration through interactive visualization (Wei et al., 2021). Additionally, another platform integrates BIM modeling and information management, enriched with safety diagnostics and maintenance plans (Byun et al., 2021; Ciccone et al., 2022). Finally, creating libraries that store bridge defect information streamlines the integration of these data into BIM models (Li et al., 2023).

4.3 Visualization and monitoring of bridge damages with BIM

Once the geometric and semantic information is integrated into the BIM model on the platform, it facilitates detailed visualization of defects, showing hierarchy, properties, and geometry (Artus et al., 2022; Shen et al., 2023). Before real-time monitoring, it is crucial to validate the model and maintenance system using Finite Element Analysis (FEA), applying static and dynamic loads to the bridge (Fawad et al., 2023). After validation, sensors are placed at critical points on the bridge to capture continuous data (Singh and Sadhu, 2020), while the use of IoT with Arduino allows for real-time monitoring and visualization of these data (Sakr and Sadhu, 2023). This methodology was applied to monitor the deflection of the bridge beam, contributing to the creation of a digital twin that continuously monitors the structure and detects any anomalies (Scianna et al., 2022; Kaewunruen et al., 2020). The literature likewise reported operational challenges: sensor-node energy autonomy ranged between 4 and 7 months under 2.4 GHz transmission, whereas network congestion imposed practical limits of 60 Hz on continuous sampling rates to prevent packet loss.

4.4 Bridge rehabilitation with BIM

The availability of a digital twin that allows continuous real-time monitoring lays the groundwork for moving towards effective bridge rehabilitation (Kaewunruen et al., 2020). Using Stadd Pro software, it is possible to simulate the structural behavior of the bridge and apply advanced rehabilitation techniques, optimizing intervention plans to restore and enhance the infrastructure (Van et al., 2022).

Despite the highlighted advantages, the adoption of BIM for bridge maintenance faced substantial limitations that constrained its operational feasibility. Interoperability issues remained, stemming from the coexistence of proprietary formats with the IFC 4.3 standard and forcing conversion workflows that introduced

geometric and semantic data loss. In addition, the initial cost of LiDAR scanners and 3-D modelling exceeded, in several case studies, 10% of the annual maintenance budget, thus lowering the incentive for agencies operating under financial constraints. The demand for specialised personnel, proficient in visual programming (e.g., Dynamo) and large-scale data management, also persisted, and such expertise was still scarce within public infrastructure agencies. Finally, the reviewed studies revealed gaps in governance and cybersecurity, particularly when BIM models were synchronised with IoT sensors in cloud environments, raising data-protection and continuous-monitoring requirements.

The documented experiences suggested that these obstacles could be mitigated through gradual strategies: workflows based on open standards, modular staff training, and cost-benefit analyses demonstrating medium-term positive returns. Nevertheless, the evidence indicated that a comprehensive resolution of these barriers remained an active research area, especially regarding regulatory frameworks capable of harmonising information management throughout the bridge life cycle.

The review further indicated that the incorporation of emerging technologies began to extend the conventional boundaries of BIM. The most recent studies investigated the use of digital twins to replicate the real-time condition of bridges, enabling scenario simulations of deterioration and more precise prioritisation of interventions. Initiatives integrating blockchain as an immutable ledger for lifecycle data were also identified, thereby strengthening trust among stakeholders. Finally, pilot applications of edge computing processed IoT sensor data on site, reducing latency and mitigating cloud congestion risks. Although these innovations remained in early adoption stages, the evidence suggested that their convergence with BIM could accelerate the shift toward predictive and collaborative maintenance models.

5 Conclusion

This study has cataloged various methodologies and tools from scientific literature for bridge maintenance using BIM. It emphasizes the significance of 3D geometric modeling, defect identification, and damage visualization and monitoring as vital practices.

Likewise, trends toward automation in monitoring and real-time structural assessment are evident, reflecting significant advancements in BIM applications. Nevertheless, critical gaps still constrained large-scale implementation. Chief among them was the absence of harmonised regulatory frameworks for transferring models across platforms, together with a need for official guidelines governing the integration of digital twins and IoT sensors into existing infrastructure. The evidence also revealed shortages in training programmes aimed at strengthening visual-programming and big-data skills among bridge managers. Addressing these regulatory and capacity gaps will be essential to consolidate predictive and collaborative maintenance strategies.

However, knowledge gaps are also identified, particularly in real-time data integration and collaborative information management throughout project lifecycles. These findings underscore the need for further research in specific underexplored areas, particularly real-time bridge monitoring (2 studies), risk inspection (1), and rehabilitation with BIM (1). It is also recommended to develop more

robust collaborative platforms that effectively integrate BIM with emerging technologies like IoT, enhancing accuracy in structural damage detection and management.

While these findings synthesise global trends, they gain greater value when translated into policy guidelines adapted to regional contexts. In Latin America, this involves adopting IFC 4.3-based exchange profiles to reduce information loss across platforms, mitigating the upfront costs of technologies such as LiDAR, which can exceed ten percent of annual maintenance budgets, strengthening the capacities of public teams in visual programming and data management, establishing minimum cybersecurity requirements for BIM workflows connected to IoT in the cloud, and promoting standardised metrics for project evaluation. Linking global evidence with these local priorities enables predictive and collaborative workflows to be effectively integrated into bridge management.

6 Research agenda and future directions

Building on the synthesis (Table 3) and the keyword network (Figure 3), this review identified actionable gaps and outlines how future work should address them.

1. Standardized performance metrics. Future studies should define interoperable metrics to compare BIM/digital-twin workflows across contexts: end-to-end latency (ms), detection accuracy (mAP/F1), cost per inspected square metre, downtime hours avoided, and ROI over 5–10 years. Multi-site reporting templates should be shared as open protocols.
2. Public benchmark datasets for bridges. The community should curate open, bridge-specific datasets (images, point clouds, annotated defects) with clear licenses and train/validation/test splits to enable fair comparisons and domain-adaptation studies of CNN/YOLO models.
3. Operational IFC 4.3 for maintenance. Research should prototype and validate maintenance-phase information schemas (attributes, property sets, exchange requirements) and run round-trip tests to quantify semantic loss across authoring and asset-management platforms.
4. Cost-benefit models for public agencies. Future work should develop decision-oriented economic models that estimate total cost of ownership and net benefits of BIM/DT adoption under budget constraints, using before-after or matched-control evaluations on real bridge portfolios.
5. Edge-AI reliability for IoT-to-BIM streaming. Experiments should characterize accuracy-latency-energy trade-offs (e.g., mWh/day, packet-loss %) for on-device inference and propose fallback strategies under network outages and cybersecurity policies.
6. Adoption in Latin America. Empirical studies should investigate organizational readiness, governance and regulatory pathways, identifying enablers and barriers for mainstream deployment, with replicable instruments (surveys, maturity indices) and policy recommendations.

Addressing these lines of research would align technical advances with procurement, budgeting and safety decisions in real bridge-maintenance programs.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fbuil.2025.1693644/full#supplementary-material>

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