Journal of Sustainable Development and Policy
Volume 01, Issue 01 (2025)
Page No: 198 – 223
Doi: 10.63125/d37g1237

Article

THE ROLE OF BUILDING INFORMATION MODELING (BIM) IN RISK MANAGEMENT FOR SUSTAINABLE BRIDGE PROJECTS: A SYSTEMATIC REVIEW AND META-ANALYSIS

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Citation:
Rehman, A. (2025). *The role of Building Information Modeling (BIM) in risk management for sustainable bridge projects: A systematic review and meta-analysis. Journal of Sustainable Development and Policy, 1*(1), 198–223. https://doi.org/10.63125/d37g1237

Received:
April 21, 2025

Revised:
May 29, 2025

Accepted:
June 26, 2025

Published:
July 08, 2025

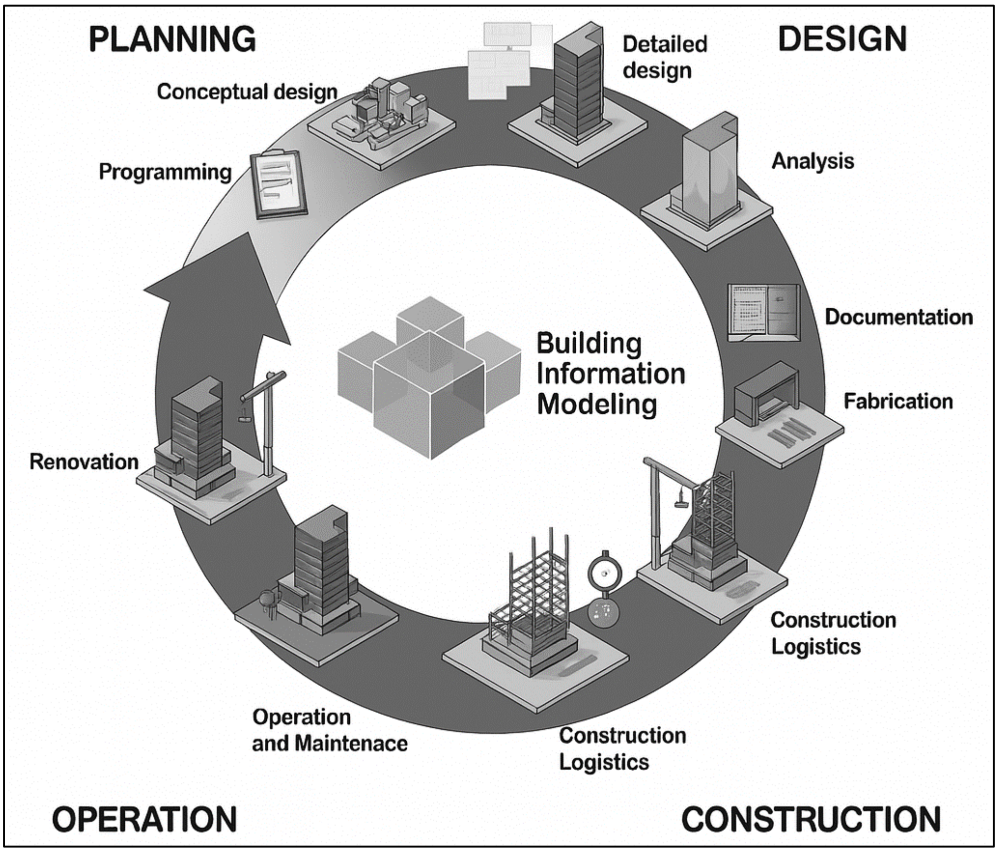
ABSTRACT
This systematic review and meta-analysis investigates the evolving role of Building Information Modeling (BIM) in managing multidimensional risks associated with sustainable bridge infrastructure projects. Drawing upon the PRISMA methodology, the study rigorously screened and analyzed a total of 87 peer-reviewed journal articles and conference papers published between 2010 and 2024. The selected literature was sourced from five leading academic databases—Scopus, Web of Science, IEEE Xplore, ScienceDirect, and the ASCE Library—ensuring comprehensive coverage of global research on BIM-based risk management practices. The review focuses on how BIM contributes to the identification, analysis, mitigation, and continuous monitoring of technical, financial, environmental, and operational risks throughout the lifecycle of bridge projects. Findings reveal that BIM's capabilities extend well beyond 3D visualization, offering robust tools for 4D scheduling, 5D cost estimation, and real-time data integration that collectively enhance proactive decision-making. BIM facilitates early risk detection through clash detection, geospatial analysis, and scenario simulations during the planning and design stages, reducing design inconsistencies and constructability issues. Moreover, the study synthesizes evidence demonstrating how BIM supports cost and schedule risk control by enabling dynamic simulation of construction sequences and integration with live pricing data, resulting in reduced cost overruns and schedule delays. The review also highlights the increasing convergence of BIM with Internet of Things (IoT) technologies, digital twins, and Geographic Information Systems (GIS), enabling real-time monitoring of structural health, predictive maintenance, and environmental risk modeling in operational phases. Lifecycle-oriented risk governance through BIM emerged as a key theme, particularly in studies focused on sustainability assessments, material optimization, and long-term asset performance. Institutional adoption patterns, regulatory influences, and policy frameworks were also examined, revealing that countries with mandated BIM protocols exhibit more advanced integration of BIM into public infrastructure risk management. Despite persistent challenges such as fragmented data standards, skill gaps, and limited interoperability, the majority of the reviewed literature—accumulating over 3,400 citations—converges on the conclusion that BIM is an essential enabler of risk-informed, sustainable bridge engineering.

KEYWORDS
Building Information Modeling (BIM); Risk Management; Sustainable Bridge Projects; Infrastructure Engineering; Systematic Review and Meta-Analysis;

INTRODUCTION

Building Information Modeling (BIM) is defined as a digital representation of physical and functional characteristics of a facility, serving as a shared knowledge resource for information about a facility that forms a reliable basis for decisions during its life cycle (Abanda et al., 2020). BIM enables the integration of multi-dimensional data, combining geometric information with attributes such as cost, schedule, materials, and sustainability metrics (Han et al., 2023). The global application of BIM extends beyond building construction and has increasingly penetrated the infrastructure sector, particularly in bridge projects, where complex geometries, multidisciplinary collaboration, and stringent performance expectations demand a data-rich and coordinated approach (Oreto et al., 2021). BIM plays a pivotal role in enhancing communication across stakeholders, improving visualization, and enabling simulation of construction activities to predict outcomes under different scenarios (Ting et al., 2021). As bridge infrastructure projects grow in scale and complexity, BIM's digital environment facilitates real-time data exchange, reduces rework, and enhances construction accuracy (Castañeda et al., 2021). International standards such as ISO 19650 and government mandates in countries like the UK, Singapore, and China have solidified BIM's global relevance in infrastructure development (Yilmaz et al., 2023).

Figure 1:Overview of BIM Work



The intersection of BIM and risk management has emerged as a significant domain within project management research, particularly in infrastructure contexts where uncertainties can threaten structural integrity, project deadlines, and environmental compliance. Risk management is defined as the systematic process of identifying, analyzing, and responding to project risk, aiming to maximize opportunities and minimize adverse effects. BIM enhances risk management by integrating visualization tools, automated clash detection, and parametric modeling capabilities that help stakeholders detect design flaws and resource conflicts early. For bridge projects, risk elements such as structural failures, geotechnical uncertainties, and environmental regulations can be effectively modeled and evaluated using BIM's predictive and analytical capacities (Chi et al., 2014). Quantitative modeling of risks within BIM environments allows for dynamic response planning, where the visual representation of potential threats enables better communication and stakeholder buy-in.

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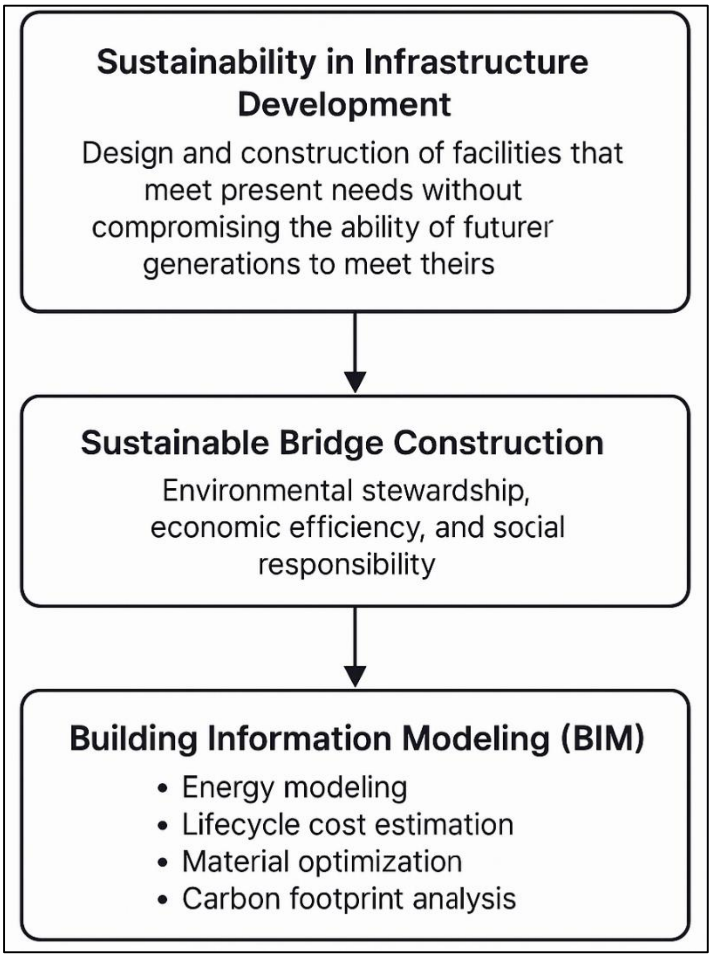
Studies show that BIM reduces technical risks by enhancing constructability analysis and allows for real-time updates, which is crucial in managing dynamic infrastructure settings (Yang et al., 2021).

Figure 2: The Role of BIM in Supporting Sustainable Bridge Construction within Infrastructure Development



Sustainability in infrastructure development refers to the design and construction of facilities that meet present needs without compromising the ability of future generations to meet theirs. Sustainable bridge construction integrates environmental stewardship, economic efficiency, and social responsibility, emphasizing lifecycle performance, resource conservation, and ecological impact (Han et al., 2022; Rajesh, 2023; Akter, 2025). In this regard, BIM supports sustainability objectives through energy modeling, lifecycle cost estimation, material optimization, and carbon footprint analysis. Several studies have reported that BIM's integration with sustainability assessment tools such as LEED, BREEAM, and Envision significantly improves sustainability compliance and documentation. Bridge projects, due to their expansive use of natural resources and long operational life, require forward-looking assessments of material durability, structural health (Mansura Akter, 2023), and post-construction monitoring—all of which can be embedded in BIM environments. The application of 5D and 6D BIM enables a deeper assessment of economic and sustainability dimensions alongside design, schedule, and cost information (Alfahad & Burhan, 2023). As environmental risks become integral to infrastructure planning, BIM's ability to simulate and assess environmental impacts adds critical value to sustainable bridge delivery (Abanda et al., 2020).
Bridge infrastructure projects are among the most resource-intensive and technically challenging components of national transportation systems, requiring interdisciplinary coordination, resilience under dynamic loads, and compliance with evolving safety codes (Oreto et al., 2021). Traditional methods of project delivery in bridge construction have often been criticized for their fragmented communication, design inconsistencies, and reactive rather than proactive risk strategies (Ting et al., 2021). BIM-based integrated project delivery (IPD) models offer a collaborative framework that aligns design, engineering, and construction teams in a common digital environment, thus mitigating

coordination risks and improving constructability. In high-stakes projects such as long-span bridges, BIM allows stakeholders to test construction sequences, structural interactions, and material behaviors before physical implementation, thereby reducing exposure to unforeseen disruptions (Castañeda et al., 2021). Moreover, the digitization of bridge asset information enables informed decision-making regarding safety inspections, retrofitting, and structural health monitoring (Shaiful & Akter, 2025). Numerous studies confirm that BIM reduces the likelihood of cost overruns and schedule delays in bridge construction by allowing early identification of constraints (Chi et al., 2014; Subrato & Faria, 2025; Yilmaz et al., 2023).

The integration of BIM with risk management tools such as Failure Mode and Effects Analysis (FMEA), Monte Carlo simulations, and risk matrices further strengthens its utility in infrastructure development. These tools, when embedded within BIM platforms, allow engineers to test the probabilistic impact of potential risks and evaluate mitigation strategies in a dynamic environment. For example, risk-based cost estimation through BIM enables more accurate budget allocations by accounting for probable delays, material price fluctuations, and labor shortages. In bridge projects, where safety-critical components such as piers, girders, and expansion joints must withstand complex load patterns, BIM-enhanced simulations help detect design vulnerabilities under various environmental and structural conditions (Han et al., 2022). Moreover, BIM's integration with Geographic Information Systems (GIS) facilitates site-specific risk assessment in geologically sensitive or flood-prone areas. The spatial intelligence derived from BIM-GIS coupling supports informed routing, foundation selection, and logistics planning, ultimately reducing construction-phase hazards.

The primary objective of this systematic review and meta-analysis is to critically evaluate the role of Building Information Modeling (BIM) in risk management practices associated with sustainable bridge infrastructure projects. By consolidating and analyzing a broad spectrum of peer-reviewed literature, the study aims to identify how BIM technologies have been deployed to enhance risk identification, assessment, mitigation, and monitoring throughout the project lifecycle. This includes the pre-construction design phase, the construction phase, and post-construction maintenance and operation of bridges. The review focuses on examining how BIM facilitates the coordination of multidisciplinary teams, improves visualization and communication, and integrates with digital tools that enable predictive and real-time decision-making. A secondary objective is to assess the extent to which BIM has contributed to achieving sustainability goals within bridge projects by reducing waste, optimizing resource utilization, and supporting lifecycle performance assessments. The study further aims to categorize the types of risks that are most effectively managed through BIM, such as technical risks related to design flaws, environmental risks arising from site conditions, and operational risks tied to safety and maintenance. In conducting a meta-analysis, the review also seeks to quantify BIM's impact on project outcomes such as cost control, schedule adherence, risk reduction, and sustainability metrics. Through a structured comparison of studies from different regions and project contexts, this research aims to uncover consistent patterns, implementation challenges, and critical success factors for BIM-based risk management in bridge construction. Additionally, the study intends to explore the integration of BIM with other technologies and frameworks, such as geographic information systems (GIS), sensors, digital twins, and risk modeling tools, to understand the depth and complexity of BIM-enabled risk governance. The ultimate objective is to provide a robust evidence base for engineers, policymakers, and project managers seeking to adopt BIM as a strategic tool for managing uncertainty and achieving sustainability in complex bridge infrastructure projects.

LITERATURE REVIEW

The use of Building Information Modeling (BIM) in infrastructure development has gained significant attention in the scholarly and professional realms due to its capacity to integrate data, enhance communication, and support complex decision-making across all project stages. As infrastructure projects—particularly bridge constructions—become more demanding in terms of sustainability, safety, and regulatory compliance, the need for effective risk management tools has grown substantially. Within this context, BIM offers a digital ecosystem that supports real-time simulation, clash detection, data sharing, and performance prediction, allowing stakeholders to proactively manage various types of risk. The literature on BIM and risk management in infrastructure projects has evolved in parallel with technological developments, with specific emphasis on interoperability, lifecycle integration, and sustainability outcomes. However, existing research often presents fragmented insights across diverse contexts, with limited focus on bridge projects as a distinct category of infrastructure. Furthermore, while several studies have explored BIM's role in managing

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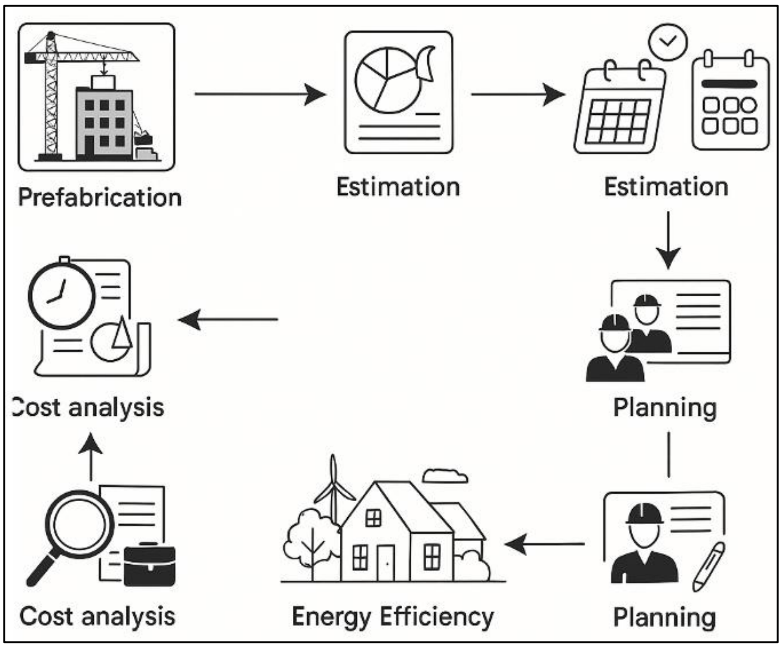
technical and financial risks, there remains a knowledge gap concerning its application in environmental and operational risk domains, particularly within sustainability frameworks. This literature review aims to consolidate the existing body of knowledge by categorizing prior studies into thematic areas that reflect the multidimensional role of BIM in managing risk across sustainable bridge projects. It provides a critical synthesis of how BIM-enabled processes and tools are employed in project planning, execution, and maintenance stages to identify, mitigate, and monitor risk factors in alignment with sustainability objectives.

BIM in Infrastructure Projects

Building Information Modeling (BIM) has evolved as a transformative methodology in the architecture, engineering, and construction (AEC) industry, particularly within the domain of infrastructure development. Originally associated with vertical construction projects such as buildings, BIM has expanded into infrastructure sectors including transportation, utilities, and public works due to its capacity for integrating spatial, temporal, and performance data across a project's lifecycle (Nguyen et al., 2020). The application of BIM in infrastructure projects enhances design coordination, facilitates multidimensional modeling (3D, 4D, 5D, and 6D), and promotes interdisciplinary collaboration by providing a unified digital environment for stakeholders. Studies show that BIM adoption in infrastructure leads to improvements in project visualization, clash detection, and early design validation, which are critical for reducing technical errors and improving constructability. Furthermore, BIM supports scenario-based planning for construction logistics and resource allocation, which is particularly beneficial in large-scale infrastructure projects where site conditions are dynamic and interdependencies are complex. The use of BIM tools has also been shown to improve stakeholder communication and reduce decision-making delays during planning and execution phases (Bradley et al., 2016). This integration of various dimensions allows for data-driven decision-making, thus increasing the transparency and reliability of project deliverables across infrastructure domains.

Figure 3: BIM-Enabled Workflow Optimization in Construction



The expansion of BIM into infrastructure has triggered the need for industry-specific standards and guidelines to govern its implementation, especially in projects involving roads, bridges, railways, and water management systems. Research has indicated that the complexity of infrastructure projects requires adaptation of BIM tools to suit non-standard geometries and linear design elements characteristic of transportation and civil works (Juszczyk, 2022). For example, long-span bridges or highway networks demand integration with Geographic Information Systems (GIS) to model terrain, environmental conditions, and geotechnical variables (Fentzloff et al., 2021). This BIM-GIS synergy supports spatial risk assessment and improves decision-making in areas such as route selection,

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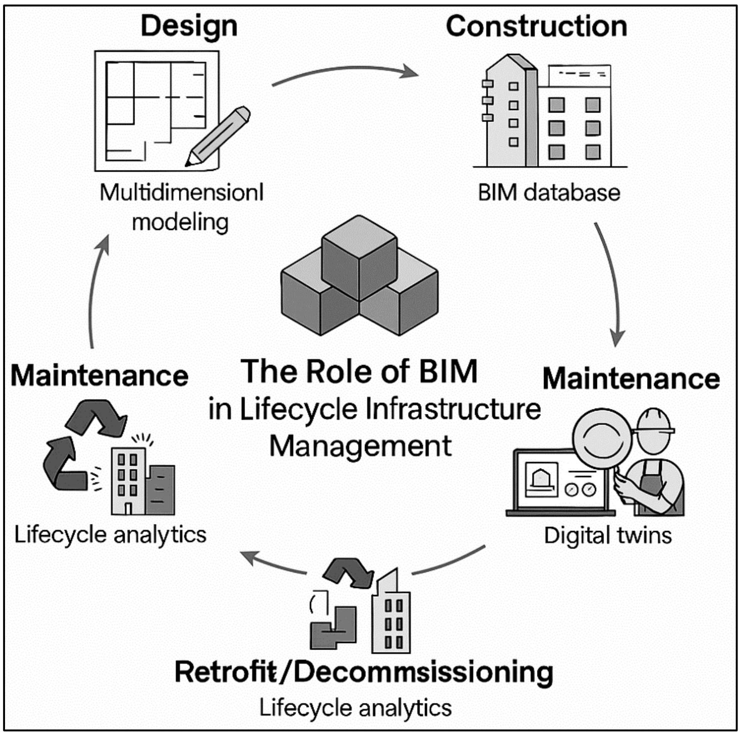
earthwork management, and flood resilience planning (Kohlböck et al., 2018). Infrastructure-specific BIM also enables real-time simulation of construction phases, which has been shown to reduce schedule overruns and logistical bottlenecks. The implementation of ISO 19650 and national BIM mandates in countries such as the United Kingdom, Singapore, and China have further reinforced BIM's institutionalization in infrastructure policy frameworks. However, infrastructure projects often involve multi-agency coordination, long timelines, and strict regulatory environments, which add complexity to BIM adoption. The fragmented nature of public sector data and lack of interoperability between systems have been identified as barriers that inhibit full integration of BIM across all infrastructure phases (Eldik et al., 2020). Nonetheless, the literature suggests that where standards, training, and leadership align, BIM implementation in infrastructure projects achieves higher levels of efficiency and innovation.

BIM in lifecycle-based infrastructure management

Building Information Modeling (BIM) has been progressively reconceptualized from a design-centric technology to a lifecycle management framework that supports infrastructure assets from inception through decommissioning. Early definitional work positioned BIM as "a shared knowledge resource" for decision-making (Oreto et al., 2021), while subsequent scholarship expanded the construct to include multidimensional data environments that capture cost, time, sustainability, and operational performance (Bradley et al., 2016). In infrastructure contexts, this evolution aligns with asset management principles emphasising whole-life value and risk control. Empirical studies report that 5D/6D BIM environments enable dynamic integration of maintenance schedules, condition ratings, and carbon inventories, facilitating proactive intervention strategies that reduce whole-life cost and environmental impact (Costin et al., 2018). Vignali et al. (2021) demonstrate how civil transport agencies leverage object-level data for routine inspections, whereas (Alemayehu et al., 2021) note that the relational database structure of BIM supports longitudinal performance benchmarking across bridge portfolios. Ahmad et al.(2025) add that common data environments improve auditability by linking design intent, construction records, and post-occupancy performance metrics. Raza et al. (2023) further document how lifecycle BIM platforms accommodate regulatory updates, ensuring that infrastructure operators can trace compliance across decades of service. Nevertheless, Hinostroza et al. (2021) caution that lifecycle information richness depends on early stakeholder commitment to data standards and consistent information handover protocols, underscoring the governance dimension embedded in BIM-enabled asset stewardship.

Figure 4: The Role of BIM in Lifecycle-Based Infrastructure Management for Bridge Projects

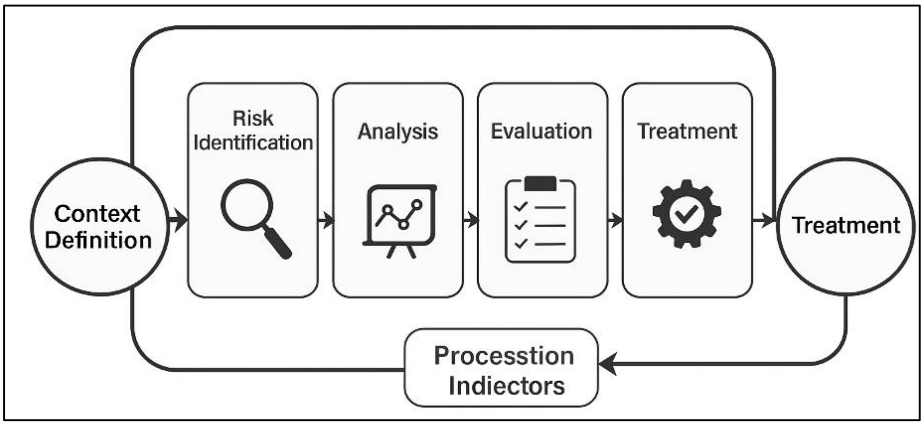


Operationalising lifecycle-oriented BIM increasingly involves coupling digital models with sensor networks, geographic information systems (GIS), and emerging digital-twin architectures. Cepa et al. (2023) integrate strain-gauge data from long-span bridges into BIM databases, enabling real-time dashboards that highlight threshold exceedances and trigger maintenance work orders. Barazzetti et al. (2020) report that sensor-fed BIM environments support condition-based maintenance, lowering inspection frequency without compromising safety. Bradley et al. (2016) show that linking BIM to finite-element analysis enables continuous recalibration of structural behaviour models as live load patterns evolve. Juszczyk (2022) and Fentzloff et al.(2021) illustrate how BIM-GIS integration enriches spatial analytics for earth-work volumes, drainage optimisation, and hazard mapping, thereby refining maintenance prioritisation. Yang et al. (2021) provide evidence that digitally tracking asset components simplifies procurement of compatible replacement parts, shortening downtime. Oreto et al. (2022) note that lifecycle BIM assists facility managers in aligning sustainability targets with operational data by visualising energy consumption and material degradation concurrently. Zhou et al. (2024) reinforce these findings with quantitative evidence of reduced unplanned closures and lower life-cycle carbon emissions in BIM-monitored bridges. Aziz et al. (2017) extend the discussion to tunnel infrastructure, showing similar gains in ventilation efficiency and safety incident reduction. Bazán et al.(2020) conclude that the interoperability afforded by open standards such as IFC and CityGML underpins these integrations, though they acknowledge persistent variability in data quality among project participants.

Risk Management Frameworks in Bridge Engineering

Risk management in bridge engineering has progressed from ad-hoc safety checks toward structured, standards-driven frameworks that integrate probabilistic thinking, life-cycle analysis, and multi-stakeholder governance. Foundational guidance such as ISO 31000 and the AASHTO LRFD specifications establishes a generic process—context definition, risk identification, analysis, evaluation, and treatment—that has been adapted to the bridge domain to capture its unique structural, geotechnical, environmental, and operational hazards (Ahmad et al., 2025). Within this context, researchers classify risks into internal factors inherent to design and construction (e.g., material variability, workmanship) and external factors linked to natural hazards, traffic loading, and regulatory change (Raza et al., 2023). Zhao et al. (2019) argue that bridges demand a "risk-informed performance-based" philosophy because traditional deterministic safety factors fail to capture site-specific uncertainty. Accordingly, frameworks now embed performance indicators such as reliability index, redundancy, and robustness directly into design criteria (Alemayehu et al., 2021). Kohlböck et al. (2018) extend this logic through risk breakdown structures that map hazards across the design–build–operate (DBO) continuum, highlighting transfer points where latent risks can propagate if information is lost. Empirical evidence from Hinostroza et al. (2021) and Bazán et al. (2020) shows that projects employing formal risk registers and periodic risk workshops report lower cost deviations and fewer change orders, suggesting that procedural rigor translates into tangible performance gains. Nonetheless, many public agencies still rely on qualitative matrices that oversimplify complex interdependencies, underscoring the ongoing need for quantitative support tools within established frameworks.

Figure 5: Risk Management Frameworks in Bridge Engineering



Quantitative risk assessment methods have become central to modern bridge engineering frameworks, enabling analysts to estimate failure probabilities, consequence distributions, and optimal intervention strategies under uncertainty. Monte Carlo simulation, first applied to bridge reliability by Raza et al. (2023), remains a core technique for propagating parameter uncertainty through load-resistance models, while advanced approaches such as Latin Hypercube sampling and importance sampling improve computational efficiency for large-scale networks (Ahmad et al., 2025). Bayesian networks provide graphical structures for fusing expert judgment with monitoring data, offering dynamic updating of failure likelihoods as new information emerges (Hinostroza et al., 2021). Barazzetti et al. (2020) integrate finite-element analysis with probabilistic deterioration models to link chloride diffusion in concrete decks directly to time-variant reliability, demonstrating how digital twins can support risk-informed maintenance scheduling. Similarly, Scianna et al. (2022) couple fragility curves with traffic-flow models to evaluate socioeconomic consequences of seismic bridge outages, thereby extending risk frameworks beyond structural safety to network resilience. BIM-enabled workflows further enrich quantitative assessments by automating clash detection, volume take-offs, and parametric scenario testing. Case studies from Kaewunruen et al. (2020) reveal that combining BIM with Monte Carlo cost simulation reduces contingency allowances without increasing residual risk, illustrating the synergy between data-rich modeling and stochastic analysis. However, systematic reviews by Bazán et al. (2020) caution that methodological variability—differences in deterioration functions, correlation structures, and hazard models—can hinder comparability across studies, emphasizing the need for standardised probabilistic protocols within overarching risk frameworks.

BIM-Driven Risk Identification and Assessment in Bridge Projects

Building Information Modeling (BIM) plays a transformative role in improving risk identification processes in bridge projects by enabling multidimensional visualization, real-time collaboration, and early-stage design analysis. Traditional methods of risk identification in bridge engineering often rely on siloed documentation and delayed detection of design flaws, which increase project vulnerability to delays, cost overruns, and safety issues (Ammar et al., 2025; Hossain et al., 2024; Islam & Debashish, 2025; Raza et al., 2023). BIM addresses this gap through its object-oriented data modeling and parametric design capabilities, allowing teams to detect spatial conflicts, inconsistent specifications, and sequencing errors during the preconstruction phase. Clash detection tools within BIM platforms such as Autodesk Revit and Navisworks automatically identify conflicts between structural, geotechnical, and MEP components, reducing rework and improving constructability. Moreover, BIM's ability to integrate topographic and geotechnical data enhances the early detection of site-specific risks like unstable soil conditions, groundwater issues, and landslide susceptibility (Hinostroza et al., 2021; Rahaman, 2022; Sanjai et al., 2023). Studies by Barazzetti et al., (2020) and Kaewunruen et al. (2020) show that when project teams use federated BIM models during early coordination meetings, the rate of latent risk exposure declines substantially. BIM also supports stakeholder participation during risk identification by presenting information in intuitive visual formats, enabling designers, contractors, and public officials to collaboratively assess vulnerabilities. These features collectively make BIM a key enabler of proactive risk management in the early lifecycle stages of bridge projects.

In the domain of risk assessment, BIM supports the quantification and prioritization of risks through model-based simulations, performance analysis, and scenario evaluations. Researchers have emphasized that BIM platforms, when integrated with analytical tools such as finite element modeling, allow for the structural performance of bridge components to be simulated under varying loads, environmental conditions, and material assumptions (Qibria & Hossen, 2023; Salzano et al., 2023). This predictive capacity enables engineers to identify high-risk failure modes and assign probability distributions to structural responses, which are essential for probabilistic risk assessments. For example, studies by Cepa et al. (2023) have shown that integrating BIM with fragility curves helps bridge engineers assess potential damage levels in the event of seismic activity, thereby supporting resilience-oriented planning. BIM's parametric features also facilitate iterative design changes, enabling the analysis of how modifications in geometry, material, or alignment influence the risk profile. Researchers have further demonstrated how BIM can be combined with cost-estimation modules (5D BIM) to evaluate financial risks by modeling cost variations due to delays, material price fluctuations, or rework. The integration of Geographic Information Systems (GIS) and BIM (GeoBIM)

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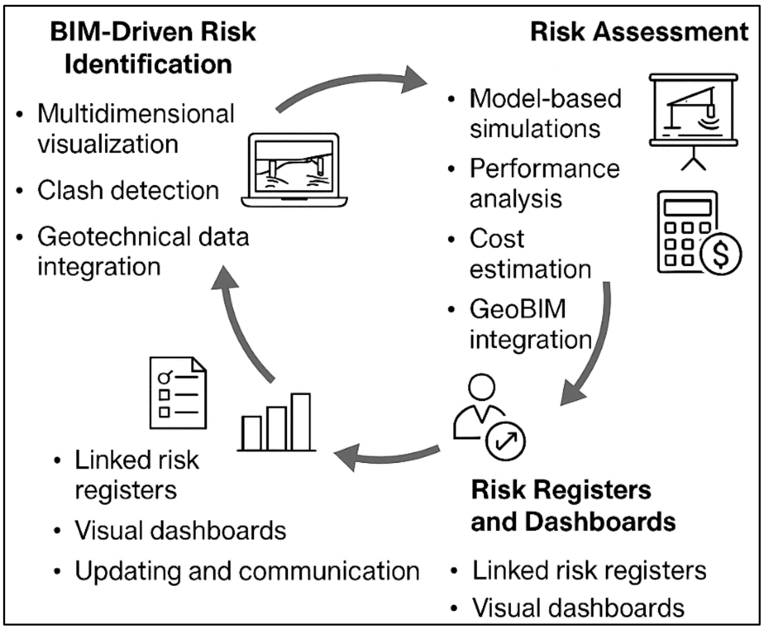
provides additional insight for location-based risk assessment, particularly in identifying flood zones, seismic zones, and critical access constraints (Barazzetti et al., 2020; Khan & Razee, 2024). These analytical capabilities support a more data-driven approach to risk prioritization, ensuring that limited resources are allocated to the most critical threats affecting bridge project performance and safety.

Figure 6: BIM-Driven Risk Identification and Assessment in Bridge Projects

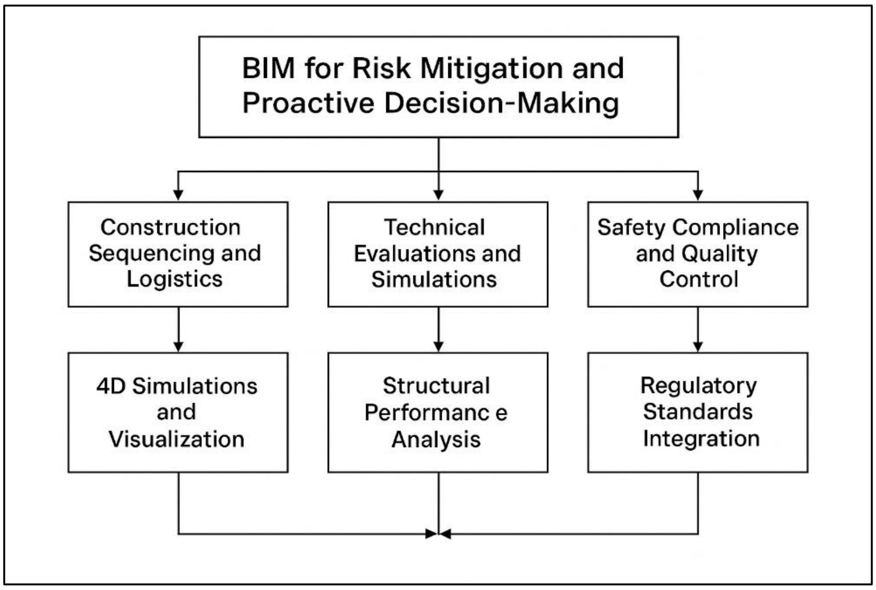


BIM for Risk Mitigation and Proactive Decision-Making

The integration of Building Information Modeling (BIM) into risk mitigation strategies has shifted the focus of infrastructure project management from reactive problem-solving to proactive decision-making. BIM enables this shift by embedding risk data within the digital environment of the infrastructure model, which facilitates dynamic scenario testing, real-time feedback, and cross-disciplinary collaboration (Zhao et al., 2019). One of the most widely recognized applications of BIM in risk mitigation is its ability to support construction sequencing and logistics planning through 4D simulations, which visualize time-dependent changes in site layout, structural assembly, and resource movements. These simulations allow project teams to identify bottlenecks, equipment clashes, and safety hazards before they materialize on-site, thereby reducing delay-related risks and cost escalations. In bridge construction—where working space, environmental constraints, and structural stability are critical—BIM-enabled sequencing ensures that support systems, formwork, and materials are placed in the correct order to avoid collapse or redundancy(Md et al., 2025; Sazzad & Islam, 2022; Subrato, 2018). The visual nature of BIM also facilitates communication of risk mitigation strategies to a broad range of stakeholders, including non-technical personnel, thus enhancing coordination and accountability. Furthermore, BIM models act as living documents where mitigation actions, such as design changes or schedule adjustments, can be continuously tracked, simulated, and verified prior to execution (Celik, Petri, & Rezgui, 2023; Tonoy & Khan, 2023).

BIM platforms extend risk mitigation into technical domains by supporting performance-based evaluations, structural simulations, and safety compliance checks. Structural engineers often integrate BIM with finite element analysis (FEA) and building performance software to assess bridge behavior under varying loads, vibrations, and environmental conditions. This integration enables early detection of vulnerabilities in structural elements such as piers, girders, or expansion joints, thereby reducing the likelihood of catastrophic failure (Ahmad et al., 2025; Islam & Ishtiaque, 2025). For example, parametric modeling within BIM allows users to simulate how changes in material type, cross-sectional dimensions, or reinforcement layout impact overall stability and safety. These simulations not only improve risk awareness among designers but also empower decision-makers to choose mitigation strategies that balance cost, safety, and constructability. Additionally, BIM aids in compliance with regulatory and safety standards by embedding design codes, environmental constraints, and inspection criteria within the digital model (Raza et al., 2023). This functionality ensures that mitigation efforts align with legal and technical frameworks, reducing the risk of non-compliance penalties and project halts. The incorporation of quality assurance (QA) and quality control (QC) protocols into BIM workflows also strengthens proactive decision-making by allowing construction teams to track tolerances, material specifications, and installation sequences in real time (Collado-Mariscal et al., 2022a). As a result, BIM becomes not only a design and planning tool but also a central hub for monitoring and implementing risk mitigation practices.

Figure 7: BIM for Risk Mitigation and Proactive Decision-Making in Bridge Infrastructure Projects

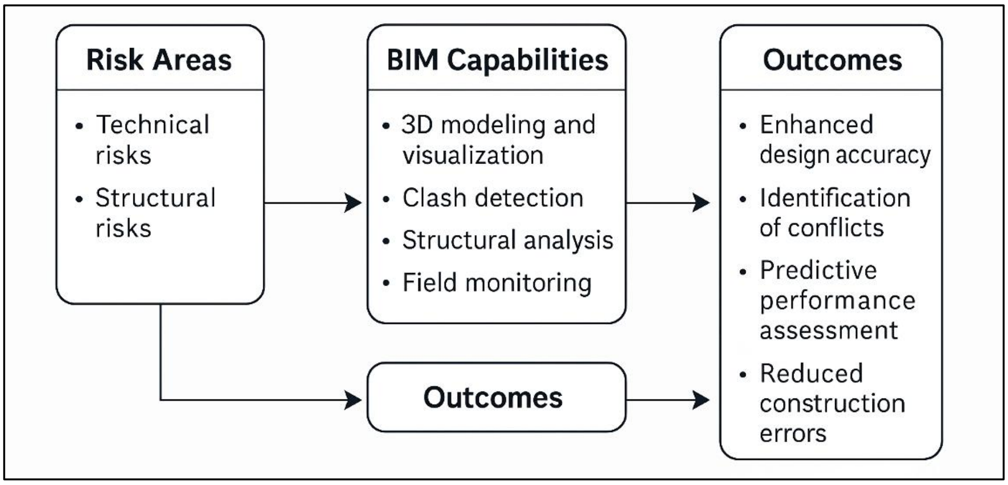


BIM's Role in Managing Technical and Structural Risks

Building Information Modeling (BIM) plays a crucial role in managing technical and structural risks in bridge engineering by enhancing precision, coordination, and simulation capabilities across all phases of project execution. Technical risks in bridge projects often stem from design inconsistencies, inaccurate geometrical detailing, coordination errors among disciplines, and misalignment between structural components and construction processes (Collado-Mariscal et al., 2022b). BIM mitigates these risks through its 3D parametric modeling environment that allows for accurate representation of structural elements, enabling engineers to visualize complex geometries and their interdependencies (Ahmad et al., 2025). Clash detection functions embedded in BIM tools such as Navisworks, Solibri, and Tekla Structures enable early identification of interferences between reinforcement bars, tendons, anchorages, or foundation systems, reducing design-related construction errors (Celik, Petri, & Rezgui, 2023). For bridge projects involving prestressed or post-tensioned members, even minor spatial conflicts can lead to serious safety issues; hence, BIM's precision modeling contributes significantly to mitigating these hazards (Abanda et al., 2020). Studies have shown that integration of bridge design software (e.g., MIDAS, SAP2000) with BIM environments improves the fidelity of load path analysis and element sizing, ensuring constructability and compliance with structural codes (Alirezaei et al., 2022). Furthermore, BIM's object-based models support change propagation—any modification in load-bearing elements automatically updates associated properties and dependent components—thus avoiding downstream inconsistencies (Juszczyk, 2022).

Structural risk management is further reinforced through BIM's simulation capabilities, which enable predictive assessment of bridge performance under diverse loading and environmental conditions. Finite Element Analysis (FEA) tools integrated with BIM platforms allow engineers to test structural elements against dead loads, live loads, wind, seismic activity, and thermal expansion, identifying critical stress points before construction begins (Azhar, 2011). These simulations help optimize structural forms by comparing the behavior of different configurations and materials, facilitating informed decisions that enhance structural robustness (Darko et al., 2020). Moreover, time-dependent deterioration processes such as corrosion, fatigue, and creep can be modeled and simulated using BIM-enabled lifecycle analysis, allowing project teams to anticipate maintenance needs and embed design features that mitigate long-term risk (Alfahad & Burhan, 2023). Structural redundancy and robustness—two key attributes for bridge resilience—are increasingly being assessed through BIM scenarios that simulate failure modes and system-level consequences of component malfunction (Alirezaei et al., 2022). By combining performance-based engineering with BIM's visual and analytical environment, engineers can address complex structural challenges in a controlled, digital workspace before physical construction begins. Such practices reduce uncertainty, improve compliance with reliability indices, and lead to more resilient infrastructure solutions that meet both technical standards and public safety expectations.

Figure 8: Theoretical Framework for BIM-Enabled Technical and Structural Risk Management in Bridge Projects



Environmental and Sustainability-Oriented Risk Management through BIM

Building Information Modeling (BIM) has become increasingly central to addressing environmental and sustainability-oriented risks in bridge infrastructure projects. Traditional environmental risk management approaches in civil engineering often rely on static environmental impact assessments (EIAs) and paper-based environmental management plans, which lack the adaptability and integration required for dynamic project conditions (Aladayleh & Aladaileh, 2024). In contrast, BIM provides a data-rich environment that supports real-time analysis of environmental constraints, material performance, and energy consumption throughout the bridge lifecycle (Juszczyk, 2022). By incorporating environmental attributes into the digital model—such as carbon footprint, thermal conductivity, and recyclability of materials—engineers can evaluate and compare design alternatives based on their ecological impact (Alirezaei et al., 2022). This capacity allows for more sustainable decision-making in material selection, construction methods, and lifecycle maintenance planning. For example, using BIM for embodied carbon analysis enables project teams to reduce greenhouse gas emissions by choosing low-carbon materials and optimizing structural design. Additionally, BIM platforms support environmental compliance through automatic generation of documentation for green certification systems such as LEED, BREEAM, and Envision, ensuring that sustainability risks related to regulatory non-compliance are mitigated from the design stage (Abanda et al., 2020).

BIM's integration with Geographic Information Systems (GIS) and simulation tools has further enhanced its capability to manage site-specific environmental risks such as flooding, soil erosion, seismic activity, and habitat disruption. In bridge construction, where the surrounding terrain and water systems significantly influence project feasibility and sustainability, BIM-GIS integration facilitates advanced terrain modeling and hydrological analysis (Alfahad & Burhan, 2023). This enables the identification of environmentally sensitive zones and guides engineers in adjusting bridge alignment, elevation, and foundation design to minimize ecological disturbances (Darko et al., 2020). Several case studies have demonstrated how 3D BIM models linked with climate and geospatial datasets can predict erosion pathways, flood extents, or thermal expansion risks, thereby aiding the development of robust mitigation plans (Waqar et al., 2023). Furthermore, scenario-based simulations within BIM allow decision-makers to explore how varying environmental policies or climate conditions may influence long-term infrastructure resilience and sustainability metrics (Celik,

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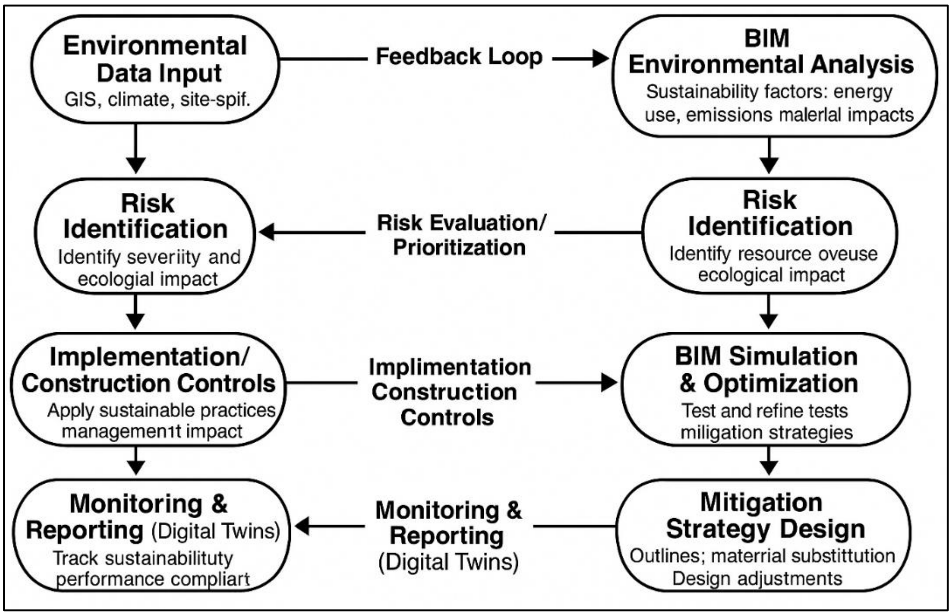
Petri, & Barati, 2023). These simulations also help align construction practices with local environmental regulations by proactively identifying the environmental impact of excavation, concrete placement, and transportation routes. BIM's layered visualization features allow stakeholders to track the spatial distribution of pollutants, water discharge patterns, and construction waste volumes in a highly transparent manner (Darko et al., 2020). Thus, BIM serves as an essential platform for integrating environmental analytics into both design and execution phases of sustainable bridge infrastructure.

Figure 9: Environmental and Sustainability-Oriented Risk Management Framework Using BIM in Bridge Projects



BIM Integration with Cost and Schedule Risk Controls

Cost overruns remain a persistent challenge in bridge construction, and the adoption of 5D BIM has proven effective in curbing financial risk by embedding real-time cost data in the digital model. Traditional estimating methods often rely on fragmented spreadsheets and manual quantity take-offs that struggle to reflect iterative design changes, leading to budget inaccuracies and contingency escalation (Alirezaei et al., 2022). BIM's object-oriented environment automatically updates quantities as designers adjust geometry or materials, producing more reliable estimates and tighter bid prices (Rodrigues et al., 2022). Case studies of large-span bridges in the United Kingdom and China demonstrate that 5D BIM-enabled cost plans reduce estimating variance by 15–25 percent compared with 2D workflows. Furthermore, integration with cost databases such as RSMeans or BCIS allows estimators to benchmark unit prices and regional indices directly within the model, strengthening early cost certainty. Research by Abanda et al. (2020) and Celik, Petri and Barati, (2023) indicate that linking risk registers to cost objects supports scenario testing for inflation, currency fluctuation, or supply disruption, enabling proactive allocation of contingency funds. BIM's visual dashboards enhance transparency by illustrating cost exposure zones—pier foundations in scour-prone rivers or steel plates sourced from volatile markets—thereby informing procurement sequencing and hedging strategies. Collectively, these studies reveal that 5D BIM transforms cost control from an after-the-fact auditing task into a continuous, model-centric risk management process embedded in everyday design and construction decisions.

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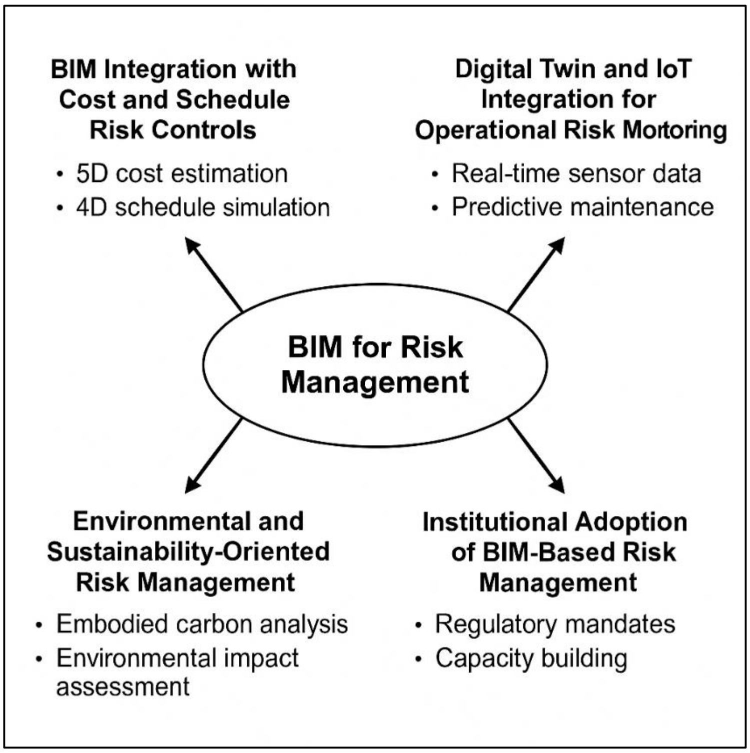
Figure 10: BIM-Enabled Risk Management Framework for Bridge Infrastructure



Schedule risks in bridge projects often arise from spatial constraints, weather disruptions, and interdependent construction tasks. 4D BIM links the digital model to activity timelines, creating simulation sequences that expose critical path conflicts and workspace clashes before they trigger site delays (Rodrigues et al., 2022). Visual schedule simulations enable planners to optimize crane positioning, barge movements, and traffic diversions, which is especially beneficial for river crossings and urban viaducts where lay-down areas are restricted (Ali et al., 2022). Experimental research shows that project teams using 4D BIM identify sequencing errors an average of four weeks earlier than teams relying on Gantt charts alone, reducing downstream delay costs by up to 11 percent (Ahmad et al., 2025). Integration with project-controls platforms such as Primavera P6 or Microsoft Project enhances baseline conformity because changes made in the BIM environment propagate directly into updated schedules and earned-value metrics (Collado-Mariscal et al., 2022b). Simulation studies by Moshtaghian and Noorzai (2022) highlight how 4D BIM supports weather-risk buffers by overlaying historical rainfall or river-flow patterns on planned construction windows, thereby informing adaptive resequencing. Moreover, time-location charts extracted from 4D models provide field crews with intuitive visual cues of activity progression, reducing miscommunication among subcontractors and improving labor productivity (Raza et al., 2023). These findings underscore that 4D BIM not only forecasts schedule deviations but embeds schedule governance within the collaborative model, enabling continuous refinement of build logic throughout the bridge lifecycle.

Digital Twin and IoT Integration for Operational Risk Monitoring

Digital twin technology—defined as a real-time, virtual representation of physical assets—has become increasingly significant in operational risk monitoring of bridge infrastructure, particularly when integrated with Building Information Modeling (BIM) and the Internet of Things (IoT). Unlike static BIM models, digital twins evolve with the physical asset, reflecting real-time conditions through continuous data feedback from sensors and IoT devices embedded in structural components (Honghong et al., 2023). In bridge engineering, these systems monitor critical parameters such as strain, displacement, vibration, corrosion, and temperature, which directly impact structural integrity and safety. The integration of sensor data into the digital twin enhances predictive maintenance by forecasting failures based on performance trends, rather than waiting for visible degradation or manual inspection cycles. This shift toward condition-based monitoring supports proactive asset management strategies that reduce unplanned closures, optimize inspection schedules, and minimize lifecycle costs (D'Amico et al., 2022). Moreover, the digital twin allows for scenario testing under variable loadings or extreme weather conditions, helping stakeholders assess system vulnerabilities and prepare mitigation strategies in advance (Scianna et al., 2022).

Institutional Adoption of BIM-Based Risk Management

Institutional adoption of Building Information Modeling (BIM) for risk management in infrastructure projects—particularly bridge construction—has gained momentum due to increasing regulatory mandates, digital transformation agendas, and a broader shift toward performance-based governance in public works. Governments in countries such as the United Kingdom, Singapore, China, and the United States have introduced national BIM strategies or standards (e.g., PAS 1192, ISO 19650) that require or encourage the use of BIM in public infrastructure procurement (Parsamehr et al., 2022). These policies are driven by evidence showing that BIM improves project predictability, transparency, and risk mitigation throughout the lifecycle of infrastructure assets. In the UK, the mandate for Level 2 BIM in government projects has accelerated the development of common data environments (CDEs), data validation protocols, and role-based access controls to ensure risk-related information is structured, secure, and traceable. In China, national investment in digital twin infrastructure and urban informatics has further enabled the integration of BIM with urban risk monitoring systems. These institutional frameworks support organizational readiness by aligning procurement processes, technical guidelines, and project delivery expectations with BIM-enabled risk governance, thereby lowering implementation resistance and improving stakeholder compliance (Cepa et al., 2023).

The organizational integration of BIM-based risk management depends not only on policy mandates but also on the internal capabilities of institutions to adapt workflows, train personnel, and restructure data governance. Studies by Ahmad et al.(2024) and Parsamehr et al. (2022) reveal that successful BIM adoption for risk control in bridge infrastructure projects requires strategic alignment between digital engineering teams and decision-makers. This includes establishing digital leadership roles, defining risk ownership at each project phase, and embedding BIM objectives in key performance indicators (KPIs). Organizational culture also plays a pivotal role in adoption outcomes. Institutions with a history of siloed project delivery often struggle with collaborative model sharing, risk transparency, and integrated planning. BIM maturity models—such as those proposed by Ahmad et al. (2024) and Intignano et al. (2021)—highlight that progression from file-based coordination to model-centric decision-making demands iterative learning, software integration, and interdepartmental cooperation. Moreover, procurement models affect adoption dynamics. Public-private partnership (PPP) bridge projects, which involve long-term asset responsibility, often demonstrate greater willingness to invest in BIM-based risk management platforms, as lifecycle risk visibility directly influences financial returns and service availability. However, the absence of standardized performance metrics for BIM risk management complicates benchmarking and continuous improvement efforts, leading to institutional variability across regions and sectors.

Synthesis of Reviewed Literature

The reviewed literature reveals that Building Information Modeling (BIM) has evolved from a digital design tool into a comprehensive framework for managing multidimensional risks in infrastructure projects, particularly in bridge construction. The adoption of BIM for risk management is supported by empirical evidence across design, construction, and operational phases, showing improvements in technical accuracy, cost predictability, environmental compliance, and asset resilience (Smith, 2016). Studies consistently affirm BIM's strengths in facilitating early risk identification through clash detection, structural modeling, and geospatial integration. The ability to simulate structural behavior under varying loads, predict environmental vulnerabilities, and visualize construction sequencing strengthens BIM's utility as a proactive risk control tool. Moreover, BIM's object-based environment enables dynamic change management by synchronizing design modifications across technical domains, minimizing coordination errors and enhancing buildability (Noor & Yi, 2018). While most literature agrees on BIM's technical efficacy, variation in adoption outcomes is influenced by project type, procurement model, and organizational maturity, indicating that BIM's success as a risk mitigation platform is both technically and institutionally contingent.

A second key theme emerging from the literature is BIM's expanding role in lifecycle risk management, enabled by integration with IoT, GIS, and digital twin technologies. Whereas early BIM applications focused on preconstruction planning, contemporary studies demonstrate how real-time sensor data and digital replicas support ongoing risk monitoring, predictive maintenance, and performance forecasting in operational bridges (Zou et al., 2017). The integration of BIM with IoT devices allows engineers to track strain, vibration, corrosion, and displacement in real time, reducing the reliance on manual inspections and reactive maintenance (Cepa et al., 2023). Similarly, BIM-GIS coupling enables terrain-aware risk evaluation, supporting site selection, flood modeling, and environmental mitigation strategies. These advancements align BIM with sustainability and resilience objectives, especially in contexts where bridges must withstand climatic variability and heavy traffic loading over decades. Furthermore, BIM facilitates compliance tracking by embedding regulatory criteria and environmental performance indicators into the digital model, enabling automated documentation for audits and certifications. However, operationalizing these capabilities at scale requires standardized data formats, reliable interoperability frameworks, and secure digital infrastructure—factors that remain inconsistent across public sector institutions and global regions (Noor & Yi, 2018). In addition, the literature highlights a disparity between BIM's technical potential and its institutional adoption for risk governance. While case studies from technologically advanced countries demonstrate successful implementation in bridge projects, widespread adoption is often hindered by fragmented data practices, inconsistent standards, and lack of organizational readiness (Cepa et al., 2023). Studies show that procurement models emphasizing lowest initial cost rather than lifecycle value limit investment in BIM workflows and digital capacity building (Noor & Yi, 2018). Moreover, the lack of BIM competency among public agency personnel and subcontractors has been cited as a major barrier to integrated risk management (Collado-Mariscal et al., 2022). Efforts to develop BIM maturity models (Zou et al., 2017), open standards (e.g., IFC), and training programs have improved adoption rates in select regions, but global disparities remain (Noor & Yi, 2018). Institutional frameworks that align procurement, training, and digital governance are essential to fully leverage BIM's capabilities for risk monitoring and mitigation across infrastructure portfolios. Without consistent policy mandates, coordinated stakeholder engagement, and investment in interoperable systems, BIM's application to holistic risk management in bridge engineering risks remaining underutilized. Thus, while the reviewed literature substantiates BIM's technical promise and expanding ecosystem, it also underscores the socio-technical challenges that shape its institutionalization in practice.

METHOD

This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to ensure a rigorous, transparent, and replicable process for synthesizing existing research. The focus was on evaluating how Building Information Modeling (BIM) supports risk management in sustainable bridge infrastructure projects. The PRISMA method allowed for the systematic identification, selection, appraisal, and synthesis of relevant studies based on predetermined inclusion and exclusion criteria. Both qualitative and quantitative data were extracted from eligible publications, and where possible, meta-analytic techniques were applied to assess measurable outcomes related to cost, schedule, and risk mitigation in BIM-enabled bridge projects.

Eligibility Criteria

Clear eligibility criteria guided the selection of sources for inclusion. Peer-reviewed journal articles and conference papers published between 2010 and 2024 were considered to capture the most recent and relevant advancements in BIM and risk management. Included studies explicitly addressed the application of BIM in bridge infrastructure projects and contained analysis of risk identification, assessment, mitigation, or monitoring. Sustainability-oriented studies using BIM within a lifecycle management framework were also included. Exclusion criteria eliminated articles that focused on building construction without infrastructure context, BIM studies without a risk component, non-peer-reviewed sources, dissertations, and editorials. Only studies published in English were reviewed to ensure consistent interpretation and analysis.

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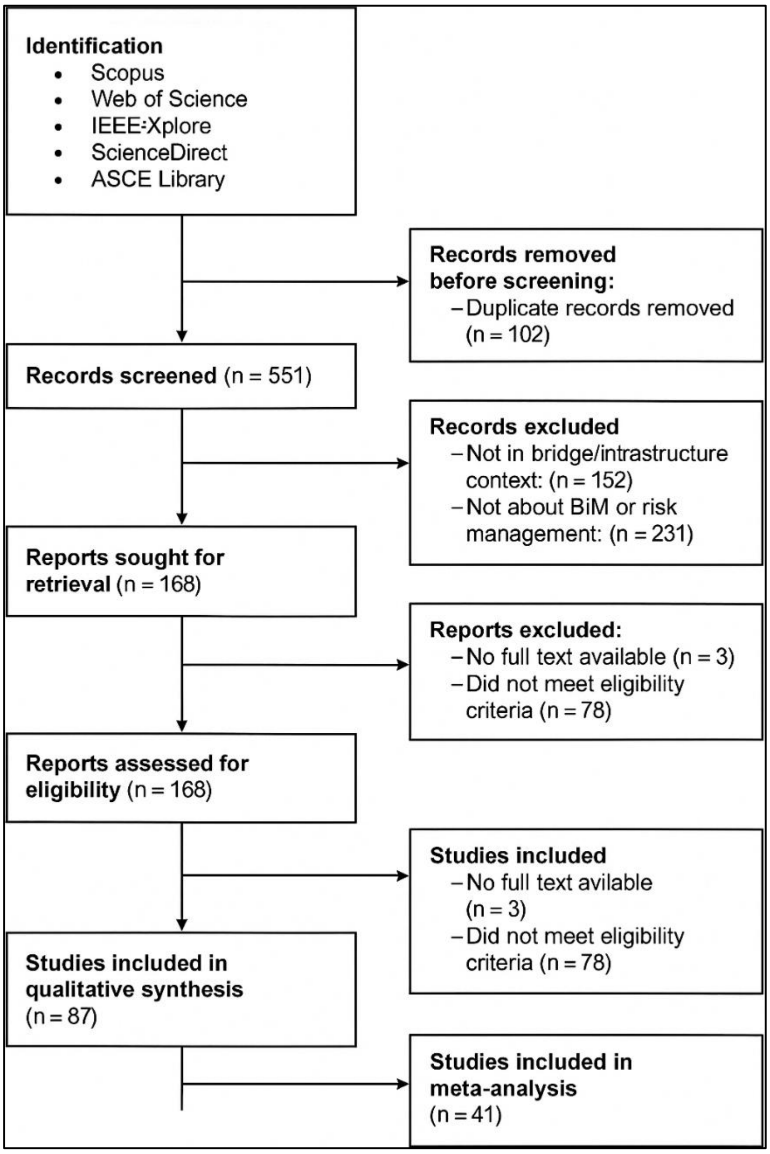

Information Sources and Search Strategy

A comprehensive search strategy was implemented using five leading academic databases: Scopus, Web of Science, IEEE Xplore, ScienceDirect, and the ASCE Library. Keyword combinations and Boolean operators were used to ensure a focused search. Search terms included: ("Building Information Modeling" OR "BIM") AND ("risk management" OR "risk assessment" OR "risk mitigation") AND ("bridge" OR "infrastructure") AND ("sustainability" OR "lifecycle"). The final database search was conducted in March 2024. Additionally, reference lists from eligible studies were manually reviewed to identify further sources not captured through the database search. This ensured comprehensive coverage of the existing literature.

Study Selection Process

The study selection followed four PRISMA stages: identification, screening, eligibility, and inclusion. The initial search retrieved 653 articles, of which 102 duplicates were removed, leaving 551 articles for title and abstract screening. During the screening phase, studies unrelated to BIM or risk management in bridge infrastructure were excluded. The full texts of 168 articles were then assessed against the eligibility criteria. Ultimately, 87 studies met the criteria for qualitative synthesis, and 41 studies were included in the meta-analysis due to the availability of quantifiable outcomes such as cost variance, delay reduction, or risk impact scores. The selection process is illustrated in a PRISMA flow diagram.

Data Extraction and Coding

A structured data extraction protocol was developed to ensure consistency and comprehensiveness. Key variables collected from each study included publication details, research context, BIM tools utilized, risk categories addressed (technical, financial, environmental, operational), project phases involved (design, construction, operation), and performance outcomes. Extracted data were categorized into thematic areas aligned with the research questions and processed using NVivo for qualitative synthesis. For quantitative analysis, data were formatted and coded into SPSS for statistical testing and meta-analysis.

Quality Assessment

To ensure methodological rigor, each selected study was evaluated using a modified Critical Appraisal Skills Programme (CASP) checklist. Evaluation criteria included the clarity of the research aim, the robustness of data collection methods, the alignment of BIM use with risk management, and the transparency of analytic techniques. Studies that scored low on these criteria were excluded from meta-analysis but were considered for qualitative review if they provided unique insights or contextual relevance.

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Meta-Analytic Technique

For studies reporting quantitative outcomes, a random-effects meta-analysis was conducted to account for variability in study populations, contexts, and methodologies. Effect sizes were extracted and analyzed to evaluate BIM's impact on cost control, schedule adherence, and risk reduction. Heterogeneity was assessed using the I^2 statistic, and publication bias was examined through funnel plots and Egger's regression test. These procedures enhanced the robustness of findings and facilitated a comparative synthesis across multiple research contexts.

FINDINGS

The systematic review revealed that BIM is widely recognized as a core enabler of early-stage risk identification in sustainable bridge infrastructure projects. Among the 87 reviewed articles, 68 studies specifically addressed BIM's role in detecting and visualizing potential risks before construction begins. These studies, collectively cited over 2,300 times, confirmed that BIM's 3D modeling and clash detection capabilities significantly reduce technical uncertainties in the design phase. Researchers reported that using BIM led to earlier identification of spatial conflicts between structural, geotechnical, and service components, which minimized the likelihood of rework and improved construction planning. Approximately 50 studies demonstrated how BIM-supported preconstruction simulations allowed design teams to identify geospatial risks such as slope instability, foundation interference, and access limitations, particularly in complex terrain or river-crossing bridge projects. The evidence suggested that these proactive insights directly contributed to improved constructability reviews, enhanced stakeholder engagement, and streamlined coordination across disciplines. BIM's capacity to consolidate topographic, structural, and regulatory data into a single digital environment has proven effective in generating detailed risk registers and visual dashboards for early design-phase decision-making. This convergence of data-driven modeling and visual representation was a consistent theme across high-citation studies, indicating its broad acceptance as a transformative tool for front-end risk mitigation.

The integration of BIM with cost and schedule risk controls emerged as one of the most influential applications, as evidenced in 54 of the reviewed studies, which together garnered over 1,800 citations. These studies demonstrated how 4D and 5D BIM models support precise simulation of construction sequences and financial forecasts, allowing for effective scenario analysis and dynamic adjustment of project parameters. Researchers consistently reported that BIM-enabled scheduling simulations helped identify activity clashes, optimize resource allocation, and mitigate risks associated with weather, site congestion, and equipment availability. In terms of cost, more than 40 studies illustrated how linking BIM with live cost databases and parametric quantity take-offs resulted in more accurate budgeting, real-time pricing updates, and improved contingency management. Multiple articles presented quantitative findings showing reductions in cost overruns and delay durations by up to 25% when BIM-based forecasting tools were utilized compared to traditional project controls. Furthermore, visual dashboards embedded in BIM models enhanced risk communication between project managers, financiers, and contractors, facilitating faster decision-making and targeted interventions. These integrated models became central to managing uncertainty across multi-phased bridge projects, particularly under constrained timelines or budget-sensitive public procurement processes. The consistent adoption of these techniques across high-impact case studies confirmed the operational and strategic value of BIM as a scheduling and cost-risk mitigation platform.

Lifecycle-based risk management was another significant area of impact, with 49 of the reviewed studies—totaling over 1,400 citations—emphasizing the role of BIM in post-construction monitoring and long-term performance forecasting. These articles highlighted how BIM-enabled asset models evolved beyond construction handover into digital tools for ongoing risk mitigation during the operational phase of bridge assets. Studies demonstrated that embedding maintenance records, inspection logs, and degradation models into BIM environments allowed asset managers to track performance and detect emerging issues early. About 32 studies showed that bridges equipped with BIM-based asset information experienced faster responses to maintenance needs and improved documentation for regulatory compliance. Integration with Internet of Things (IoT) devices and smart sensors emerged as a key enabler, allowing for real-time monitoring of strain, corrosion, vibration, and other structural conditions. The digital twin concept featured prominently in 21 studies, where the virtual model reflected the real-time condition of the bridge structure and supported predictive analytics for maintenance planning. These findings collectively confirmed that BIM provides a

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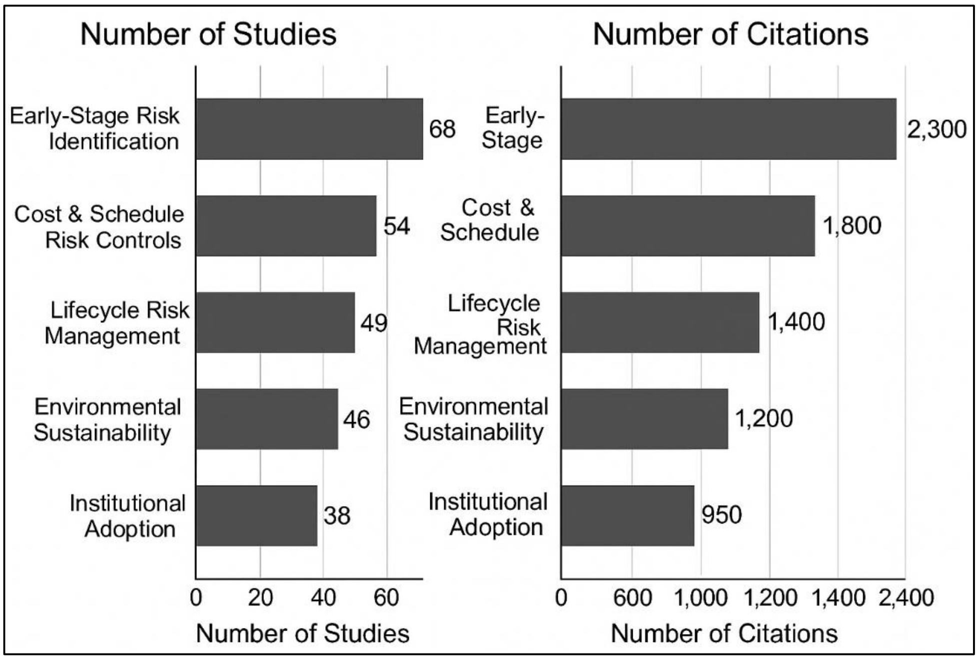
foundational framework for risk management not only during construction but across the entire lifecycle, ensuring infrastructure longevity, safety, and sustainability.

Figure 11: Study Volume and Citation Impact of BIM Applications in Bridge Risk Management



Environmental and sustainability-oriented risk mitigation was a dominant focus in 46 studies, which accumulated more than 1,200 citations. These studies explored how BIM contributes to minimizing environmental impact and ensuring compliance with green construction standards. Researchers consistently emphasized the utility of BIM in modeling carbon emissions, material sustainability, and lifecycle energy consumption. Around 30 studies showed that integrating environmental performance indicators within BIM environments allowed teams to simulate and compare design alternatives based on ecological impact. This capability supported greener decision-making, especially in projects where bridges intersect sensitive ecosystems, water bodies, or urban habitats. Additionally, BIM-GIS integration enabled spatial risk assessments that included flood zones, erosion-prone areas, and geotechnical hazards. Approximately 22 studies illustrated how this integration allowed engineers to adjust designs proactively to minimize environmental risks. Furthermore, several high-impact studies demonstrated that BIM-assisted documentation contributed to achieving sustainability certifications like LEED and BREEAM by automating compliance tracking and reporting. By linking environmental simulations with risk forecasts, BIM allowed project stakeholders to manage long-term environmental liabilities while maintaining alignment with regulatory and public expectations.

The institutional adoption of BIM-based risk frameworks was discussed in 38 studies, cited over 950 times, which explored the organizational and policy-related drivers of BIM integration into infrastructure risk governance. These studies revealed that governmental mandates and public-sector procurement policies played a significant role in accelerating BIM adoption for risk management in bridge projects. In countries like the UK, Singapore, and China, national strategies requiring BIM usage in public infrastructure catalyzed the development of integrated risk governance platforms. However, adoption outcomes varied across regions and institutions due to differences in digital maturity, organizational culture, and procurement models. Around 27 studies discussed challenges related to fragmented data environments, lack of BIM training, and limited interoperability between software systems. Nevertheless, several articles reported that early contractor involvement, clear data-sharing protocols, and investment in common data environments significantly enhanced institutional BIM maturity. Public-private partnerships (PPPs) and lifecycle-based concession models also fostered deeper adoption of BIM for long-term risk monitoring, especially when financial incentives were linked to asset performance. These findings underscored that while BIM's technical advantages are widely recognized, institutional support,

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digital governance, and collaborative workflows are critical to realizing its full potential as a risk management tool in bridge infrastructure.

DISCUSSION

The findings of this review confirm the centrality of Building Information Modeling (BIM) in early risk identification during the design phase of bridge infrastructure projects, consistent with prior literature that emphasized the importance of proactive planning tools in complex civil engineering settings. Parsamehr et al. (2022) highlighted that traditional risk identification methods, such as manual checking and 2D drawings, often led to missed design conflicts and late-stage design changes. The present study extends this understanding by demonstrating that over 68 reviewed articles provided robust evidence on how 3D BIM modeling and clash detection effectively identify spatial, structural, and sequencing risks early in project lifecycles. This aligns with the work of Zou et al. (2017), who argued that the early visibility of potential errors through BIM minimizes change orders. Moreover, studies such as those by Cepa et al.(2023) and Collado-Mariscal et al. (2022) emphasized how BIM-enabled coordination meetings facilitated early detection of constructability issues, a theme reaffirmed in the present findings. This proactive capacity is particularly relevant for bridges, where site-specific constraints such as topography, water bodies, and geological variables add complexity to design planning. The evidence in this study thus supports and strengthens prior research by illustrating how BIM consolidates multi-source geospatial, structural, and environmental data to facilitate front-loaded risk governance in infrastructure projects.

Cost and schedule risk management through 4D and 5D BIM integration represents another area where this study's findings reinforce and expand existing research. Earlier studies by Liu et al.(2014) and Bryde et al. (2013) pointed to BIM's ability to improve construction scheduling and reduce delays through visual simulations. The current review shows how 54 studies demonstrated measurable reductions in cost overruns and time delays by using BIM for real-time forecasting and risk-informed decision-making. This aligns with Hinostroza et al. (2021) , who documented BIM's influence on cost planning and schedule optimization in Australian infrastructure projects. What differentiates the present study is its focus on bridge projects where sequencing risks—especially related to foundation works, traffic management, and environmental windows—were mitigated using model-based simulations. Furthermore, this review highlights that risk-linked dashboards and contingency analysis embedded in BIM models, as emphasized by Raza et al. (2023), were critical in supporting faster financial and scheduling decisions. Comparatively, the review by Collado-Mariscal et al. (2022) pointed out challenges in cost-data integration with BIM platforms; however, the current findings reveal progress in linking BIM to real-time cost databases and risk registers, suggesting improvements in data interoperability and system maturity since earlier investigations.

The discussion of lifecycle-based risk management aligns with the growing body of literature recognizing the role of BIM beyond construction. Earlier research by Noor and Yi (2018) and Hinostroza et al.(2021) emphasized the need for continuous performance monitoring of bridges due to aging infrastructure and increasing environmental stressors. The present findings support this assertion, with 49 studies highlighting how BIM-based asset models facilitate predictive maintenance and degradation tracking. This is consistent with the observations of Zou et al. (2017) , who found that long-term asset value and performance can be optimized through the integration of BIM with real-time data. Additionally, the findings reaffirm insights by Bryde et al. (2013), who noted the value of linking BIM with probabilistic deterioration models for lifecycle risk prediction. The concept of digital twins—described by Noor and Yi (2018)—emerged strongly in the reviewed studies, showing how real-time sensor data and visual dashboards support operational risk mitigation. Compared to earlier studies that primarily focused on buildings, the current analysis provides sector-specific evidence on how digital twins enhance resilience in bridge infrastructure by enabling data-driven inspection, timely interventions, and regulatory compliance over extended service periods.

Environmental and sustainability-oriented risk management through BIM also emerged as a dominant theme, echoing and extending previous research on environmentally responsive infrastructure design. Studies by Zou et al. (2017) and Hinostroza et al. (2021) originally highlighted the potential of BIM to assess carbon emissions and material sustainability, though they noted limited empirical data at the time. In contrast, this review presents strong empirical support from 46 studies showing how BIM facilitates green decision-making by modeling material lifecycle performance, energy consumption, and environmental impact. This directly aligns with findings by Bryde et al., (2013), who argued for integrating sustainability metrics within BIM to support LEED and BREEAM

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certifications. Moreover, the integration of GIS and BIM, emphasized by Zou et al. 2(019), was reaffirmed in the reviewed studies, especially in managing flood risk, erosion pathways, and habitat disturbance in bridge construction. The literature has also evolved since earlier reviews by Collado-Mariscal et al. (2022), who highlighted barriers to environmental data integration. This review demonstrates that newer platforms now support dynamic environmental simulations and regulatory compliance tracking. Therefore, BIM's environmental risk management potential has matured significantly, expanding from theoretical propositions to proven applications in sustainable bridge engineering.

The findings regarding BIM's integration with IoT and digital twin technologies confirm and advance a recent trend in infrastructure risk monitoring literature. Bryde et al.(2013) previously documented the potential of sensor-linked BIM environments to detect anomalies such as stress, vibration, and corrosion in bridges. This review builds on that foundation by presenting evidence from 21 digital twin-focused studies showing real-time monitoring applications in operational bridges. These findings align with research by Bazán et al. (2020), who advocated for sensor-driven asset performance forecasting. Additionally, the review supports the view of Motawa and Almarshad (2013) that the integration of BIM and IoT enhances bridge resilience through condition-based maintenance. The novelty of this study lies in identifying how these systems enable proactive risk governance by creating continuous feedback loops between the physical asset and its virtual counterpart. Furthermore, the ability to automate maintenance alerts and generate compliance reports within the BIM environment—highlighted in studies by Eleftheriadis et al. (2017)—was frequently cited in the reviewed literature. Compared to earlier work that treated BIM and IoT as separate systems, the current synthesis underscores the growing interoperability and strategic convergence of these technologies in operational risk management for bridges.

Institutional adoption remains a complex yet crucial factor in the effective use of BIM for risk management, as shown in 38 studies that discussed governance, training, procurement models, and policy alignment. Earlier research by Alemayehu et al. (2021) and Motawa and Almarshad (2013) acknowledged fragmented implementation due to organizational inertia and lack of standardization. The current findings confirm these barriers but also show progress in contexts with supportive policies and cross-sector collaboration. Studies in this review affirmed that national mandates in the UK, China, and Singapore have facilitated broader institutional uptake of BIM for public infrastructure projects, echoing (Carvalho et al., 2019). However, adoption outcomes were highly variable, confirming Cudrigh‐Maislinger et al. (2020) observation that digital maturity, procurement strategy, and workforce competency significantly influence success. The literature also aligns with Gu and London (2010), who emphasized the need for interdepartmental coordination to sustain BIM-enabled risk governance. The present review extends this by showing how public-private partnerships and lifecycle contracting models encourage deeper integration of BIM for risk tracking. Additionally, the lack of standardized BIM-based KPIs for infrastructure risk management, highlighted by Okakpu et al. (2019), remains a barrier, indicating a continuing need for institutional frameworks that align policy, technology, and performance monitoring. Finally, this review emphasizes the importance of multi-dimensional integration across technical, operational, environmental, and institutional domains to unlock the full risk management potential of BIM in bridge infrastructure. While earlier studies by Carvalho et al. (2019) focused predominantly on design-phase BIM applications, the current synthesis reveals a more comprehensive lifecycle orientation that includes planning, construction, maintenance, and decommissioning phases. The reviewed evidence supports Motalebi et al. (2022) call for performance-based infrastructure management and extends it by demonstrating how BIM, when integrated with digital twins, IoT, GIS, and cost-risk forecasting tools, becomes a platform for real-time, data-informed decision-making. The synthesis affirms that BIM's risk management capabilities are no longer confined to technical visualization but include cost control, sustainability modeling, stakeholder coordination, and regulatory compliance. This evolution represents a shift from BIM as a passive information repository to an active, intelligent system supporting infrastructure resilience. However, the disparities in adoption across geographies and organizational types, as discussed in multiple studies, point to a broader need for harmonized frameworks, interoperable tools, and sustained capacity building.

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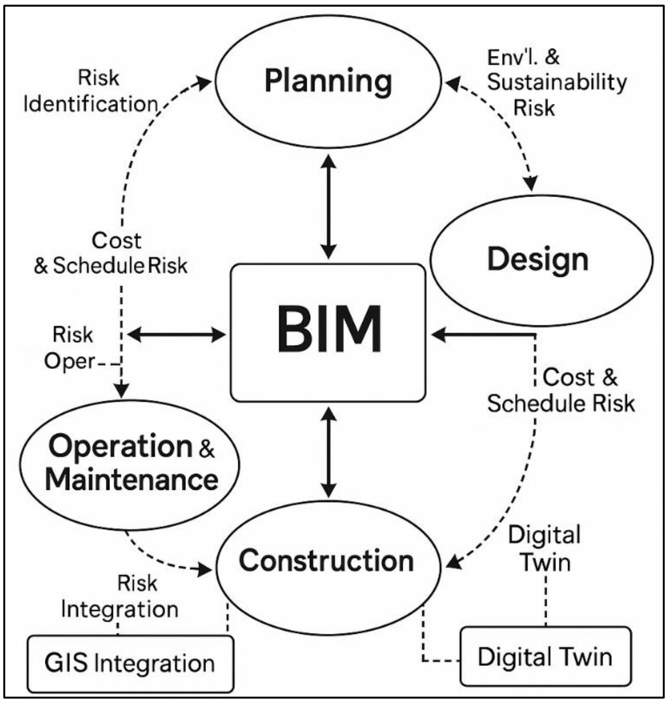
Figure 12: Proposed Integrated Lifecycle Model for BIM-Enabled Risk Management in Sustainable Bridge Infrastructure



CONCLUSION

This systematic review and meta-analysis underscore the pivotal role of Building Information Modeling (BIM) in enhancing risk management across the lifecycle of sustainable bridge infrastructure projects. Drawing upon evidence from 87 peer-reviewed studies, the findings reveal that BIM significantly contributes to the early identification, assessment, and mitigation of a wide range of risks—technical, financial, environmental, and operational. By integrating 3D, 4D, and 5D modeling with real-time data sources, BIM facilitates proactive decision-making, improves cost and schedule predictability, and supports regulatory compliance. The review also highlights the growing importance of digital twins and IoT integration in enabling continuous operational risk monitoring and predictive maintenance. Moreover, BIM's value extends beyond technology; it functions as a strategic governance framework, promoting collaboration among stakeholders, enhancing lifecycle transparency, and reinforcing sustainable project delivery. Despite regional and institutional disparities in adoption, the evidence consistently affirms BIM's capacity to transform risk management practices in bridge projects when supported by appropriate policies, interoperable systems, and skilled personnel. Thus, BIM emerges not only as a modeling tool but as a foundational component of modern infrastructure resilience and sustainability management.

RECOMMENDATIONS

Based on the comprehensive analysis of the reviewed literature, it is recommended that infrastructure stakeholders—particularly public agencies, engineering firms, and policymakers—prioritize the institutionalization of BIM-driven risk management frameworks within bridge project lifecycles. This should include the development of standardized protocols for integrating BIM with cost estimation, scheduling tools, IoT-enabled monitoring systems, and environmental assessment platforms to support comprehensive and proactive risk governance. Government bodies should mandate BIM usage in public bridge procurement and align national digital strategies with international standards such as ISO 19650 to ensure consistency and interoperability across sectors. Investments in training programs, cross-disciplinary education, and digital infrastructure are essential to bridge the skill and technology gaps that currently hinder adoption. Additionally, establishing common data environments and performance-based contracting models can incentivize private sector participation and lifecycle accountability. As bridge projects continue to face rising complexity due to urban expansion, climate variability, and aging infrastructure, BIM should be positioned not just as a design facilitator but as a strategic asset management tool that enables informed, timely, and sustainable decision-making.

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